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Coir Fiber Reinforced Polypropylene Composite Panel for Automotive Interior Applications

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Abstract: In this study, physical, mechanical, and flammability properties of coconut fiber reinforced polypropylene (PP) composite panels were evaluated. Four levels of the coir fiber content (40, 50, 60, and 70 % based on the composition by weight) were mixed with the PP powder and a coupling agent, 3 wt % maleic anhydride grafted PP (MAPP) powder. The water resistance and the internal bond strength of the composites were negatively influenced by increasing coir fiber content. However, the flexural strength, the tensile strength, and the hardness of the composites improved with increasing the coir fiber content up to 60 wt %. The flame retardancy of the composites improved with increasing coir fiber content. The results suggest that an optimal composite panel formulation for automotive interior applications is a mixture of 60 wt % coir fiber, 37 wt % PP powder, and 3 wt % MAPP.

Keywords: Coir fiber, Composite panel, Natural fiber, Polypropylene, Reinforced thermoplastic composite

Introduction

Natural fiber reinforced thermoplastic composites have successfully proven their high qualities in various fields of technical application. Over the past two decades, natural fibers have received considerable attention as a substitute for synthetic fiber reinforcements in plastics. As replacements for conventional synthetic fibers like aramid and glass fibers, natural fibers are increasingly used for reinforcement in thermoplastics due to their low density, good thermal insulation and mechanical properties, reduced tool wear, unlimited availability, low price, and problem-free disposal [1]. Natural fibers also offer economical and environmental advantages over traditional inorganic reinforcements and fillers. As a result of these advantages, natural fiber reinforced thermoplastic composites are gaining popularity in automotive and non-structural construction applications. The major market for natural fiber reinforced thermoplastic composites is as a replacement for glass fiber in automotive components. They are used as trim parts in dashboards, door panels, parcel shelves, seat cushions, backrests and cabin linings.

Several types of natural fibers such as kenaf [2], jute [3], sisal [4], flax [5], and hemp [6] were studied as reinforcement for thermoplastics such as polypropylene (PP) and polyethylene. Among the natural fibers, the coir fiber has remarkable interest in the automotive industry owing to its hard-wearing quality and high hardness (not fragile like glass fiber), good acoustic resistance, moth-proof, not toxic, resistant to microbial and fungi degradation, and not easily combustible [7]. The coir fibers are also more resistant to moisture than other natural fibers and withstand heat and salt water [8].

The coir fiber is a thick and coarse fiber obtained from the husk of the fruit of the coconut palm tree (*Cocos nucifera*), which grow extensively in tropical countries. Although coconut palms grow throughout the world's tropical regions, the vast majority of the commercially produced coir fibers come from Indonesia, Philippines, India, Brazil, Sri Lanka, Thailand, Vietnam, and Malaysia [9]. Coconut palms are grown in an area of about 12.05 million ha in the worldand the total production has been 61.1 million nuts per annum in recent years [9]. The high increase in the consumption of the coconuts and the industrialization of the processing of the coconut water has increased the generation of green coconut trash, which corresponds to around 85 % of the weight of the fruit. The coir fiber is used for making a wide variety of floor furnishing materials, yarns, ropes, mats, mattresses, brushes, sacking, caulking boats, rugs, geo-textiles, and insulation panels. However, production of these traditional coir products is approximately 450 thousand tonnes annually which is only a small percentage of total world production of coconut husk [10]. Hence, research and development centers work to find new markets for value added products containing the coir fiber.

In general, making composites with large particles is difficult with the extrusion process. In addition, the range of thickness and width of the natural fiber reinforced plastic

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composites made using extrusion process are lower than those of wood-based panels such as fiberboard and particleboard. Another little explored possibility is to produce natural fiber reinforced thermoplastic composites on a flat-press like the traditional wood-based panels. The advantage of this technology is that only a relatively low pressure level is required as compared to the extrusion and injection molding. As a consequence, the natural fiber structure is maintained and considerably lower material density (compared to the extrusion process) is possible. The productivity of the pressing technology is much higher than that of injection molding and extrusion. The flat-pressed thermoplastic composites made using a dry-blending process have a clear cost advantage. In this study, physical, mechanical, and flammability properties of the 10 mm thick coconut fiber reinforced PP composite panels made using dry blending process under laboratory conditions were investigated. Four loading levels of the coir fiber content, 40, 50, 60, and 70 % based on the composition by weight, were mixed with the PP powder and 3 wt % maleic anhydride grafted PP (MAPP) powder as a coupling agent. The objectiv e was to determine the optimal composite formulation for automotive interior applications such as door trim and cabin linings.

Experimental

Materials

The coir fibers with length of 120-140 mm were obtained from the coconut husks abstracted from the coconut fruits naturally grown in Thailand. Literature values for the chemical properties of the coir fiber are presented in Table 1 [7]. The fibers were chopped into 15-17 mm length to ensure easy blending with polymer matrix. The chopped fibers were then dried at 100 °C for 48 h (Figure 1). The moisture content of the fibers, as determined by oven-dry weight, was found to be 1-2 % prior to the treatment.

Virgin PP (T_m=160 °C, ρ=900 kg/m^3, MFI/230 °C/2.16 kg= 6.5 g/10 min) produced by *Petkim Petrochemical* Co., Izmir, Turkey, was used as the polymeric material. The coupling agent, Maleic anhydride-grafted PP (MAPP, Optim-425®; the reactive modifier maleic anhydride content=1 wt %), was supplied by Pluss Polymers Pvt. Ltd. in India. The PP and MAPP granules were processed by a rotary grinder to pass through a US 40-mesh screen and retained on a US 80-mesh screen. The PP was chosen as the matrix material in this study because of its good balance of property range, low processing temperature, low price, and good thermal stability.

Table 1. Chemical composition and microfibrillar angle of the coir (coconut) fibers [7]

Chemical composition and microfibrillar angle	Unit (weight %)
Lignin	40-45
Cellulose	32-43
Hemicellulose	0.15-0.25
Pectin	3-4
Water soluble	5
Ash	2
Microfibrillar angle (degree)	30-49

Figure 1. Hammer-milled coir (coconut) fibers used in the manufacture of the reinforced polypropylene composite panel.

Preparation of the Composite Panels

The coir fiber reinforced PP composite panels were manufactured at the laboratory using standardized procedures that simulated industrial production. After mixing the coir fibers with the PP and MAPP powders, the mixture was placed in a rotary drum blender. After blending the mixture for approximately 10 min, the mixture was weighed and a box was used to form the mixture into a mat on an aluminum caul plate. Teflon sheets were used to avoid direct contact of PP powder with the hot press metal platens during heating and pressing. To reduce the mat height and densify the mat, the mat was initially cold pressed. This procedure allowed for easy insertion of the mats into the hot-press. The mats were then subjected to hot-pressing using a manually controlled electrical-heated press. The maximum press pressure, pressing temperature, and total press cycle were 5 N/mm^2, 200 °C, and 5 min, respectively. At the end of the press cycle, the composite panel was removed from the press for cooling. The panel size was 350 mm×350 mm×10 mm after the cooling process. A total of 8 coir fiber reinforced PP composite panels, two for each type of panel, were manufactured. The average density of the panels was 750 kg/m^3.

Determination of Water Resistance

Wood-based panel standards were used for the experiments because EN 15534-1 [11] which specifies test methods for characterization of natural fiber reinforced thermoplastic composites such as wood plastic composite refers to test methods for wood-based panels. Thickness swelling (TS) and water absorption (WA) tests were carried out according to EN 317 [12]. Sixteen replicate samples from each type of composite panel were used for the TS and WA testst. The TS and WA tests were done with the same sample. Dimensions were 50 mm×50 mm×10 mm. Prior to the tests, the samples were conditioned at 20 °C and 65 % relative humidity (RH). Duration of the conditioning process was determined by regular weighting of the specimens until no changes in the weights were detected.

The samples were immersed in water at a temperature of 20 °C. The weights and thicknesses of the samples were measured at different time intervals during the long period of immersion. After being immersed in the water for 1, 14, and 28 days, the samples were removed from the water and all the surface water were wiped off with a dry cloth. The samples were weighed to the nearest 0.01 g and measured to the nearest 0.001 mm. The sample thickness was determined by taking a measurement at a specific location, the diagonal crosspoint, on the sample. Densities of the samples were evaluated according to EN 323 [13].

Determination of Mechanical Properties

The flexural properties of samples conditioned at 20 °C and 65 % RH were determined according to EN 310 [14]. A total of twelve replicate samples with dimensions of 250 mm ×50 mm×10 mm (six parallel and six perpendicular to each other) were tested for each type of composite panel to determine the flexural strength and modulus of elasticity. The flexural tests were conducted in accordance with the third point loading method at a span-to-depth ratio of 20:1. The crosshead speed was adjusted so that failure would occur within an average of 60 s±10. The samples were tested on an Instron testing system Model-4466 equipped with a load cell with a capacity of 10 kN.

The internal bond (IB) tests were conducted according to EN 319 [15]. Ten replicate samples with dimensions of 50 mm×50 mm×10 mm from each type of composite panel were used to determine the IB strength. For the tensile strength parallel to the plane of the panel, six samples with dimensions of 250 mm×38 mm (the minimum width of each sample at the reduced section)×10 mm from each type of composite panel were tested according to ASTM D 1037-06a [16].

The modified Janka ball, 11.28 mm in diameter with a 100 mm^2 projected area, was used to determine surface Janka hardness (JH) of samples with dimensions of 75 mm× 150 mm according to ASTM D 1037-06a [16]. The face JH is defined as the load at which the ball has penetrated to half its diameter. The load was continuously applied to the samples throughout the test at a rate of 6 mm/min. The maximum load required to embed the ball to one half its diameter was recorded for each specimen. To achieve the minimum thickness (25 mm) for the JH test, three pieces of the 10 mm thick samples were glued together to produce one 30 mm thick test specimen. Six replicate specimens were tested for each type of composite panel to determine the JH.

Limiting Oxygen Index (LOI) Test

The LOI of the samples with 40, 50, 60, and 70 wt % coir fiber were determined in a Oxygen Index Tester (Model CS-178B, Custom Scientific Instruments, Inc.). The LOI is the minimum percentage oxygen that is required to maintain flaming combustion of a specimen under specified laboratory conditions. The ASTM International standard is ASTM D 2863-10 [17]. The 10 mm thick panels were cut into 4 mm wide and 100 mm long specimens for the LOI tests. An oxygen analyzer (Model 1420B, Servomex Co.) was used to measure the oxygen concentration in the O_2-N_2 mixture. The test specimen was ignited at the top. Between individual test specimens of a given sample, the oxygen levels were adjusted upward or downward by approximately 0.2 % oxygen depending on whether the specimen continued to burn. The LOI was recorded as the lowest percentage oxygen level that allowed 50 mm of the specimen to be burned or continued flaming for 180 sec duration. One determination of LOI was made for each of the four types of samples (40, 50, 60, and 70 wt % coir fiber).

Statistical Analysis

An analysis of variance, ANOVA, was conducted ($p<0.01$) to evaluate the effect of the coir fiber loading level on the physical and mechanical properties of the composite panels. Significant differences between the average values of the composite types were determined using Duncan's multiple range test. Regression analysis was conducted on the LOI data.

Results and Discussion

Physical Properties

The TS and WA values of the samples as a function of increasing the coir fiber content are presented in Table 2. Statistical analysis found some significant differences among the composite types. Significant differences are shown by letters in Table 2. The water resistance of the samples significantly decreased with increasing the coir fiber content due to the hydrophilic property of the natural fibers. For example, the TS and WA values (28-days) of the samples having 40 wt % the coir fiber (composite panel type: A) were 3.94 and 10.26 % while they were 9.45 and 21.69 % for the samples having 70 wt % the coir fiber (composite panel type: D), respectively. The TS and WA values of the samples increased with increasing water exposure time due to the hydrogen bonding of the water molecules to the free hydroxyl groups present in the cellulosic cell wall materials and the diffusion of water molecules into the fiber- polymer matrix interface. The TS

Table 2. Physical properties of the coir fiber reinforced polypropylene composite panels as a function of increasing the coir fiber content

Composite panel type	Composite panel composition (wt %)			Physical properties						
				Density (kg/m^3)	Thickness swelling (%)			Water absorption (%)		
	Coir fiber	Polypropylene	MAPP		1 day	14 days	28 days	1 day	14 days	28 days
A	40	57	3	749 (10)	0.91[1] (0.08) A	2.08 (0.13) A	3.94 (0.20) A	1.34 (0.10) A	6.20 (0.38) A	10.26 (0.59) A
B	50	47	3	750 (25)	1.37 (0.12) B	2.70 (0.16) B	5.10 (0.39) B	2.30 (0.16) B	8.64 (0.55) B	15.34 (0.74) B
C	60	37	3	751 (30)	1.48 (0.11) B	3.34 (0.14) C	6.78 (0.42) C	2.42 (0.12) B	10.72 (0.44) C	17.87 (0.69) C
D	70	27	3	752 (15)	2.32 (0.14) C	4.75 (0.19) D	9.45 (0.51) D	3.38 (0.18) C	13.04 (0.51) D	21.69 (0.86) D

[1]Groups with same letters in column indicate that there is no statistical difference ($p<0.01$) between the samples according Duncan's multiply range test. The values in the parentheses are standard deviations. MAPP: maleic anhydride-grafted polypropylene.

and WA values of the samples considerably increased beyond 60 wt % of the amount of the coir fibers (Table 2). This result was consistent with a previous study by Gardner and Murdock [18]. They reported that when wood content increased beyond 65 wt %, WA of the WPC increased accordingly because the wood was less likely to be fully encapsulated by the polymer matrix. Similarly, Hargitai *et al.* [19] reported that TS and WA of thermoplastic composites increased with increasing content of hemp fibers. They found that the TS and WA values of the PP composites reinforced with 30 wt % the hemp fiber were 6 and 7 % after 19-days of submersion while they were 18 and 53 % for the PP composites with 70 wt % the hemp fiber, respectively. Increasing natural fiber content in thermoplastics enables more water penetration into the interface through micro cracks or voids induced by the swelling of fibers that creates swelling stresses leading to composite failure [20].

Wood-based panel standards were used here for comparison of the TS and the WA values of the samples since there were no established maximum TS and WA requirements for the natural fiber reinforced thermoplastic composite panels in EN 15534-2 [21]. TS values (28-days) of all the composite types, except for panel D, met maximum requirements of EN 312 [22] and EN 622-5 [23] with respect to particleboard Type 7 (1-day: 9 %) and medium density fiberboard (MDF) Type HLS (1-day: 10 %). The TS and WA values of the samples were also much less than those of fiberboards made using urea-formaldehyde resin [24].

The water resistance of the coir reinforced PP composites was found to be better than published results for thermoplastic composites reinforced with other natural fibers such as hemp [6], kenaf [2], jute [3], sisal [4], flax [5], and empty fruit bunch of oil palm [25]. For example, Karina *et al.* [25] found that the average WA value of empty fruit bunch of oil palm reinforced PP composites with MAPP (empty fruit bunch of oil palm: 50, PP: 47.5, and MAPP: 2.5 wt %) after 1-day of submersion was 3.05 %. In other study, Chow *et al.* [2] found that average TS and WA values of kenaf fiber reinforced PP composites with MAPP (kenaf fiber: 50, PP: 47, and MAPP: 3 wt %) after 1-day of submersion were 3 and 3 %. 1-day submersion WA and TS results for the coir fiber composites ranged from 1.34 to 3.38 % and 0.91 to 2.32 %, respectively (Table 2). The TS and WA values for the coir reinforced samples were much lower than those for wood fiber reinforced PP composites. For example, Ayrilmis and Jarusombuti [26] investigated TS and WA properties of 10 mm thick WPC panels (800 kg/m^3) made from dry-blended rubberwood fibers and PP powder with MAPP using a conventional flat-pressing process. They found that the average TS and WA values of the WPC panels containing 60 wt % rubberwood fibers, 37 wt % PP, and 3 wt % MAPP powder after 1-day of submersion were 5.82 and 7.85 %, respectively. Although the lignin-rich coir fiber is weaker than cellulose-rich fibers such as sisal, jute, pineapple, etc., certain unique properties such as a layer of the lignin and low hemicelluloses content make it attractive for using it as reinforcement in thermoplastic composites. Higher water resistance of the PP composites reinforced with the coir fiber than the composites reinforced with other natural fibers was mainly attributed to the lignin-rich layer of the coir fiber cells. The TS and WA results showed that the lignin layer made the coir fibers attractive for using as reinforcement in thermoplastic composites needing a high dimensional stability.

Lignin is a phenol propane-based amorphous solidified resin, filling the spaces between the polysaccharide fibers. It is a highly polymeric material and the most nonpolar (hydrophobic) constituent of the fiber [7]. Another possible explanation of the better water resistance of the coir fiber reinforced PP composites than other fibers such as hemp, jute, and sisal is that the lignin acts as a natural lubricant facilitating the coir fiber dispersion within the polymer matrix [27]. Wood products having a high content of lignin or natural waxes produce improved dispersion and adhesion with nonpolar hydrocarbon polymers [28]. Winandy and Krzysik [29] reported that increasing lignin content could suggest improved moisture resistance for wood fibers.

The cellulose content of the coir fiber (32-43 %) are lower than other natural fibers, such as sisal (67-78 wt %), hemp (70-74 wt %), jute (61-71.5 wt %), kenaf (45-57 wt %) and flax (71 wt %) [7]. As known, TS and WA of the natural fiber reinforced thermoplastic composites are due to the hydrogen bonding of water molecules to the hydroxyl groups of cellulose hemicellulose, and diffusion of the water molecules into the fiber-matrix interface. In previous studies, it was reported that decreases in the amounts of cellulose and hemicelluloses of the lignocellulosic caused a low uptake of water in the wood-based composites [29-31]. The TS and WA results showed that the thermoplastic composites reinforced with the coir fiber had a superior dimensional stability compared to the ones reinforced with other natural fibers due to the coir fiber's low cellulose and hemicellulose contents, as shown in Table 1.

Mechanical Properties

Flexural Properties

The flexural properties of the samples as a function of increasing the coir fiber content in the composite are presented in Table 3. All the composite types significantly differed from each other. Significant differences are shown by letters in Table 3. The flexural strength of the samples increased by 26 % when the coir fiber content increased from 40 to 60 wt %. However, the further increment of the fiber content in the composite decreased the flexural strength of the samples. This fact is due to the decrease of the amount of the binding of the coir fibers by the plastic. One explanation of the improvement of the flexural strength with up to 60 wt % fiber content could be increased network system by the coir fiber which has a high aspect ratio. It is generally accepted that longer fibers obtain an increased network system by themselves and result in increased bending properties of composites [32]. Schirp and Stender [6] reported that flexural strength of hemp fiber reinforced PP composites was better than wood fiber reinforced PP composites due to higher aspect ratio of hemp fibers.

The modulus of elasticit of the samples increased by 32 % when the coir fiber content increased from 40 to 70 wt % (Table 3). This observation showed that increasing the coir fiber content significantly improved the stiffness of the samples. The moduli of natural fibers are higher than that of the PP [33]. Increasing modulus of elasticity of the samples with increasing the coir fiber content was mainly attributed to natural fibers having higher moduli than the thermoplastics. The large increase of the modulus suggests an efficient stress transfer between the polymer and fiber. Incorporation of the coir fibers into the polymer matrix (the PP) increased the modulus because the mobility in the amorphous region becomes increasingly restrained as the fibers are stiffer than the polymer matrix. The good dispersion of the coir fibers also contributes to the large increase in the modulus of the samples. A similar result was found by Hargitai *et al.* [19]. They reported that the modulus of elasticity of the hemp fiber reinforced PP composites increased from 3500 to 4700 N/mm^2 when the hemp fiber content increased from 30 to 70 wt %. The decrease in the flexural strength of the samples beyond 60 wt % of the amount of the coir fibers was due to the stress concentration and dispersion problems. The flexural strength and modulus values of all the composite panel types (Table 3) met particleboard Type 5 (18 and 2550 N/mm^2) and general-purpose MDF (22 and 2500 N/mm^2) minumum requirements of EN 312 [22] and EN 622-5 [23], respectively. There were no established minimum flexural strength and modulus of elasticity requirements for the natural fiber reinforced thermoplastic composites in EN 15534-2 [21].

Although the flexural strength and modulus of elasticity of the samples improved with increasing the coir fiber content, they were found to be inferior than thermoplastic composites reinforced with other natural fibers such as abaca [34], hemp [6], and kenaf [2]. For example, Schirp and Stender [6] found that flexural strength and modulus of elasticity of hemp fiber (70 % wt) reinforced PP composites with MAPP (3 wt %) and lubricant (1.5 wt %) were 34.1 and 4582 N/mm^2, respectively. In other study, Chow *et al.* [2] reported that flexural strength and modulus of elasticity of 50 wt % kenaf fiber reinforced PP composite panels with 3 wt % MAPP were 66.5 and 4910 N/mm^2, respectively. The corresponding flexural strength and modulus of elasticity results for the 70 wt % coir fiber composites were 27.3 and 3345 N/mm^2, respectively (Table 3). One of the main reasons for the lower flexural strength and modulus of elasticity of the coir fiber reinforced PP composites compared to the thermoplastic composites reinforced other natural fibers was the lower cellulose content of the coir fibers (32-43 wt %) than other natural fibers such as sisal (66-78 wt %), hemp (70-74 wt %), jute (61-71.5 wt %), and flax (71 wt %) [7]. With regard to the fiber morphology, microfibril angle of the secondary cell wall (S_2) of the coir fibers is higher (30 to 49^{o}; [7] than that of the wood fiber (10 to 30^{o}; [35]. A high microfibril angle leads to a low degree of orientation of cellulose chains [1]. This in turn leads to the low mechanical performance.

Tensile Strength

The tensile strength of the samples increased by 35 % when the fiber content increased from 40 to 60 wt % in the composite (Table 3). However, the further addition of the coir fiber beyond 60 wt % decreased the tensile strength of the samples because there was a decrease in the amount of the bonding between the coir fibers as a result of decreasing polymer content. The improvement in the tensile strength of the samples as a function of increasing the coir fiber content up to 60 wt % was mainly attributed to the increased stress transfer from the polymer matrix to the coir fiber. In addition, increasing the coir fiber content suggested a uniform stress distribution from the polymer matrix to fibers. The compatibilizing agent (the MAPP) was used to enhance the interfacial bonding strength between the fiber and the polymer matrix. The MAPP has a positive effect on the physical and mechanical properties of the polymer composites because it improves the interfacial bonding between the hydrophilic fiber and the hydrophobic polymer matrix [7].

The tensile strength values of the coir fiber reinforced PP composites were lower than those of thermoplastic composites reinforced with other natural fibers such as kenaf [2], jute [3], sisal [4], and flax [5]. For example, Chow *et al.* [2] found that tensile strength of 50 wt % kenaf fiber reinforced PP composite panels with 3 wt % MAPP was 37.9 N/mm^2. The corresponding tensile strength result for the 50 wt % coir fiber composites was 15.5 N/mm^2 (Table 3). This result was caused by the lower cellulose content of the coir fibers compared with the other natural fibers. As known, cellulose content plays an important role in the tensile strength of natural fiber because cellulose chains have high resistance in tension. Cellulose is the strongest polymer in wood, thus is highly responsible for strength in the wood fiber. It has a high degree of polymerization and linear orientation. Tensile strength of any composite is related to the chemical composition of the fiber and its internal structure [36]. The coir fiber has low strength due to its low cellulose content which play important role in contribute to the strength of natural fiber [7]. The low tensile strength of the coir fiber reinforced PP samples compared with thermoplastic composites reinforced with other natural fibers could be also explained by the higher microfibril angle of the secondary cell wall of the coir fibers.

Internal Bond Strength

The IB strength of the samples decreased by 33 % when the coir fiber content increased from 40 and 70 wt % in the composite (Table 3). This is likely due to the decrease in the amount of binding of the coir fibers by the plastic because when the fiber content increases and so the amount of the plastic, as the adhesive, decreases. Similar results were also found in previous studies [26,35,37]. For example, Ayrilmis and Jarusombuti [26] reported that IB strength of rubberwood fiber reinforced PP composites panels with 3 wt % MAPP decreased from 0.96 to 0.69 N/mm^2 when the rubberwood fiber content increased from 40 to 60 wt % in the composite. The IB values of all the composite panel types met particleboard Type 7 (0.75 N/mm^2) and MDF Type HLS (0.80 N/mm^2) minimum requirements of EN 312 [22] and EN 622-5 [23], respectively.

Janka Hardness

The JH of the samples increased by 69 % when the coir fiber content increased from 40 to 70 wt % in the composite (Table 3). This was consistent with previous studies [3,38-40]. The improvement in the JH of the samples as a function of increasing the coir fiber content was mainly caused by the high lignin content of the coir fibers. Lignin, amorphous polymeric material, acts as cement in bonding the cellulose filaments providing stiffness to the coir fiber. The coir fiber has the highest lignin percentage by volume among the natural fibers, which makes the coir fiber very tough and stiffer when compared to other natural fibers [41]. The JH of the samples with 70 wt % the coir fiber content was comparable to those of the wood-based panels such as MDF and particleboard. In a previous study, average JH of MDF panels (760 kg/m^3) made from pine wood fibers was found to be 5210 N [24].

Limiting Oxygen Index

The LOI values of the samples increased with increasing coir fiber in the composite (Figure 2). The LOI values were 20.1, 20.4, 21.2, and 21.5 % for the 40, 50, 60, and 70 wt % coir fiber in the reinforced PP composites, respectively. The

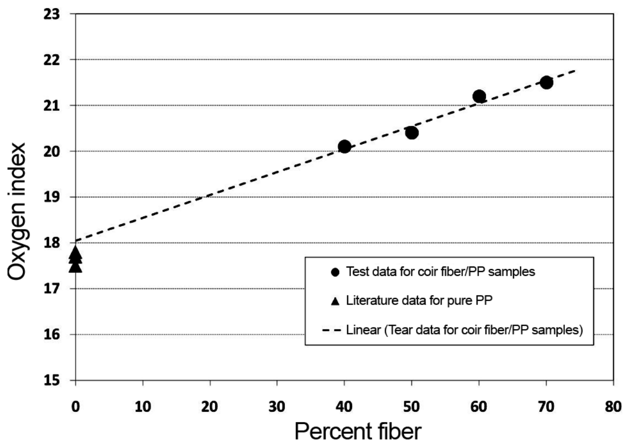

Figure 2. Limiting oxygen index values of the coir fiber reinforced polypropylene composites as a function of the coir fiber content.

Table 3. Mechanical properties of the coir fiber reinforced polypropylene composite panels as a function of increasing the coir fiber content

Composite panel type[1]	Mechanical properties				
	Flexural strength (N/mm^2)	Modulus of elasticity (N/mm^2)	Tensile strength (N/mm^2)	Internal bond strength (N/mm^2)	Janka hardness (N)
A	24.3[2] (0.80) A	2538 (79) A	13.2 (0.49) A	1.89 (0.18) A	2914 (117) A
B	26.8 (0.90) B	2760 (102) B	15.5 (0.65) B	1.63 (0.11) B	3589 (148) B
C	30.6 (1.06) C	3129 (90) C	17.8 (0.54) C	1.33(0.15) C	4130 (139) C
D	27.3 (0.87) B	3345 (118) D	16.0 (0.60) B	1.26 (0.09) C	4916 (124) D

[1]See Table 2 for panel composition, [2]Groups with same letters in column indicate that there is no statistical difference (p<0.01) between the samples according Duncan's multiply range test. The values in the parentheses are standard deviations.

linear regression analysis of the data indicated a R^2 of 0.96 and a standard error for the predictor (LOI) of 0.16. The slope of the line (Figure 2) was 0.05 with a standard error of 0.007.

The results are consistent with literature LOI results for untreated wood and plastics. The LOI values of 22.0 to 25.1 % were reported in the literature for 3 mm by 6.5 mm by 100 mm specimens of sawn southern pine [42]. The LOI values of neat PP reported in the literature include 17.7 % [43], 17.5 % [44] and 17.8 % [45]. The literature values for pure PP are very close to the y-intercept of 18.0 % resulting from the linear regression of the PP/coir fiber data (Figure 2). These results for PP samples are for 3 mm thick and 6.5 (or 6) mm wide samples. The samples in this study were 4 mm thick and 10 mm wide, an alternative size recommended for molding materials in more recent editions of the ASTM standard. Increasing the dimensions of the test specimens can increase the LOI [42,43]. LOI results for fire-retardant-treated materials are higher than the coir fiber reinforced PP samples without a fire-retardant. For example, LOI values for fire-retardant-treated wood have been reported as high as 78.6 % [42].

The test results revealed that LOI value of the PP, namely oxygen concentration, was significantly increased by the addition of the coir fiber (Figure 2). This was consistent with previous studies [46,47]. For example, Ton-That *et al.* [46] reported that LOI value of PP composites reinforced with 40 wt % flax fiber was 18.7 %. In other study, Stark *et al.* [47] found that LOI values of wood flour-polyethylene composites (12.7 mm by 3.2 mm by 127 mm specimens) reinforced with 50 and 60 wt % of WF were 19.7 and 20.2 %, respectively. The pure polyethylene samples had LOI of 19.3 %. As shown in Figure 2, the PP composites with 70 wt % coir fiber require the highest concentration (21.5 %) of the oxygen to burn while the PP composites with 40 wt % coir fiber require the lowest concentration (20.1 %) of the oxygen to burn. The higher LOI results of the coir fiber/PP specimens compared with the wood fiber/PE of Stark *et al.* [47] were attributed to the slightly larger specimen and the higher lignin to cellulose ratio in the coir fiber compared with lignin content of wood. Gani and Naruse [48] reported that cellulose can easily decompose and burn, comparing with lignin. In a previous study, Susott [49] examined 43 samples from different species and found that foliar material combusted more rigorously than woody material, due to the higher cellulose to lignin ratio in the foliar material of the investigated species.

Since the LOI test is widely used in evaluating the flammability of plastics, the LOI test was used in this study as an initial evaluation of the flammability of the coir fiber/PP material. However, it should be noted that the LOI test has limited value in predicting corresponding results in other types of fire tests and real fires [50].

Conclusion

This study showed that the coir fiber (1200 kg/m^3) is a potential candidate in the manufacture of reinforced thermoplastic composites, especially for partial replacement of high-cost and heavier glass fibers (2500 kg/m^3). The coir fiber reinforced PP composites can be used for non-structural applications, such as in the internal parts (for example door panel) of automotive vehicles. The TS and WA results showed that the lignin layer of coir fibers significantly improved the dimensional stability of the composites. With increasing coir fiber content up to 60 wt %, the flexural and tensile strengths of the composites increased by 26 and 35 %, respectively. However, the further increment of the fiber content decreased the flexural and tensile strengths because the polymer matrix was insufficient to cover all the surface of the coir fiber. As for the modulus of elasticity, it increased with increasing coir fiber content up to 70 wt %. The IB strength was negatively affected by increasing coir fiber content due to the decrease of the amount of binding of the coir fibers by the plastic. With increasing the coir fiber content up to 70 wt %, the modulus of elasticity, the JH, and the flame retardancy of the composite panels increased by 32, 69, and 7 %, respectively. Based on the findings of the present study, it may be said that the optimal composite panel formulation for automotive interior applications was obtained from a mixture of 60 wt % the coir fiber, 37 wt % the PP powder, and 3 wt % the MAPP.

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