J Polym Environ (2014) 22:260–266
DOI 10.1007/s10924-013-0634-7

ORIGINAL PAPER

Wood Plastic Composite Panels: Influence of the Species, Formulation Variables and Blending Process on the Density and Withdrawal Strength of Fasteners

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Published online: 17 December 2013

Abstract In this work, the influence of four variable parameters including fiber types (poplar and rice straw), fiber contents (45, 60, and 75 wt%), fiber sizes (20–40 and 40–60 mesh), and blending methods (hot-pressing and extrusion) on the physico-mechanical properties of wood plastic composite panels were studied. Generally, the results showed that each of the above-mentioned parameters had significant effect on the nail and screw withdrawal strength (pull-out load) and density, whereas their interactions did not have highly impressive effects on the properties. All tested properties vary significantly with fiber origin. Composites filled with larger fiber size, produced panels with higher withdrawal strength and density. The effect of blending method on density was maximal. Withdrawal strength values of each sample decreased with increase in fiber loading. The lowest withdrawal strength values of nail and screw were obtained from the samples filled with rice straw. It was found that strength properties of the composites can be improved moderately by adding 45 wt% fiber, 20–40 mesh particle and poplar flour. According to the results, the blending method is a significant variable in the determination of withdrawal strength. Therefore, the blending method can be recommended based on the end product applications.

Keywords Wood plastic composite · Withdrawal strength of fasteners · Blending method · Particle size · Rice straw

Introduction

Man has a long history of using lignocellulosic materials for producing composites. Its beginning can be traced back to the ancient times when the Egyptians added straw to mud to make bricks, which proved to be very strong and durable. Today, bio-based composites are becoming attractive in both commercial and non-commercial applications [1]. Wood plastic composites (WPCs) are widely used throughout the world; the most common type of such panels is produced by mixing wood flour and plastics. These composites are transformed by extrusion processes to obtain structural building applications including, profiles, sheathings, decking, roof tiles, and window trims, with improved thermal and creep performance compared with unfilled plastics [2, 3]. In general, the stability of any building system consisting of interconnected components is directly related to the performance of the fastening elements. Common wire nails and screws are widely used for making joints on WPCs particularly in decking, outdoor furniture, etc., because of their good performance and low cost [4]. Therefore, knowledge of the withdrawal strength of nails and screws for WPCs will provide useful information about the stability and durability of the materials in the building system [5, 6]. Although numerous studies have been carried out to evaluate the withdrawal strength of different types of fasteners (such as dowel, nail, and screw) embedded in wood species and wood-based panels [7–11], little information has been reported on the withdrawal strength of nail and screw in WPCs [6, 12–14].

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Accelerated deforestation and forest degradation, in addition to a growing demand for wood-based products, have raised an important issue regarding the sustained supply of raw materials [15, 16]. Consequently, there is need for alternative resources to substitute wood raw materials. Therefore, researchers, both in industry and academia, are looking for new sources of lignocellulosic materials. Among the possible alternatives, the development of composites using agricultural residues, non-wood plant fibers, and fast-growing species could play a major role in providing the balance between supply and demand for the manufacturing of wood-based composites such as WPC [13]. Agricultural residues are excellent alternative waste materials to substitute wood because they are plentiful, widespread, and easily available. Aside from their abundance and renewability, utilization of agricultural residues has advantages for economy, environment, and technology [17].

Iran has poor natural forest resources that cover only about 7 % of the country's land area. Similar to many developing Asian countries, deforestation and over-harvesting in Iran have created environmental issues [18]. On the other hand, increasing demand for forest resources in various applications has led to the shortages of wood supply. For these reasons, in the recent years, research in Iran and elsewhere has been focused on a wide range of alternative fibers as supplements to, or as a direct substitutes for wood in the manufacture of wood-based products [19, 20]. Besides, the decision to utilize a new material in place of an established one should be taken with utmost care to ensure that all the characteristics of the new material are well understood. Therefore, this work attempts to investigate and compare the suitability of rice straw and poplar flour (a fast-growing tree) as lignocellulosic raw materials for WPC manufacture. In addition, the effects of four variables in terms of fiber origin, fiber loading level, particle size, and blending process on withdrawal strength properties of the WPCs were investigated. It is to be noted that WPCs are usually manufactured by the extrusion method, however, the size of extruded panels are limited [21]. In addition, the straw resources from agriculture are used in extrusion; thermo-degradation often occurs under the combination of high temperature and pressure [22]. Hence, in this study, hot-pressing method has been used as the alternative blending process.

Experimental

Materials

Two different types of fibrous materials were used in this study: rice straw (RS) and poplar flour (PF). The RS was obtained from farms in the northern part of Iran. The straw was cut into pieces of 4–6 cm long sticks, and then reduced to particles using a laboratory hammer-mill. The fresh poplar (*Populus deltoids*) wood was collected from experimental forest field of the Gorgan University of Agricultural Sciences and Natural Resources (Gorgan, Iran). The poplar pieces were ground into flour form using a small laboratory mill. Both particles were manually screened on a sieve and classified into two fractions, 20–40 and 40–60 mesh, and then were dried to less than 3 % moisture content. Consequently, the particles were stored in sealed plastic bags prior to compounding. Chemical compositions of the used materials are shown in Table 1.

Table 1 Chemical composition of the used materials

Material	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)	Wax (%)
Poplar	48–55	23–25	25–27	0.1–0.2	1–3
Rice straw	43–49	23–28	12–16	15–20	3–4

Table 2 Formulations of the studied WPCs

Code	PP (wt%)	MAPP (wt%)	PF (wt%)	RS (wt%)	Size[a] (mesh)
PF1	51	4	45	–	20–40
PF2	36	4	60	–	20–40
PF3	21	4	75	–	20–40
PF4	51	4	45	–	40–60
PF5	36	4	60	–	40–60
PF6	21	4	75	–	40–60
RS1	51	4	–	45	20–40
RS2	36	4	–	60	20–40
RS3	21	4	–	75	20–40
RS4	51	4	–	45	40–60
RS5	36	4	–	60	40–60
RS6	21	4	–	75	40–60

[a] Particle size

The polymer used as matrix in the experiments was polypropylene (PP) with trade name of V30S. It was supplied by Arak Petrochemical Co. (Iran). The PP was in the form of pellets with a melt flow index of 18 g/10 min at 190 °C and a density of 0.92 g/cm^3.

Maleic anhydride functionalized polypropylene, MAPP, in the form of pellets with a density of 0.91 g/cm^3, a melt flow index of 64 g/10 min, and maleic anhydride of 2 wt%, was procured from Kimia Javid Sepahan Co. (Iran).

Lab Production of Composite Panels

The whole experimental plan is shown in Table 2, where the blending formulations are summarized. Composite panels were produced with two different blending processes namely, hot-pressing and extrusion.

In the extrusion method, the raw materials were physically premixed based on the formulations, before being fed into the first zone of the extruder. All the experiments were performed in a co-rotating twin-screw extruder. The barrel temperatures of the extruder were controlled at 165, 170, 180, and 190 °C for zones 1, 2, 3, and 4, respectively. The melt temperature at the die zone was held at 190 °C and the rotation speed was 30 rpm. The temperature used for injection molded samples was 190 °C from feed zone to die zone. Finally, the specimens were conditioned at temperature of 25 ± 2 °C and relative humidity of 65 ± 5 %.

In the hot-pressing method, the raw materials were preblended based on the formulations and were then placed in a wooden molding frame and spread to fill evenly. Consequently, the materials were pre-pressed into panel mat using a laboratory scale hydraulic press (OTT, Germany). A three-step press cycle was used to allow degassing and thereby avoid panel delamination [6]. The mats were hot-pressed at 190 °C for 7 min at 3–3.5 MPa pressure, followed by removal of the pressure for 1 min to allow steam to be ejected. Then, for a second time the 3–3.5 MPa pressure was applied for 7 min. The panels were cooled at 4 MPa pressure by placing them between the two cold plates of press for 5 min. The nominal dimensions of the panels were 30 × 20 × 1 cm^3. The thickness of the panel was controlled by stop bars and the target density was 1.0 ± 0.1 g/cm^3. Consequently, all panels were trimmed and conditioned for 24 h at 65 % RH and 25 °C.

Withdrawal Testing

Specimens were tested following BS standard CEN/TS 15534-1 for withdrawal strength (pull-out load) of screw and nail fasteners using a Universal Testing Machine (PT100L). The panel samples were cut to the dimension of 5 × 5 × 1 cm^3 for the withdrawal tests. The nail and screw withdrawal tests determine the load required to pull a nail or screw from the panel specimen. The round wire nails with length of 50 mm and diameter of 2.8 mm were used. The threaded length and diameter of screw were 50 and 4.3 mm, respectively. The nail and screw was hand-driven perpendicular to the face of each specimen immediately before testing. Three nails and three screws were tested for each panel type. The nails and screws were withdrawn at a uniform rate of speed (2 mm/min) until maximum load was recorded at room temperature (23 ± 2 °C). The withdrawal strength was then determined using the following equation:

$$W = \frac{P_{max}}{L} \tag{1}$$

where W is withdrawal strength (N/mm), P_{max} is ultimate load (N) required to pull out a screw or nail from the specimen, and L is the depth of the penetrated part of the screw or nail (mm) in specimen.

Density

The densities of the composites were determined by measuring the mass and volume of each sample. The air-dried samples were oven-dried up to 103 ± 2 °C until they reached constant weights. Then, the samples were cooled in a desiccator containing calcium chloride and weighed in an analytic balance with ±0.01 g sensitivity. The mass of each sample was obtained by calculating the arithmetic mean of the mass of all of the test samples taken from the same panel. Afterward, the dimensions of the specimens were measured using a digital caliper with ±0.001 mm sensitivity and the volumes were determined by the stereo metric method. The density (D) was then calculated using Eq. (2):

$$\text{Density} = \frac{M_0}{V_0} \tag{2}$$

where M_0 is the oven dry weight (g) and V_0 is the dry volume (cm^3) of the composite sample.

Statistical Analysis

Statistical analysis was conducted using SPSS programming (version 18) method in conjunction with analysis of variance (ANOVA) techniques. Duncan's multiple range test (DMRT) was used to determine the statistical differences among the variables investigated at the 99 % confidence level.

Results and Discussion

Results of the ANOVA are shown in Table 3. The ANOVA shows that all studied properties varied significantly with single parameters in terms of blending method, fiber type, size, and content, but the effect of fiber size on density was not significant. However, there was no highly significant difference for the interactions of variable parameters. For easier comparison, changes (reduction or increment) for the properties are presented in Fig. 1.

Table 3 Analysis of variance on the effects of SD and NC contents and their interaction on some mechanical and physical properties

Source of variations	df	Mean of squares			Nail		Screw		Density	
		Nail	Screw	Density	F-value	*P* value	F-value	*P* value	F-value	*P* value
A	1	1,342.7	30,691.6	0.13	116.309	0.000**	173.939	0.000**	5.925	0.019^{ns}
B	1	788.2	17,789	0.13	69.199	0.000**	100.817	0.000**	5.593	0.022^{ns}
C	1	57.4	2,602	0.09	5.042	0.029^{ns}	14.747	0.000**	0.017	0.896^{ns}
D	2	1,087.8	32,111.6	0.03	95.504	0.000**	181.987	0.000**	13.198	0.000**
A × B	1	160.6	2,734.5	0.015	14.097	0.000**	15.497	0.000**	6.594	0.013*
A × C	1	3,780	76.6	0.02	3.333	0.074^{ns}	0.434	0.531^{ns}	8.786	0.005**
A × D	2	12.1	97.0	0.81	1.067	0.352^{ns}	0.550	0.581^{ns}	35.609	0.000**
B × C	1	16.8	780.4	0.001	1.481	0.23^{ns}	4.423	0.041*	0.570	0.454^{ns}
B × D	2	86.6	1,235.3	0.003	7.608	0.001**	7.001	0.002**	0.108	0.339^{ns}
C × D	2	25.3	498.8	0.006	2.224	0.119^{ns}	2.828	0.069^{ns}	2.658	0.08^{ns}
A × B × C	1	0	353.5	0.004	0.000	0.983^{ns}	2.003	0.163^{ns}	1.889	0.018^{ns}
A × B × D	2	29.7	384.6	0.001	2.606	0.084^{ns}	2.180	0.124^{ns}	0.371	0.692^{ns}
A × C × D	2	7.8	600	0.004	6.221	0.084^{ns}	3.400	0.420^{ns}	1.815	0.174^{ns}
B × C × D	2	10.6	142.4	0.001	0.935	0.399^{ns}	0.807	0.452^{ns}	0.282	0.756^{ns}
A × B × C × D	2	5.3	227.2	0.004	0.467	0.63^{ns}	1.288	0.285^{ns}	1.657	0.201^{ns}
Error	48									
Total	72									

A = Blending method, B = Fiber type, C = Fiber size (mesh), D = Fiber content, df = degree of freedom

** Significant difference at the 99 % level, * Significant difference at the 95 % level, ns = not significant

Effect of Fiber Type

The physico-mechanical proprieties of the WPCs vary significantly with fiber type (Table 3). Figures 1a and b illustrate the nail and screw withdrawal strength, respectively, of the composites made with various cellulosic fiber types. WPCs made with poplar particles exhibit the highest nail and screw withdrawal strength, whereas samples filled with rice straw show the lowest properties. Average nail withdrawal strength ranges from 40.4 to 58.5 N/mm for poplar flour WPCs, while maximum screw withdrawal strength is approximately 306 N/mm. The determined withdrawal strength values were the lowest for rice straw material. The reasons for these may be the lower density of composites filled with rice straw (Fig. 1c). The mechanical properties of WPCs depend on the properties of constituents and the interface interaction. However, when considering the withdrawal strength, homogeneity of the overall composite needs to be taken into account [23].

Effect of Fiber Size

At certain amount of fiber content, the different withdrawal strengths among the manufactured panels can be attributed to the role of fiber size. The effect of particle size on the mechanical properties investigated in this study is highly significant (Table 3). In general, increasing fiber size improves both nail and screw withdrawal strength properties. As it can be seen from Figs. 1a and b, composites filled with the 20–40 mesh fiber improved the fastener strengths much more than the 40–60 mesh. This result is consistent with previous reports on wood-particle thermoplastic composites [24, 25]. Various parameters influence the withdrawal strength of WPCs including the fiber aspect ratio, fiber-matrix adhesion, stress transfer at the interface and mixing temperatures.

Results also showed that different size of poplar and rice straw had significant effect on density (Table 3; Fig. 1c). The highest values were observed in samples containing 20–40 mesh of cellulosic fibers. With decreasing size of poplar flour (40–60 mesh), the density values were significantly decreased. A similar trend can also be seen in the values of composite made with rice straw.

Effect of Fiber Content

In hot-pressing method, increasing fiber loading decreases the withdrawal strength and density of the composites. The trend results of screw withdrawal strengths of the WPCs were similar to those of nail withdrawal strengths, which were discussed earlier. The fastener strengths of the WPCs were highly significant with poplar and rice straw loading levels (Table 3). Composites made with 45 wt% poplar flour (PF1 and PF4) exhibited the highest screw withdrawal

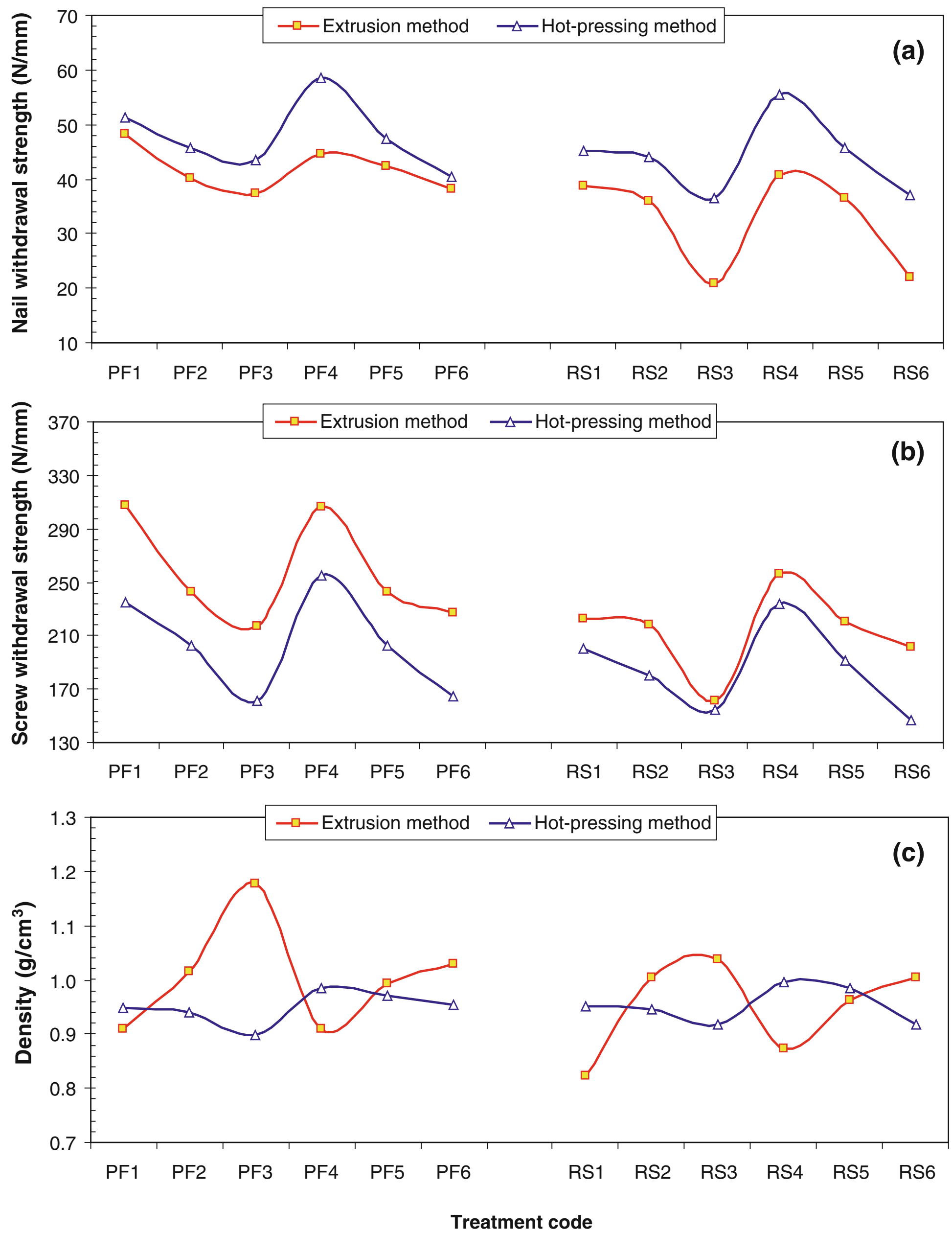

Fig. 1 Comparison of **a** nail, **b** screw withdrawal strength and **c** density of the composites

resistances; whereas composites filled with 75 wt% rice straw (RS3 and RS6) showed the lowest properties. In other words, further addition of fiber content did not show any improvement in the withdrawal strengths, which is consistent with previous reported results [26]. The decrease in withdrawal strength at higher fiber loading may be due to the poor interfacial adhesion between the lignocellulosic material and the polymer matrix resulting in weak interfacial regions.

Regardless of the blending method, comparison of the results for composites with varying fiber contents shows that the nail withdrawal strength of the composites decreases with increase in fiber content. When an amount of 45 wt% PF or RS was added, the withdrawal strength showed the highest values compared with samples filled with 60 and 75 wt% fiber contents. This could be explained by the low stiffness of cellulosic fiber compared with PP matrix. Another possible reason might be related to the formation of weak bonds between fiber and PP matrix. Similar trend was reported by Madhoushi et al. [6]. Dänyädi et al. [27] observed that, at large wood content, considerable particle aggregation takes place, leading to lower strength due to the filler's failure to sustain the stress transferred from the polymer to the matrix. They concluded that increased wood fiber content results in increased steady state torque and viscosity. Lu and coworkers [28] reported that the mechanical properties of the resultant WPC increase only at low weight percentages of wood filler. They found that mechanical strengths reach a maximum at 35 wt% wood content, and gradually decrease with a further increase in wood particle content.

The composites made with extrusion method and filled with 75 wt% cellulosic fibers showed the highest values for density amongst the composites evaluated, whereas composites with 75 wt% fiber and fabricated with hot-pressing method exhibited the lowest densities. In hot-pressing method, the volumes of the panels are almost fixed, hence, with increasing the fiber content from 45 to 75 wt% the densities decreased. It is to be noted that the bulk density of cellulosic fibers are much lower than PP matrix. Stark and Rowlands [29] reported that fiber content, rather than particle size, has the greatest effect on density. They suggested that particle size does not affect specific gravity.

Effect of Blending Method

The withdrawal strength of the WPCs varies significantly with blending method (Table 3). Figure 1a and b illustrate nail and screw withdrawal strength of the WPCs, respectively. Unlike nail withdrawal strength, the strength of panels made with extrusion method is significantly higher than hot-pressed composites. The values of extrusion method range from 161 to 255 N/mm for poplar flour, while the withdrawal strength varies from 146 to 200 N/mm for hot-pressing method. In other words, screw withdrawal strengths of the composites are enhanced between 10 and 27 %. The withdrawal strengths of nail and screw from panels are likely to be function of the mechanical properties of the base material, the process variables involved in the manufacture of the panel, and the geometry of the particles [5].

Better screw withdrawal results were obtained with extrusion method because of the higher density and more homogeneous structure of composites. This gives a smooth hole in the drilling process and smooth surfaces increase the bonding strength [11]. Usually it is difficult to mix straw particles uniformly with PP due to their different bulk densities. The straw particles are much lighter than the same volume of PP pellets [22]. In the hot-pressing method, the behavior of PP is to accumulate in the lower part of the mat, which results in no bonding medium existing between some straw particles.

Blending process has highly significant effect on the densities of composites (Fig. 1c). For instance in hot-pressing method, when average particle size increases from 40–60 to 20–40 mesh, density increases. However, completely different results were obtained for extrusion method.

Conclusions

In this study, the effects of fiber variability, size, content, and blending method on selected mechanical and physical properties of WPCs were investigated. The following conclusions can be drawn from the results and discussions presented above:

1. Single variable parameters studied in this work showed that they have significant effects on withdrawal strength and density, while their interactions are not very significant.
2. The poplar flour showed superior properties compared with rice straw due to its chemical components and density.
3. The overall withdrawal strength of the composites filled with poplar was found to be higher than those made with rice straw. Maximum screw and nail strengths were 306 and 58.5 N/mm for composite type PF4, respectively.
4. Fiber content and size are influential factors in WPC processing and properties. The improvement in withdrawal strength of fasteners achieved can be significantly attributed to lower fiber (45 wt%) content and larger fiber (20–40 mesh) size.
5. It was observed that extrusion method provided much higher screw withdrawal strengths than the hot-pressing method. However, hot-pressing method had the higher withdrawal strength of nail. It is due to the manufacture process of the panel, density, and the geometry of the particles in the panels.
6. The results provide better understanding of the behavior and performance of pull-out resistance for building systems.

References

1. Ashori A, Nourbakhsh A (2009) J Appl Polym Sci 111:2616
2. Viksne A, Berzina R, Andersone I, Belkova L (2010) J Appl Polym Sci 117:368
3. Hamzeh Y, Ashori A, Mirzaei B (2011) J Polym Environ 19:120
4. Ramesh M, Palanikumar K, Reddy KH (2013) Compos Part B 48:1
5. Wang Y, Su W, Kasemsiri P, Hiziroglu S (2011) Wood Mater Sci Eng 6:213
6. Madhoushi M, Nadalizadeh H, Ansell MP (2009) Polym Test 28:301
7. Chui YH, Craft S (2002) Can J Civil Eng 29:384
8. Celebi G, Kilic M (2007) Constr Build Mater 21:894
9. Salari A, Tabarsa T, Khazaeian A, Saraeian A (2013) Ind Crops Prod 42:1
10. Oh SC (2013) J Korean Wood Sci Technol 41:211
11. Özcan C, Uysal B, Kurt S, Esen R (2013) J Adhes Sci Technol 27:843

12. Chaharmahali M, Tajvidi M, Najafi SK (2008) Polym Compos 29:606
13. Zahedi M, Tabarsa T, Ashori A, Madhoushi M, Shakeri A (2013) J Appl Polym Sci 129:1491
14. Haftkhani AR, Ebrahimi G, Tajvidi M, Layeghi M, Arabi M (2011) Mater Design 32:4062
15. Ashori A (2008) Bioresour Technol 99:4661
16. Madhoushi M, Gray, M., Tabarsa, T (2010) In proceedings of the 11th World Conference on Timber Engineering (WCTE 2010), 20–24 June, Trentino, Italy
17. Çöpür Y, Güler C, Akgül M, Taşçioğlu C (2007) Build Environ 42:2568
18. Ashori A, Nourbakhsh A (2009) Waste Manage 29:1291
19. Azizi K, Tabarsa T, Ashori A (2011) Compos Part B 42:2085
20. Leu S-Y, Yang T-H, Lo S-F, Yang T-H (2012) Constr Build Mater 29:120
21. Ayrilmişş N, Benthien JT, Thoemen H (2012) Compos Part B 43:325
22. Wang W, Yuan S, Bu F, Li G, Wang Q (2011) J Thermoplast Compos Mater 24:251
23. Faruk O, Matuana LM (2008) Compos Sci Technol 68:2073
24. Dikobe DG, Luyt AS (2007) J Appl Polym Sci 103:3645
25. Bouafif H, Koubaa A, Perré P, Cloutier A (2009) Compos Part A 40:1975
26. Wechsler A, Hiziroglu S (2007) Build Environ 42:2637
27. Dányádi L, Janecska T, Szabó Z, Nagy G, Móczó J, Pukánszky B (2007) Compos Sci Technol 67:2838
28. Lu JZ, Wu Q, Negulescu II (2005) J Appl Polym Sci 96:93
29. Stark NM, Rowlands RE (2003) Wood Fiber Sci 35:167