Influence of Birch False Heartwood on the Physical and Mechanical Properties of Wood-plastic Composites

Heikko Kallakas,[a,*] Gbenga S. Ayansola,[a] Tanel Tumanov,[a] Dmitri Goljandin,[b] Triinu Poltimäe,[a] Andres Krumme,[c] and Jaan Kers [a]

The influence of birch false heartwood was investigated relative to the physical and mechanical properties of wood-plastic composites. Birch wood (sapwood and false heartwood) particles were modified with 5 wt% NaOH (by wood content) and 5 wt% 3-aminopropyl-triethoxysilane (by wood content) before being compounded with polypropylene in a co-rotating twin-screw extruder. The compounded composites were then injection moulded into standard test samples. The resulting composites were grouped into four categories: birch sapwood, modified birch sapwood, false heartwood, and modified false heartwood. Neat polypropylene samples were produced as a reference. The samples were tested for their tensile and flexural properties, water absorption, thickness swelling, and ultraviolet aging. The compositions of the composites were analysed using Fourier transform infrared spectroscopy. The results showed that the tensile strength of all of the samples decreased after water absorption. Water absorption decreased the impact strength of all of the composites. Ultraviolet radiation degraded the neat polypropylene and lowered the mechanical properties of all of the composites. Surface chalking was observed in all of the wood-plastic composites exposed to ultraviolet aging, with colours ranging from brown and brownish black to white.

Keywords: Birch; False heartwood; Wood-plastic composite; Polypropylene; Mechanical properties; Water absorption; UV radiation

*Contact information: a: Laboratory of Wood Technology, Department of Materials and Environmental Technology, TalTech University, Ehitajate tee 5, 19086 Tallinn, Estonia; b: Department of Mechanical and Industrial Engineering, TalTech University, Ehitajate tee 5, 19086 Tallinn, Estonia; c: Laboratory of Polymers and Textile Technology, Department of Materials and Environmental Technology, TalTech University, Ehitajate tee 5, 19086 Tallinn, Estonia; *Corresponding author: heikko.kallakas@taltech.ee*

INTRODUCTION

Birch (*Betula pendula*) is abundant and it often develops a brown colouration in its heartwood that is referred to as false heartwood or red heartwood. This is a wood defect common to birch and other wood species, such as beech, maple, ash, poplar, linden, *etc.*, and its occurrence increases with the tree age. The formation of false heartwood is induced by diverse exogenous factors, including various kinds of injuries or stresses that damage the tree, which trigger a succession of processes (Hörnfeldt *et al*. 2010). The extent of both normal and false heartwood increases as the tree ages. When the tree age exceeds approximately 70 years to 90 years, the wood material near the pith is often darkened by decay. A common cause of stress in birch is drought; another is the breakage of branches, which creates openings or stem injuries, thereby exposing injured cells to atmospheric conditions. Several factors are responsible for this type of discolouration and these factors are generally similar to those of the formation of normal heartwood. These include the

emptying of the living contents of cells in the stems, decrease in the conductive capacity, excessive air penetration into the tree, aging of the parenchyma cells, drought (low temperature), presence of fungi, genetic predispositions, and forest silvicultural practices (Shigo and Hillis 1973; Prka *et al.* 2009; Hörnfeldt *et al*. 2010).

The formation process of false heartwood has been reported to begin in later stages, rather than beginning with poor soil quality (Shigo and Hillis 1973). Any mechanical damage inflicted on a tree with a dehydrated core zone results in oxygen absorption into the tree and initiates the process of tylose formation, which is an enzymatic process (Prka *et al.* 2009). Air in the ripewood (dehydrated) zone causes the parenchyma cells to die quickly. According to Shigo and Hillis (1973), false heartwood differs from heartwood in that heartwood substances are stored either on the outside or inside of the parenchyma, instead of being stored in the cell walls.

Problems associated with the use of false heartwood has often been a concern in the wood industry. False heartwood has often led to a reduction in the price of wood when wood is visually graded because of the difficulties in distinguishing between discoloured and altered wood (Hörnfeldt *et al*. 2010), as well as wood waste because false heartwood does not yield quality veneer that can be used in plywood production. Hence, false heartwood is used either as an energy source or is utilized as internal plywood layers, but never at the top of the surface. A possible use of false birch heartwood is as a filler in the manufacturing of wood-plastic composites (WPC). Wood-plastic composite is a material obtained by combining wood as a filler or reinforcement material with plastic. This often results in a product with enhanced material properties, which prolongs the durability and preserves the beauty of the product. Several works have been conducted on the properties of wood and plastic combinations, with different researchers focusing on different polymers and wood species (Bledzki and Faruk 2006; Taib *et al*. 2006; Mijiyawa *et al*. 2015). Several research areas have also been investigated for WPCs, such as artificial and natural weathering of WPC, the effects of different particle sizes and filler materials, the effects of ultraviolet (UV) radiation and resulting colour changes, the physical and mechanical properties of WPC, *etc*. (Gwon *et al*. 2010; Gallagher and McDonald 2013; Fabiyi and McDonald 2014; Peng *et al*. 2014).

This research investigated the use of false birch heartwood as a filler material in WPC. The specific objective of this study was to investigate the effect of false birch heartwood on the physical and mechanical properties of WPCs. The results were compared with birch sapwood wood-based composites.

EXPERIMENTAL

Materials

The birch wood (sapwood and false heartwood) was supplied in the form of veneers by Kohila Vineer OÜ (Kohila, Estonia). The experimental work began with the separation of the birch false heartwood from the sapwood. The false heartwood veneer pieces were separated from the birch veneer by hand crushing, after which they were carefully visually inspected to remove any sapwood veneer leftovers. The birch veneers were then initially crushed mechanically to particles using a DS-A disintegrator (Tallinn University of Technology, Tallinn, Estonia), after which the wood particles were mechanically refined into wood particles with a specific size using separation grinding with a DSL-115 disintegrator (Tallinn University of Technology, Tallinn, Estonia). The wood particle

length and distribution were measured using the analytical sieve shaker method with a Fritsch Analysette c3 (Weimar, Germany). The sieve sizes ranged from 25 mm to 0.025 mm and the samples were crushed into a particle size of 1 mm.

Polypropylene (PP) (PPH 11012 homopolymer, Total Petrochemicals, Feluy, Belgium) was used as the matrix material. The PP had a density of 0.905 g/cm^3 and a high melt flow index of 55 g/10 min. To modify the wood particles, sodium hydroxide (NaOH) with a minimum purity of 98% and 3-aminopropyl-triethoxysilane (APTES) (assay = 98%, density = 0.946 g/mL) were obtained from Sigma-Aldrich Chemical Co. (St. Louis, Missouri, USA), and acetic acid (99.8%, M = 60.05 g/mol) was obtained from Lach-Ner (Neratovice, Czech Republic).

Wood Modification

The wood particles were first treated with a 5.0 wt% (by wood content) NaOH solution at room temperature (23 °C) and left for approximately 90 min. The wood was then thoroughly washed with distilled water to neutralize the excess NaOH and then oven-dried at 60 °C for 24 h. The alkaline disrupted the hydrogen bonds that were present on the fibre surface. Before silane modification of the wood particles, APTES (5.0 wt% by wood content) was immersed in a solution of ethanol and distilled water at a ratio of 6:4 and continuously stirred for 1 h for silane hydrolysis. At the same time, the pH of the solution was adjusted to a range of 4 to 5 with acetic acid while stirring. Thereafter, the silane solution was poured onto the wood particles and left for 2 h at room temperature. The wood particles were then oven-dried at 60 °C for 24 h. Then, the modified wood particles were collected and placed in a sealed airproof plastic bag to prevent moisture absorption.

Composite Processing

The wood particles were mixed with PP at a ratio of 60 wt% wood to 40 wt% PP for all of the samples. The composites were compounded in a Brabender Plasti-Corder PLE 651 co-rotating twin-screw extruder (Duisburg, Germany). The barrel had four melting temperature zones that were set to 180 °C, 185 °C, 190 °C, and 190 °C. The rotation screw speed was 60 rpm throughout the process. The extruded materials were allowed to cool naturally and granulated afterwards. The test samples were made by injection moulding (Battenfeld BA 230E, Vienna, Austria), according to ISO 527-2 (2012). Prior to injection moulding, the composite granules were oven-dried at 80 °C for 24 h to remove any moisture in the material. The injection moulding machine was set to temperatures between 170 °C and 180 °C, with an injection pressure of 7 MPa. Table 1 shows the composition of the raw materials in the composites.

Table 1. Composition of the Composites

Sample	PP (wt.%)	Birch (wt.%)	NaOH (wt.%)	APTES (wt.%)
PP	100	-	-	-
SW	40	60	-	-
MSW	40	60	5	5
FHW	40	60	-	-
MFHW	40	60	5	5

SW – sapwood; MSW – modified sapwood; FHW – false heartwood; and MFHW – modified false heartwood

Methods

Mechanical properties

The tensile and flexural tests were performed on an Instron 5866 (Norwood, Massachusetts, USA) in accordance with ISO 527-2 (2012) and ISO 178 (2010), respectively. The test speed was 5 mm/min, and the tensile strength, flexural strength, and modulus were calculated. The test was conducted at room temperature and a relative humidity of 50%. The thicknesses of the specimens were measured with a calliper and at least six test specimens were tested. The notched Charpy impact strength was tested with a Zwick 5102 pendulum impact tester (Ulm, Germany) in accordance with ISO 179-1 (2010) at room temperature.

Water absorption and thickness swelling

The water absorption and thickness swelling were measured according to EN 15534-1 (2014). Each test specimen was weighed, and its thickness was recorded. The samples were completely immersed in water at room temperature for 672 hours, with measurements taken at 24 h, 48 h, 96 h, 168 h, 336 h, and 672 h. For each sample, at least six specimens were examined, and the water level was monitored daily to ensure constant and complete immersion in water. The percentage change in the mass relative to the initial mass was calculated. At the end of the water absorption test, the specimens were tested mechanically (tensile, flexural, and impact tests) to determine the behaviour of the WPCs after exposure to water.

UV exposure and colour analysis

Ultraviolet exposure was performed in a UV chamber. The WPC samples were irradiated with UVA-351 type fluorescent lamps (TL-D 36W/08 T8 blacklight, PHILIPS, Amsterdam, Netherlands). The peak wavelength of the tube was 351 nm. The exposure cycle was performed for 2016 h, and the intensity was 5 W/m^2. The specimens were occasionally removed from the chamber and colour measurements were taken at 24 h, 48 h, 96 h, 168 h, 336 h, 840 h, 1008 h, 1176 h, 1344 h, 1512 h, 1680 h, 1848 h, and 2016 h. The colour measurement was conducted with a Minolta Chroma Meter CR-121 (Osaka, Japan) in accordance with ISO 4582 (2017) after 2016 h using the CIELAB colour system. The total colour difference (ΔE), which indicated the change in the colour, was calculated using Eq. 1,

$$\Delta E = \sqrt{(\Delta L^2 + \Delta a^2 + \Delta b^2)} \quad (1)$$

where ΔL, Δa, and Δb are the differences between the initial values and values after weathering of the L* (lightness), a* (green-red colour), and b* (blue-yellow colour), respectively.

FTIR analysis

The efficiency of the chemical modification was verified using Fourier transform infrared (FTIR) spectroscopy with a Brucker LUMOS FTIR microscope with an integrated FTIR spectrometer (Billerica, Massachusetts, United States) using the ATR-FTIR method. The spectral resolution used was 4 cm^{-1}, and the spectra were recorded over the range of 3500 cm^{-1} to 500 cm^{-1}. Thin wafers were cut from the previously produced test specimens using a scalpel. The thin wafers were placed under a clamp, and then the spectra were measured, and the peaks were marked.

RESULTS AND DISCUSSION

Tensile Strength

The results of the tensile tests are presented in Figs. 1a and 1b. The results showed that the modified birch sapwood samples had tensile strengths that were slightly higher by 6.67% than the unmodified birch sapwood samples, which were 22.71 MPa and 21.3 MPa, respectively. The modification of the wood particles with 5 wt% APTES and 5 wt% NaOH increased the tensile strength of the composites, which was also reported by Kim *et al.* (2010) and Kallakas *et al*. (2015). The modified and unmodified birch false heartwood samples had similar average tensile strength values of 21.34 MPa and 21.76 MPa before immersion and 16.34 MPa and 18.19 MPa after immersion, respectively. The addition of 5 wt% APTES and 5 wt% NaOH did not affect the tensile strength of the false heartwood at a 60% wood content before soaking. Instead, there was a 10.17% decrease in the tensile strength of the modified false heartwood after immersion in water. This suggested that silane was not able to penetrate the bonds of the heartwood to enable interfacial adhesion of the composite. The reason for this could have been that the modification process opened the PP/wood particle interface to water degradation, which consequently led to a reduction in the strength of the false heartwood composite. Other than the control sample, the false heartwood composites had higher strength values than the other composites after immersion. This was because the heartwood contained a non-living core and non-conducting tracheary elements, which inhibited the absorption of water to an extent, unlike the other samples (Smith 2015).

The results showed that after water absorption, the tensile strength decreased by 20.67%, 21%, 11.8%, and 23.4%, whereas the modulus decreased by 39.4%, 44%, 37.6%, and 48.7% for the birch sapwood, modified birch sapwood, false heartwood, and modified false heartwood, respectively. This was comparable to the 46% to 50% reduction in the tensile modulus reported by Taib *et al.* (2006). One reason the modulus showed a greater decrease may have been the high wood content (60 wt%) used in this work. Another reason for these reductions could have been that the wood, which is hydrophilic in nature, absorbed water. This led to swelling and the eventual formation of microcracks. The modified birch sapwood had the highest modulus of 4.5 GPa before immersion, while the modified false heartwood had the lowest modulus of 4.2 GPa before and after water absorption. The modified false heartwood was affected mostly by water because it had the greatest absorption. The false heartwood had a 27% higher modulus than the modified false heartwood after soaking in water. This indicated that silane had no effect on the false heartwood for improving its properties, but caused the composite to degrade more.

After exposure to UV for 2016 h, the PP lost 56% of its tensile strength and became brittle. This was because of the crystallization of PP, which resulted from a chain scission reaction of the polymers during UV weathering (Fayolle *et al*. 2008). The modified birch sapwood composites had the highest tensile strength after exposure to UV (21.41 MPa). Both the false heartwood and modified false heartwood composites had almost the same tensile strength (20.44 MPa and 20.47 MPa, respectively), which translated to a reduction of 6% and 4%, respectively. The birch sapwood composite had a tensile strength of 20 MPa, which was a reduction of 6%. Hence, the modification with 5 wt% APTES did not influence the tensile strengths of the modified composites that were exposed to UV. Similar trends were observed for the tensile modulus, as is shown in Fig. 1b. The tensile modulus, in general, decreased for the PP and all of the WPCs.

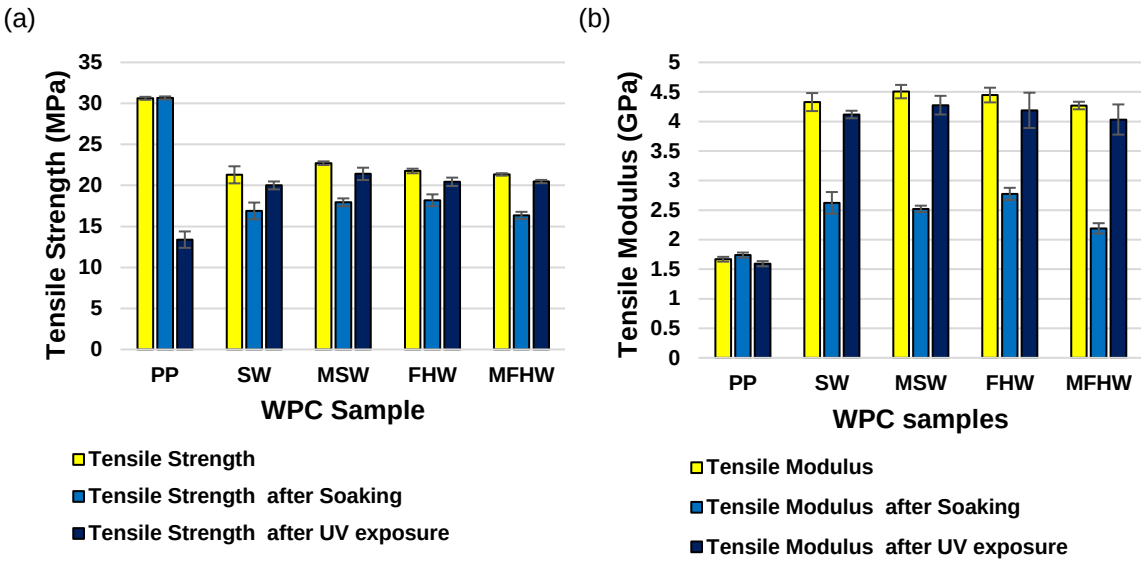

Fig. 1. Tensile Properties of the WPC samples before and after soaking in water and exposure to UV; SW – birch sapwood; MSW – modified birch sapwood; FHW – false heartwood; and MFHW – modified false heartwood

Flexural Strength

Figures 2a and 2b show the comparison of the flexural strength and flexural modulus (MOE) of all of the composites and the neat PP before and after WPCs were immersed in water and exposed to UV irradiation. The modified birch sapwood composite before soaking in water had the highest flexural strength of 46.9 MPa, which was 4.8% higher than that of the neat PP (44.7 MPa) and 2.5% higher than that of the unmodified birch sapwood composite. This indicated a strong adhesion interface between the wood fibre and APTES. An addition of 5 wt% APTES did not affect the flexural strength of the modified false heartwood as both the false heartwood and modified false heartwood had about the same strength before being soaked in water (44.2 MPa and 44.7 MPa, respectively).

However, the effect of the APTES modification was visible in the flexural strength of the modified false heartwood composites after they were soaked in water. All of the samples, apart from the neat PP, showed a reduction in the flexural strength of the composites after immersion for 28 d (Fig. 2a). The flexural strength in the birch sapwood and modified birch sapwood composites was reduced by 12.2% and 14.4%, respectively. After water absorption, the false heartwood composite showed the lowest reduction in the flexural strength of 10.6% and the modified false heartwood showed the highest reduction in the flexural strength of 16.6%. This indicated that the modified false heartwood absorbed more water than the false heartwood. This may have been because false heartwood is known to have a reduced moisture content compared with sapwood (Torelli 1984; Baettig *et al.* 2017); hence, it may be concluded that APTES can increase the permeability of false birch heartwood. This indicated the impact of modification on the rate of water absorption of the composites. The bond quality at the interface of the polymer matrix and filler impacted the strength of the composites (Stark 2001). The hydrophilic nature of wood led to the absorption of more water, which led to swelling and the formation of microcracks. The modified birch sapwood composites had the highest MOE (4.89 GPa) before immersion in water, which was higher than that of the unmodified birch saw wood, false heartwood, and modified false heartwood composites by 3.3%, 18.7%, and 12%,

respectively. After water absorption, the MOE decreased by 46.3%, 66.4%, 18%, and 72.3% for the birch sapwood, modified birch sapwood, false heartwood, and modified false heartwood composites, respectively.

The ductile PP turned brittle after exposure to UV for 2016 h and the degradation of the plastic was easily noticed as they were picked up for testing. Badji *et al*. (2017) also reported this brittleness. There was a slight decrease of 2.5% to 7.2% in the flexural strength for all of the composites. A similar result was obtained by Kallakas *et al.* (2015), who recorded a maximum decrease in the flexural strength of 6.5%. The flexural MOE for all of the composites increased after exposure to UV. This indicated that the material became ductile. The increase ranged from 3.1% for the modified birch sapwood to 16.7% for the false heartwood composites. The flexural MOE that was obtained for the false heartwood (4.8 GPa) was higher than that obtained for the modified false heartwood (4.68 GPa). A similar trend was obtained for the flexural strength of the false heartwood composite after UV exposure (43.2 MPa), which was higher than the flexural strength of the modified false heartwood composite (42.1 MPa).

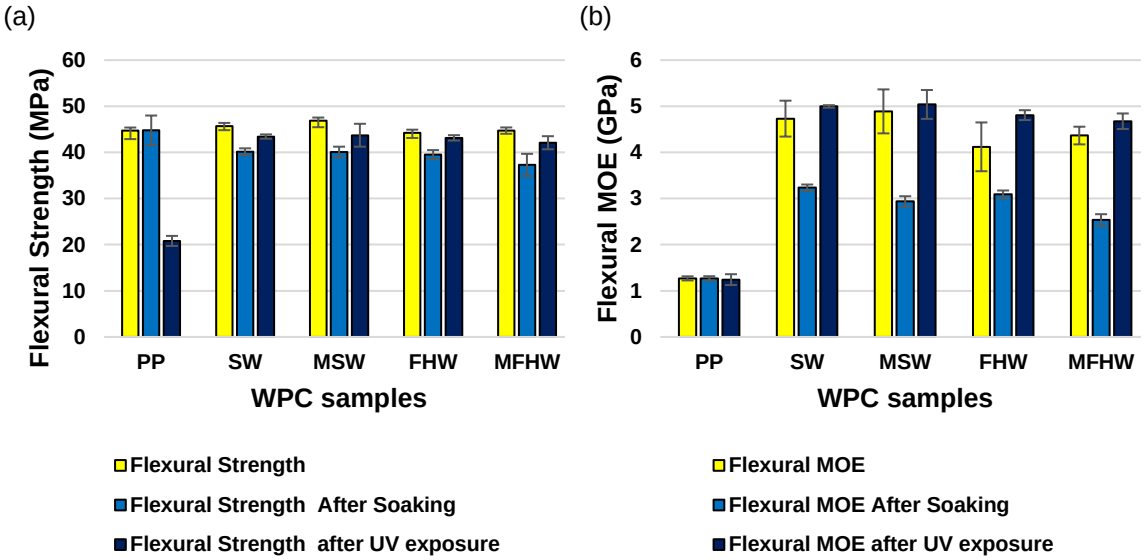

Fig. 2. Flexural Properties of the WPC samples before and after soaking in water and exposure to UV; SW – birch sapwood; MSW – modified birch sapwood; FHW – false heartwood; and MFHW – modified false heartwood

Water Absorption and Thickness Swelling

The water absorption and thickness swelling of the composites are presented in Figs. 3a and 3b, respectively. The water absorption of the composites was observed to increase with the immersion time. A similar result was reported by Bouafif *et al*. (2008). Likewise, the thickness swelling of the composites increased with the immersion time (Fig. 3b). The total immersion time was 672 h. Modification with 5 wt% APTES and 5 wt.% NaOH increased the water absorption of the modified false heartwood WPCs. The water absorption of the false heartwood WPC increased by 28%, which was greater than the increase seen for the water absorption of the modified birch sapwood WPC (4.3%). The modified false heartwood WPC had the highest absorption of 17.26% and the false heartwood WPC had the lowest water absorption of 13.47%. This was explained by the nature of heartwood, which contains non-living cells and extractives. According to Olsson *et al.* (2001), the extractives in heartwood are the main source of low water permeability.

The age and growth rate of the tree affect the content and composition of the extractives (Metsä-Kortelainen 2011).

Metsä-Kortelainen *et al.* (2006) demonstrated that a significant difference exists between the water absorption of sapwood and heartwood in Scots pine and spruce. Sapwood absorbs more water than heartwood, and heat treatment decreases water absorption in heartwood (Metsä-Kortelainen *et al.* 2006). Also, the mechanism of capillary action at the edges of the wood fibre in the composites could have been responsible for the transportation of water molecules along the fibre-polymer matrix interface of specimen cuts, taking advantage of the flaws and voids that may exist around such an interface (Taib *et al.* 2006). The absorption of water by the composites was assumed to be caused by the hydrophilic wood flour and not the hydrophobic PP because PP did not show any water absorption. Similar results have also been shown in previous research (Stark 2001). Kim *et al.* (2010) reported that the reduction values of silane-treated composites were 2.5 times greater than the values of untreated composites. This was explained by the limited exposure of water molecules to wood particles, which may have been caused by the hydrogen bonds between the hydroxyl and siloxane groups.

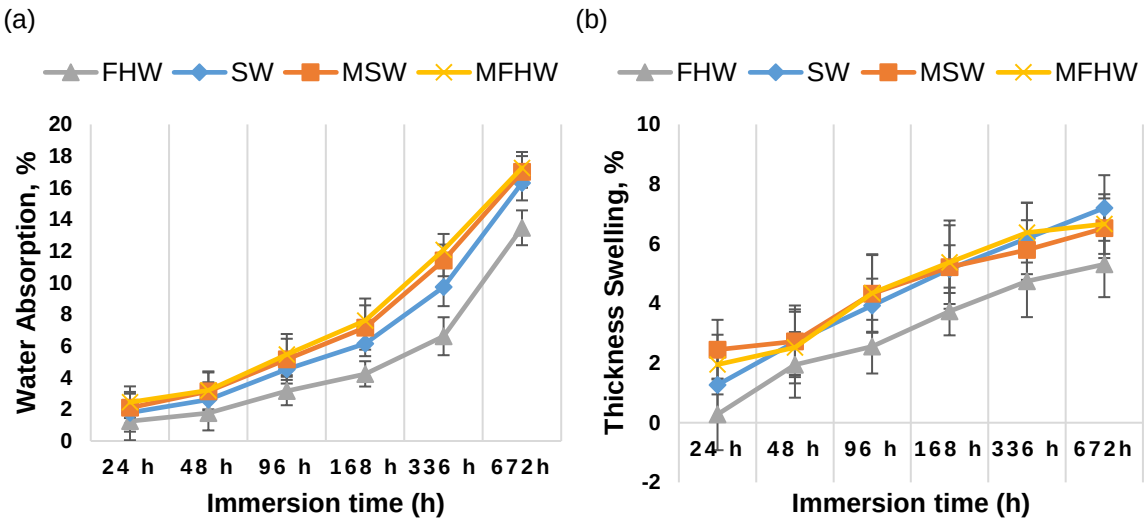

Fig. 3. Water absorption and thickness swelling of the WPC samples: SW – birch sapwood; MSW – modified birch sapwood; FHW – false heartwood; and MFHW – modified false heartwood

Colour Analysis

The colour change (ΔE) and change in brightness (L) of the neat PP and WPCs after exposure to artificial weathering compared with the initial colour before exposure are presented in Figs. 4a and 4b. No significant change was observed in colour parameters a^* and b^*. Colour changes were noted for the composites, all of which had turned lighter. This was in accordance with previous studies (Kiguchi *et al*. 2007; Stark and Mueller 2008). It was observed that weathering induced bleaching in the composites. Bleaching as a result of weathering has been reported to be caused by the lignin component in wood (Peng *et al*. 2014). Surface chalking such as the formation of a whitish, chalky powdery, friable layer was observed in all the WPCs exposed to artificial weathering, with colours ranging from brown and brownish black to white. This can be attributed to the decomposition of the lignin in the surface wood cells (Feist and Hon 1984). As was observed by Kiguchi *et al*.

(2007), cellulose, which is whitish and comparatively stable against UV, may have been the main chemical component. According to Fabiyi and McDonald (2014) and Peng *et al*. (2014), the chain scission reaction of lignin can lead to the formation of a paraquinonic structure, which can reduce to hydroquinone that causes the whitish colour of WPCs after weathering.

The colour differences of the composites and neat PP are presented in Fig. 4a. The modified birch sapwood and modified false heartwood had about the same colour change at the end of 2016 h (20.03 and 20.69, respectively), which were the greatest changes in colour among the composites. This was attributed to the effect of the modification with APTES on the wood. During modification, some of the lignin content in the wood was already degraded, which enhanced the adhesion with the polymer. Upon exposure to artificial weathering, photo-degradation of the remaining lignin, whose chromophoric groups were able to absorb UV rays and form free radical groups, took place (Peng *et al*. 2014; Badji *et al*. 2017). The neat PP had the lowest colour change of 2.16. A similar trend was observed for the brightness of all of the composites, with all of them becoming brighter, as is shown in Fig. 4b.

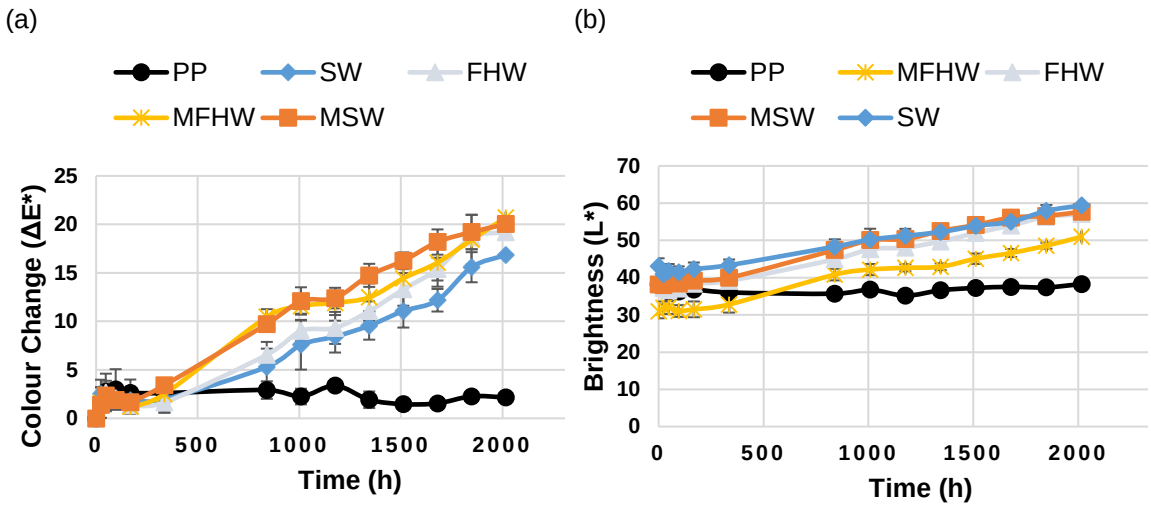

Fig. 4. Colour and brightness change of the WPC samples: SW – birch sapwood; MSW – modified birch sapwood; FHW – false heartwood; and MFHW – modified false heartwood

FTIR Analysis

The FTIR spectra of the composites are presented in Figs. 5a and 5b. The spectra showed a similar pattern for all of the samples, except for a few peaks that were not visible in the PP spectrum, but only in composites. In the fingerprint region (see Fig. 5a), the WPC showed a difference in the band absorption intensity, which was expected. The wide peak at 3347 cm^{-1} in the region 3400 cm^{-1} to 3200 cm^{-1} is assigned to –OH (hydroxyl) groups mainly from cellulose. However, the peak intensity has decreased due to the polarity reduction the surface of wood particles after modification (Lv *et al*. 2015). It can be seen that the hydroxyl group intensity is affected by the sodium hydroxide treatment which has decreased the absorption of hydroxyl groups for modified WPC samples and absorption peaks became narrower. According to Ghasemi and Farsi 2010, this indicates the emerging of amorphous region in the wood cellulose by removal of hydroxyl groups from its chain and reduction of the polarity on the wood surface. The intense peak at 2915 cm^{-1} was due to the C-H stretching in $–CH_2–$ groups. The key absorption bands of PP (Fig. 5a) included

1457 cm^{-1}, 1374 cm^{-1}, and 981 cm^{-1} (CH_3 bending) (Morent *et al*. 2008). The birch sapwood has the high hemicellulose carbonyl groups peaks at 1736 cm^{-1} and 1602 cm^{-1} which have decreased with NaOH treatment.

It can be clearly seen that the WPC samples had very strong peaks at 1049 cm^{-1}, 668 cm^{-1}, and 612 cm^{-1}. To make it clearer, enlargements of these ranges of the FTIR wavenumbers for modified and unmodified birch sapwood and false heartwood composites are shown on Fig. 5b. The peak at 1049 cm^{-1}, shown on Fig. 5b is attributed to primary alcohols and aromatic ether (C-O) stretching vibrations (cellulose, hemicellulose, and lignin) (Chen *et al*. 2017). The birch sapwood composites showed the highest absorbance, at 1049 cm^{-1} compared to false heartwood composites and modified composites, indicating that false heartwood has less hydroxyl groups available. Bankole *et al.* (2016) also reported this. The APTES modification effect was responsible for the peak changes at 1049 cm^{-1}, which corresponded to the Si-O-C band. The intense peaks at 1049 cm^{-1} and 608 cm^{-1} was from the reaction between the hydroxyl groups of cellulose and that of silanol on the wood surface, which created Si-O-Si- and -Si-O-C ether bonds (Ma *et al.* 2017). In Fig 5b, it can be observed that peak intensity for the modified sapwood and false heartwood has decreased at the corresponding range of 1049 cm^{-1}, 612 cm^{-1}, and 608 cm^{-1}. This can be explained with the reduced number of primary alcohols on the wood surface. In addition, the absorption peaks shapes have flattened, indicating the decrease of –OH bonds formed between the –OH groups (Lv *et al*. 2015).

From the FTIR results, it can be seen that the APTES had reacted with both sapwood and false heartwood, but there was no visible reaction peak between the APTES and PP. That is also the main reason why the mechanical properties were not significantly improved by the APTES modification in this research. Also, it can be observed that the false heartwood modification had been more difficult due to the lower number of available –OH groups.

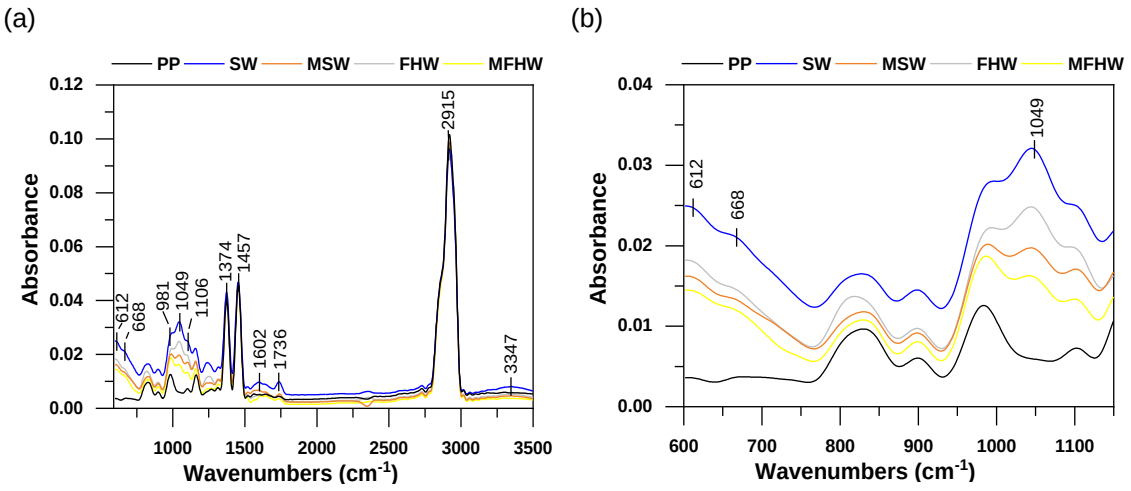

Fig. 5. FTIR spectra of the composites and neat PP: SW – birch sapwood; MSW – modified birch sapwood; FHW – false heartwood; and MFHW – modified false heartwood

CONCLUSIONS

1. The tensile strength of all of the samples was reduced after water absorption. The false heartwood and modified false heartwood had similar tensile strengths before soaking in water. After water absorption, the modified false heartwood had a 10.17% higher decrease in the tensile strength than the false heartwood.
2. The flexural strength of the false heartwood and modified false heartwood were about the same before soaking in water. However, the effect of APTES modification was visible in the flexural strength of the modified false heartwood composites after soaking in water.
3. The false heartwood composite showed the lowest reduction in the flexural strength of 10.6% and the modified false heartwood showed the highest reduction in the flexural strength of 16.6% after water absorption. This indicated that the modified false heartwood absorbed more water than the false heartwood.
4. The UV radiation degraded the neat PP and all of the composites. Surface chalking was observed in all of the WPCs exposed to artificial weathering, with colours ranging from brown and brownish black to white.
5. The use of false birch heartwood in the manufacturing of WPCs was shown to be possible. However, the modification of false birch heartwood should be improved in further studies to maximize its capabilities in WPC production.

REFERENCES CITED

Badji, C., Soccalingame, L., Garay, H., Bergeret, A., and Bénézet, J. C. (2017). "Influence of weathering on visual and surface aspect of wood plastic composites: Correlation approach with mechanical properties and microstructure," *Polym. Degrad. Stabil.* 137, 162-172. DOI: 10.1016/j.polymdegradstab.2017.01.010

Baettig, R., Guajardo, J., Salas, M., Cornejo, J., and Tapia, J. (2017). "Physical and chemical traits in false heartwood for two *Populus* hybrids," *Wood Res.-Slovakia* 62(4), 539-548.

Bankole, O. S., Rohumaa A., and Kers, J. (2016). "Microstructure study of birch false heartwood," in: *Proceedings of 12th annual meeting of the Northern European Network for Wood Science and Engineering*, Riga, Latvia, pp. 117-123.

Bledzki, A. K., and Faruk, O. (2006). "Microcellular wood fibre reinforced PP composites – A comparative study between extrusion, injection moulding and compression moulding," *Int. Polym. Proc.* 21(3), 256-262. DOI: 10.3139/217.0085

Bouafif, H., Koubaa, A., Perre, P. and Cloutier, A. (2008). "Effects of fibre characteristics on the physical and mechanical properties of wood plastic composites," in: *The 9th International Conference on Flow Processes in Composite Materials*, Montreal, Québec, Canada

Chen, F., Han, G., Li, Q., Gao, X., and Cheng, W. (2017). "High-temperature hot air/silane coupling modification of wood fiber and its effect on properties of wood fiber/HDPE composites," *Materials* 10(3), 286-302. DOI: 10.3390/ma10030286

EN 15534-1 (2014). "Composites made from cellulose-based materials and thermoplastics (usually called wood-polymer composites (WPC) or natural fibre

composites (NFC)) - Part 1: Test methods for characterisation of compounds and products," European Committee for Standardization, Brussels, Belgium.

Fabiyi, J. S., and McDonald, A. G. (2014). "Degradation of polypropylene in naturally and artificially weathered plastic matrix composites," *Maderas-Cienc. Tecnol.* 16(3), 275-290. DOI: 10.4067/S0718-221X2014005000021

Fayolle, B., Richaud, E., Verdu, J., and Farcas, F. (2008). "Embrittlement of polypropylene fibre during thermal oxidation," *J. Mater. Sci.* 43(3), 1026-1032. DOI: 10.1007/s10853-007-2242-1

Feist, C. W., and Hon, S. N. D. (1984). "Chemistry of Weathering and Protection," in: *The Chemistry of Solid Wood,* R. Rowell (ed.), American Chemical Society, Washington, pp. 401–451.

Gallagher, L. W., and McDonald, A. G. (2013). "The effect of micron sized wood fibers in wood plastic composites," *Maderas-Cienc. Tecnol.* 15(3), 357-374. DOI: 10.4067/S0718-221X2013005000028

Ghasemi, I., and Farsi, M. (2010). "Interfacial behaviour of wood plastic composite: Effect of chemical treatment on wood fibres." *Iranian Polymer Journal.* 19(10), 811-818.

Gwon, J. G., Lee, S. Y., Chun, S. J., Doh, H. G., and Kim, H. J. (2010). "Effect of chemical treatments of wood fibers on the physical strength of polypropylene based composites," *Korean J. Chem. Eng.* 27(2), 651-657. DOI:10.1007/s11814-010-0058-1

Hörnfeldt, R., Drouin, M., and Woxblom, L. (2010). "False heartwood in beech *Fagus sylvatica*, birch *Betula pendula, B. papyrifera* and ash *Fraxinus excelsior* - An overview," *Ecol. Bull.* 53, 61-76.

ISO 178 (2010). "Plastics – Determination of flexural properties," International Organization for Standardization, Geneva, Switzerland.

ISO 179-1 (2010). "Plastics – Determination of Charpy impact properties - Part 1: Non-instrumented impact test," International Organization for Standardization, Geneva, Switzerland.

ISO 4582 (2017). "Plastics – Determination of changes in colour and variations in properties after exposure to glass-filtered solar radiation, natural weathering or laboratory radiation sources," International Organization for Standardization, Geneva, Switzerland.

ISO 527-2 (2012). "Plastics – Determination of tensile properties - Part 2: Test conditions for moulding and extrusion plastics," International Organization for Standardization, Geneva, Switzerland.

Kallakas, H., Shamim, M. A., Olutubo, T., Poltimäe, T., Süld, T. M., Krumme, A., and Kers, J. (2015). "Effect of chemical modification of wood flour on the mechanical properties of wood-plastic composites," *Agronomy Research* 13(3), 639-653.

Kiguchi, M., Kataoka, Y., Matsunaga, H., Yamamoto, K., and Evans, P. D. (2007). "Surface deterioration of wood-flour polypropylene composites by weathering trials," *J. Wood Sci.* 53(3), 234-238. DOI: 10.1007/s10086-006-0838-8

Kim, T.-W., Lee, S.-Y., Chun, S.-J., Doh, G.-H., and Paik, K.-H. (2010). "Effect of silane coupling on the fundamental properties of wood flour reinforced polypropylene composites," *J. Compos. Mater.* 45(15), 1595-1605. DOI: 10.1177/0021998310385589

Lv, S., Tan, H., Gu, J., Zhang, Y. (2015). "Silane modified wood flour blended with poly(lactic acid) and its effects on composite performance," *BioResources* 10(3), 5426-5439. DOI: 10.15376/biores.10.3.5426-5439

Ma, Y., Wang, C., and Chu, F. (2017). "Effects of fiber surface treatments on the properties of wood fiber-phenolic foam composites," *BioResources* 12(3), 4722-4736. DOI: 10.15376/biores.12.3.4722-4736.

Metsä-Kortelainen, S. (2011). *Differences between the Sapwood and Heartwood of Thermally Modified Norway Spruce (Picea abies) and Scots Pine (Pinus sylvestris) Under Water and Decay Exposure*, Ph.D. Dissertation, Aalto University, Helsinki, Finland.

Metsä-Kortelainen, S., Antikainen, T., and Viitaniemi, P. (2006). "The water absorption of sapwood and heartwood of Scots pine and Norway spruce heat-treated at 170 °C, 190 °C, 210 °C and 230 °C," *Eur. J. Wood Wood Prod.* 64(3), 192-197. DOI: 10.1007/s00107-005-0063-y

Mijiyawa, F., Koffi, D., Kokta, B. V., and Erchiqui, F. (2015). "Formulation and tensile characterization of wood–plastic composites: Polypropylene reinforced by birch and aspen fibers for gear applications," *J. Thermoplast. Compos.* 28(12), 1675-1692. DOI: 10.1177/0892705714563120

Morent, R., De Geyter, N., Leys, C., Gengembre, L., and Payen, E. (2008). "Comparison between XPS- and FTIR-analysis of plasma-treated polypropylene film surfaces," *Surf. Interface Anal.* 40(3-4), 597-600. DOI: 10.1002/sia.2619

Olsson, T., Megnis, M., Varna, J., and Lindberg, H. (2001). "Study of the transverse liquid flow paths in pine and spruce using scanning electron microscopy," *J. Wood Sci.* 47(4), 282-288. DOI: 10.1007/BF00766714

Peng, Y., Liu, R., Cao, J., and Chen, Y. (2014). "Effects of UV weathering on surface properties of polypropylene composites reinforced with wood flour, lignin, and cellulose," *Appl. Surf. Sci.* 317, 385-392. DOI: 10.1016/j.apsusc.2014.08.140

Prka, M., Zečić, Ž., Krpan, A. P. B., and Vusić, D. (2009). "Characteristics and share of European beech false heartwood in felling sites of central Croatia," *Croat. J. For. Eng.* 30(1), 37-49

Shigo, A. L., and Hillis, W. E. (1973). "Heartwood, discolored wood, and microorganisms in living trees," *Annu. Rev. Phytopathol.* 11, 197-222. DOI: 10.1146/annurev.py.11.090173.001213

Smith, K. T. (2015). "Compartmentalization, resource allocation, and wood quality," *Current Forestry Report* 1(1), 8-15. DOI: 10.1007/s40725-014-0002-4

Stark, M. N., and Mueller, S. A. (2008). "Improving the color stability of wood-plastic composites through fiber pre-treatment," *Wood Fiber Sci.* 40(2), 271-278.

Stark, N. (2001). "Influence of moisture absorption on mechanical properties of wood flour-polypropylene composites," *J. Thermoplast. Compos.* 14(5), 421-432. DOI: 10.1106/UDKY-0403-626E-1H4P

Taib, R. M., Ishak, Z. A. M., Rozman, H. D., and Glasser, W. G. (2006). "Effect of moisture absorption on the tensile properties of steam-exploded *Acacia mangium* fiber-polypropylene composites," *J. Thermoplast. Compos.* 19(5), 475-489. DOI: 10.1177/0892705706062208

Torelli, N. (1984). "The ecology of discolored wood as illustrated by beech (*Fagus sylvatica* L.)," *IAWA J.* 5(2), 121-127. DOI: 10.1163/22941932-90000875

Article submitted: Nov. 27, 2018; Peer review completed: Feb. 17, 2019; Revised version received and accepted: March 9, 2019; Published: March 11, 2019.
DOI: 10.15376/biores.14.2.3554-3566