CHEMICAL FORCE MICROSCOPY ANALYSIS OF WOOD-PLASTIC COMPOSITES PRODUCED FROM DIFFERENT WOOD SPECIES AND COMPATIBILIZERS

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Abstract. Alien invasive species are posing a serious and direct threat to biodiversity, water security, and productive use of land in South Africa. Most of these species need to be cleared and are therefore regarded as waste material, which could become raw material for wood-plastic composites (WPCs). WPCs containing wood from *Pinus radiata*, *Eucalyptus grandis*, *Acacia mearnsii*, *Acacia longifolia*, *Acacia saligna*, and *Casuarina cunninghamiana* trees, low-density polyethylene (LDPE) and three different compatibilizers: namely the commercially available ethylene vinyl alcohol (EVOH), polyethylene graft-maleic anhydride (PE-g-MA), and thermally degraded LDPE (dPE)—were studied. The determined properties included MC, density, tensile strength, and adhesive forces between the wood and compatibilizer components. The adhesive forces were determined using chemical force microscopy with functionalized, coated tips. WPC samples were compounded and injection molded. EVOH as compatibilizer proved to be very sensitive to the wood species incorporated into the WPC blend. Composites containing PE-g-MA and dPE as compatibilizer had a higher tensile strength for all the wood species. Composites containing dPE as compatibilizer showed less variation in all samples for tensile strength and adhesive force measurements. The densities and tensile strengths of the samples compares well with some commercial WPCs. The study shows that the inexpensive dPE outperforms commercially available compatibilizers and effectively promotes adhesion in WPCs. It was also shown that the studied invasive wood species can be incorporated into WPCs, if the correct compatibilizer is chosen. The differences in the results of the study seem difficult to relate due to the many factors such as the wood species, MC, density, compatibilizers, and processing method. However, the micro properties can give enough information regarding the macro properties of WPCs.

Keywords: Alien invasive species, compatibilizer, adhesive force, chemical force microscopy, tensile strength, WPCs.

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INTRODUCTION

Increasing environmental concerns have necessitated the search for new materials with high performance at affordable costs. Likewise, the growing dependency on petroleum-derived plastic materials and the rising environmental and sustainable concerns have motivated researchers to explore new materials to replace conventional plastic in various applications (Sarifuddin and Ismail 2015). Wood-plastic composites (WPCs) are relatively new material class that cover a broad range of composite materials utilizing an organic resin binder (matrix) and fillers composed of cellulosic material. Over the last few years, WPCs have received considerable attention from the wood and plastic industries (Balasuriya et al 2001; Shebani et al 2012). The properties of WPCs differ from solid wood and pure plastic in the sense that they combine the advantages of both materials, which makes it a good replacement material for some applications (Kazemi-Najafi et al 2012). WPCs possess the further advantage that they can be made from waste products from the forestry/wood industry and recycled plastic obtained from household waste (Teuber et al 2013).

The polymer matrix of WPCs frequently comprises polyolefins, such as low-density polyethylene (LDPE) or polypropylene, or polyvinylchloride, whereas the wood fillers are typically softwood fibers that have a well-known chemical composition and uniform configuration (Schneider 2007). Wood is an organic and natural composite of cellulose fibers embedded in a matrix of lignin and rich in functional groups with numerous hydroxyl groups. On the other hand, most matrix polymers are hydrophobic in character and have very few functional groups. This brings about chemical incompatibility, which results in poor adhesion between the two phases and also causes nonuniform dispersion of fibers within the matrix leading to poor mechanical properties (Yang et al 2007). To improve the affinity and adhesion between fibers and the polymer matrix in production, chemical "coupling" or "compatibilizing" agents are typically employed (Kim et al 2006; Stark and Rowlands 2007; Feifel et al 2015). These compatibilizers have a polar and nonpolar ends, which attach to the wood fiber and polymer, respectively. Their primary function is to improve the homogeneity of dissimilar or incompatible materials, as lack of homogeneity can reduce the mechanical properties of the end product (Niska and Sain 2008; Stokke et al 2013). Ethylene vinyl alcohol (EVOH) and polyethylene graft-maleic anhydride (PE-g-MA) are some of the typically used conventional compatibilizers for WPCs. The ethylene segment in EVOH is compatible with the nonpolar polymeric matrix and the hydroxyl-containing component attaches to the wood filler. Similarly, the ethylene in PE-g-MA has an affinity to the polymer matrix, whereas the maleic anhydride attaches to the wood surface. Thermally degraded LDPE (dPE) has proven to be a good compatibilizer for WPCs (Ndlovu et al 2013). When LDPE undergoes thermo-oxidative degradation, carbonyl and hydroxyl groups are produced and these new functional groups allow the polymer to be used as a compatibilizer for WPCs (Ndlovu et al 2013).

In recent times, the increased use of WPCs for structural and exterior applications has resulted in the need to understand their durability better (Stark and Matuana 2007). It has been shown that the performance of WPCs as a structural material depends mainly on the quality of the stress transfer at the interphase (Lee et al 2007). The interphase is the region between the fiber and the polymer matrix and poor interaction between the two materials reduces the adhesion between them (Niska and Sain 2008). Improvement of the interphase adhesion improves WPC properties, such as tensile strength, toughness, impact, rate of water absorption, and others. Consequently, a better understanding of the interfacial properties and characteristics will help to evaluate the overall properties of WPCs (Lee et al 2007). In this regard, many analytical methods like atomic force microscopy (AFM), contact angle determination, scanning electron microscope, Fourier transform infrared spectroscopy, dynamic mechanical thermal analysis, and others have been used to study the microscopic and macroscopic mechanical, physical, and chemical properties of WPCs (Lee et al 2007; Stark and Matuana 2007; Awaja et al 2009).

One useful analytical method is chemical force microscopy (CFM), which is an extension of the AFM, in which the tip is modified with specific functional groups to provide information about the chemical composition of the surface (Bastidas et al 2005). CFM was used to study the adhesive forces on cellulose films and bleached softwood kraft pulp fibers in aqueous media by Bastidas et al (2005). They found that the magnitude of the pull-off forces between modified tips and the fiber surface were comparable with results obtained from model cellulose surfaces. Klash et al (2010) also used CFM to determine cellulose and lignin content on fiber surface of several eucalyptus species from South Africa and found significant differences in cellulose and lignin content on fiber surfaces based on-site and genotype. Using CFM, Basson (2013) found high interactions between coated tips and cellulose, lignin, and compatibilizer substrates. CFM can therefore be used to analyze and quantify the chemical interactions between the different components in WPCs on the micro scale, to help to explain physical and mechanical properties of the macroscopic composite material. Since the surface characteristics of the wood component and the interfacial properties between the wood and plastic, influence the mechanical and physical properties of WPCs (Shebani et al 2009).

In South Africa, alien invasive species (AIS), are defined as species that originate from other countries and often outcompete the original vegetation. There are 559 AIS in South Africa of which 383 are plants which are causing damage worth millions of dollars to South Africa's economy every year. Invasive Species South Africa estimates that invasive plants cover up to 10% of South Africa (ISSA 2016). These species need to be cleared from public land and can therefore also be regarded as waste materials. Using them as raw material for WPCs can be regarded as environmentally friendly value adding to a waste material. Most of the woody species are, however, hardwoods with quite different properties compared with the softwoods typically used in WPC systems.

In this study, the adhesive forces determined between AFM tips functionalized with three different compatibilizers and the different wood substrates were determined and related to macroscopic properties of WPCs in an attempt to explain the mechanical properties, such as tensile strength, of WPCs as well as to determine the feasibility to use alien invasive wood species from South Africa for the production of WPCs with the most suitable compatibilizer.

MATERIALS AND METHODS

Materials

LDPE from Sasol Polymers with melt flow index value 65 g/10 min was used as matrix polymer for the WPCs. As compatibilizers the commercially available EVOH and PE-g-MA, both from Sigma-Aldrich (Johannesburg, South Africa) were used as well as dPE, which was produced at the Department of Chemistry and Polymer Science, Stellenbosch University. The LDPE was thermally degraded in a forced-air laboratory oven at 90°C for 7 wk (Ndlovu et al 2013).

The wood fibers were obtained from six invasive tree species, namely Pine (*Pinus radiata*), Eucalyptus (*Eucalyptus grandis*), Black wattle (*Acacia mearnsii*), Long-leaved wattle (*Acacia longifolia*), Port Jackson (*Acacia saligna*), and Beefwood (*Casuarina cunninghamiana*). Extractives were obtained from a typical softwood (pine) and hardwood (eucalyptus) and no further distinction was made with regard to their composition. The wood was obtained from one softwood (pine) and five invasive hardwood species and their properties are listed in Table 1. The wood species differ significantly in their chemical and physical properties. Pine, a softwood with uniform, long tracheids and no large pores is similar to other softwood species, which are commonly used for WPC production,

Table 1. Chemical compositions and dimension of softwood and hardwood fibers (Hodzic and Shanks 2014).

Species	Wood type	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Extractives (%)	Aspect ratio (μm)
Pine	Softwood	40-45	25-30	26-34	0-5	50-200
Eucalyptus						
Black wattle						
Long-leaved wattle	Hardwood	45-50	21-35	22-30	0-10	28-86
Port Jackson						
Beefwood						

whereas the other wood species are porous hardwood species with significantly different cell types and structure. Hardwoods contain shorter fibers, vessel elements, parenchyma cells, and ray cells, resulting in a very inhomogeneous surface (Hodzic and Shanks 2014).

Wood Sections and Fibers

Blocks of clear wood with the dimensions of 15 × 15 × 15 mm were prepared from each wood species and 20-μm thick sections were cut along the grain with Leica RM 2245 rotary microtome from SMM Instruments (Cape Town, South Africa) with a 16-cm steel blade.

The wood flour for the WPCs was obtained from chipped wood that was subsequently milled in a hammer mill from Drotsky (Alberton, South Africa) with a 4-mm screen. After drying the particles were screened for size and the 180 μm fraction was used for all WPC blends.

Functionalized AFM Tips

Silicon force modulation cantilevers from Nanosensors (Neuchatel, Switzerland) were used for the tip modifications according to Bastidas et al (2005) and coated with the following compatibilizers:

EVOH (Sigma-Aldrich)
PE-g-MA (Sigma-Aldrich)
dPE

The silicon tips were first gold coated with an S150A Gold Sputter Coater from Edwards and cleaned under a 254 nm UV lamp for 1 h to ensure that all organic material was removed. A 1 mM thiol solution of 11-mercapto-1-undecanol, 1-octadecanethiol, and 11-mercapto undecanoic acid (Sigma-Aldrich) in ethanol (Kimix Chemicals) was prepared, into which the gold tips were submerged for 2 h at room temperature under argon gas (Bastidas et al 2005). A 2 mM solution of each compatibilizer was prepared in xylene or dimethyl sulfoxide (EVOH) at 40°C into which the thiol coated tips were dipped for 2 h to prepare functionalized tips with PE-g-MA, EVOH and dPE, respectively. The coated tips were then rinsed with n-heptane (KIMIX) and alcohol, and dried in an argon stream (Basson 2013).

WPC Compounding

Optimization of ratio. Initially, composites with varying amounts of wood and compatibilizer were prepared with pine as a reference species, to determine the optimum ratio and wood loading for each compatibilizer, as their optimum amount may potentially differ. Composite materials of 5 g total mass were compounded in two replicates by melt mixing. The wood content was 30, 40, and 50 wt %. This was done to determine and compare the optimum wood loading. The compatibilizer ratios were 5, 7, and 10 wt % of the polymer part. Stabilizer (2 wt% of the polymer part) was added to prevent degradation. The optimum polymer/wood ratios were found to be 70/30 with 7% EVOH compatibilizer, 70/30 with 10% dPE compatibilizer, and 50/50 with 10% PE-g-MA compatibilizer. The formulation was based on a US Patent (No. 6,942,829), which suggests possible ranges of about 20-80 wt% of a thermoplastic polymer, about 20-80 wt% of a cellulosic filler material and 0.1-10 wt% of additives (Drabeck et al 2005). It is known that not all compatibilizers have the same effect on WPC performance.

WPC processing. In a second step, composite samples were prepared by dissolving the LDPE in 80 mL xylene at 140°C and then adding the stabilizer and wood flour into the solution while stirring on a hot plate. The solution was stirred and cooled to room temperature, which was followed by precipitation in acetone. The samples were then filtered (150 mL Buchner funnel filter; Sinta Glass) and allowed to dry in a constant airflow at room temperature for 3 da and conditioned awaiting molding.

Injection molding. Composite samples were molded into tensile bars ("dog bone") in accordance with ASTM D638 (ASTM 2010) with a HAAKE Mini Jet II from Thermo Scientific (type 557-2290). Five samples were prepared of each group for tensile testing. The samples were conditioned in a climate chamber at 20 ± 3°C and RH of 65% prior to testing.

Adhesive Force Determination with CFM

The CFM measurements were performed on an Easy Scan 2 AFM from Nanosurf (Basel, Switzerland) in the force modulation imaging and spectroscopy modes. Force modulation cantilevers with a 2 N/m spring constant from Nanosensors were used and the tips were chemically modified as described above. To achieve results describing the entire sample with statistical relevance, 150 force-distance curves were measured at 15 different positions on each sample and outliners eliminated to determine the average adhesive force between the modified tip and sample surface. All CFM measurements were carried out in air at ambient conditions of 23 ± 2°C and 65 ± 2% RH.

Physical Properties

The MC of each WPC after conditioning for several weeks at 20°C and 65% RH was measured by the oven-dry method according to ASTM D-4442 (ASTM 2007) using Eq 1

$$\mathrm{MC}\ (\%) = \frac{\text{Initial mass-ovendry mass}}{\text{ovendry mass}} \times 100 \qquad (1)$$

The density was determined by volume measurement in accordance with ASTM D-2395 (ASTM 2014) and calculated with Eq 2

$$\rho = \frac{\text{ovendry mass}}{\text{green volume}} \times 100 \qquad (2)$$

Mechanical Properties

The tensile strength was determined on an LRX (Lloyd instruments) universal tensile tester in accordance with ASTM D638 (ASTM 2010). A preload of 30 N was applied at a cross-head speed of 50 mm/min. Five dumbbell shaped samples were analyzed for each WPC formulation to obtain average values. The gauge size of the samples was 15.26 mm long, 3.03 mm wide, and 0.76 mm thick. The stress and elongation tensile modulus at maximum load was calculated from the stress strain curves and average values with standard deviations are reported.

Statistical Analysis

Statistical analysis was conducted using the Origin 8.5.1 software in combination with a one-way analysis of variance (ANOVA). A Tukey's honest significant difference test was used to test the statistical significance at 0.05% probability level. To understand the relationship among the variables, regression analysis was conducted.

RESULTS AND DISCUSSION

Adhesion Forces

To understand how well the three main components forming the WPC bond to each other, chemically functionalized tips were used to quantify the adhesive force between the compatibilizer

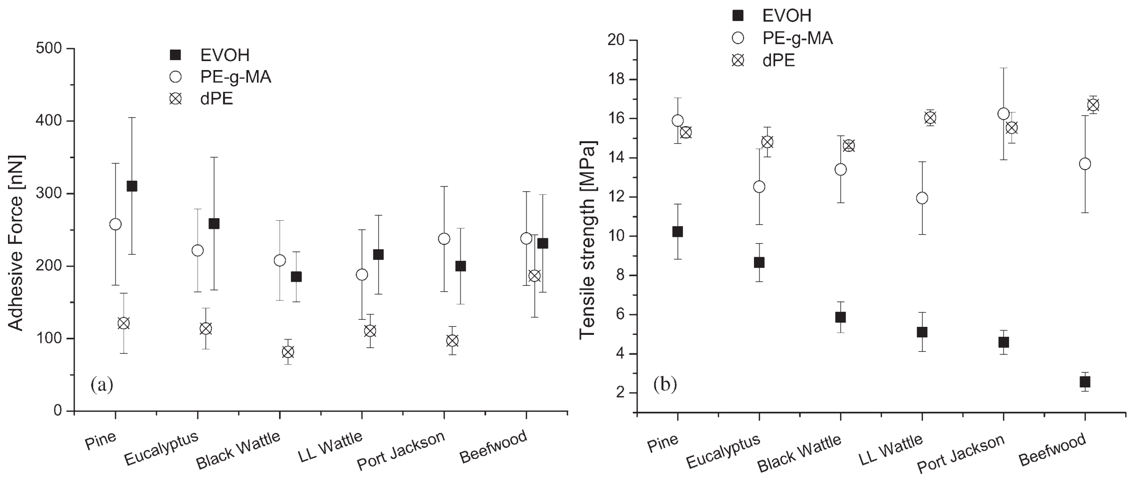

Figure 1. (a) Adhesive forces between compatibilizer coated tips and various wood surfaces and (b) tensile strength of WPCs with different compatibilizers and wood species.

coated AFM tips, the polymer, and the different wood surfaces.

The average interaction forces between the coated tips and an LDPE model film were 210.3 ± 57.71 nN for EVOH, 227.9 ± 92.07 nN for PE-g-MA, and 215.97 ± 60.56 nN for dPE. No significant differences ($p < 0.05$) were found between the results regarding the interaction between compatibiliser and LDPE.

Results of the interaction between compatibilizer coated tips and the wood surfaces are displayed in Fig 1a. The EVOH coated tip showed the highest adhesion on Pine and the lowest on Black wattle. The adhesive forces ranged from 200 to about 300 nN. The PE-g-MA coated tip showed the least variation and sensitivity on all the species and adhesion forces ranged from 200 to 250 nN. The dPE coated tip exhibited the lowest adhesive forces around 100 nN with very small inter and intra-sample variation.

Based on the experimental evidence, the large variation of the adhesive force measurements can be explained by the varied surface structure of the wood surfaces, chemical and anatomical differences between the species (Stokke and Gardner 2003). Over the scan range of about 100 μm^2, the chemical composition of the fiber surface and the cell type may change drastically, to result in a large range of adhesive forces determined between the functional groups of the compatibilizer and the wood surface, which are measured on a point the size of a few molecules.

Tips functionalized with dPE showed little variation on different wood species and although the adhesive force is generally lower than that measured between the other compatibilizers and wood substrates, it seems less sensitive to changes caused by the wood filler.

ANOVA presented in Table 2 showed significant differences between the adhesive forces observed between the compatibilizer coated tips and the wood substrates. For the EVOH coated tip, pine and eucalyptus were statistically different ($p < 0.05$) from the other species. For the PE-g-MA coated tip significant differences were found between pine, long-leaved wattle, and Port Jackson, whereas there were no significant differences between all the species for the dPE coated tip.

Physical Properties

MC and density are some of the most important factors that affect the properties of WPCs

Table 2. Physical, mechanical properties, and adhesive forces of various WPCs from six species with three compatibilizers.

		Pine	Eucalyptus	Black wattle	Long-leaved wattle	Port Jackson	Beef wood
EVOH	Tensile strength	10.24a (1.41)	8.66b (0.98)	5.87cab (0.79)	5.11dab (1)	4.59eab (0.62)	2.57fabcde (0.48)
	Density	0.74a (0.03)	0.83ba (0.02)	0.78ca (0.05)	0.8da (0.02)	0.71ebcd (0.01)	0.7fbcd (0.03)
	MC	15.84a (4.23)	5.06ba (0.99)	8.39ca (3.17)	10.99dab (3.52)	20.19ebcd (2.78)	26.87fabcde (2.4)
	Adhesive force	310.49a (94.44)	258.68ba (91.58)	185.18cab (34.4)	215.92dabc (54.47)	199.75eab (52.53)	231.25face (67.5)
PE-g-MA	Tensile strength	15.9a (1.17)	12.53 (1.93)	13.41 (1.71)	11.95da (1.85)	16.25ed (2.34)	13.69 (2.48)
	Density	0.95a (0.02)	0.97 (0.01)	0.99ca (0.02)	0.98da (0.01)	0.99ea (0.01)	0.98fa (0.01)
	MC	5.32 (1.72)	4.31 (0.99)	4.2 (0.36)	4.36 (1.09)	4.25 (0.13)	4.27 (0.16)
	Adhesive force	257.75a (84.03)	221.67ba (57.27)	207.86ca (55.2)	188.3dab (61.82)	237.64ecd (72.69)	238.16ecd (64.88)
dPE	Tensile strength	15.3a (0.27)	14.81b (0.75)	14.62c (0.13)	16.05dbc (0.41)	15.54e (0.79)	16.7fabce (0.45)
	Density	0.92 (0.01)	0.91 (0.01)	0.91 (0.01)	0.92 (0.01)	0.91 (0.01)	0.91 (0.01)
	MC	3.73a (1.18)	2.09ba (0.11)	2.17ca (0.29)	2.3da (0.13)	2.35ea (0.06)	2.42fa (0.3)
	Adhesive force	121.17a (41.61)	113.84 (28.23)	81.68 (17.48)	110.63 (22.93)	97.24 (19.35)	186.55 (56.84)

dPE, degraded low-density polyethylene EVOH, ethylene vinyl alcohol; PE-g-MA, polyethylene graft-maleic anhydride. Values within the same line row by same letters are significantly different at $\alpha = 0.05$. Standard deviation in brackets.

and they are listed in Table 2. The highest MC (27%) was observed for Beefwood and the lowest for Eucalyptus (5%) composites containing EVOH as compatibilizer. The MC for PE-g-MA composites ranged from 4 to 5% for the different composites. The results of an ANOVA indicated no significant difference ($p < 0.05$) between the wood species. Composites made with dPE had the lowest MC, ranging from 2 to 4%. Apart from Pine, there was no significant difference ($p < 0.05$) between the other species. The high MC of EVOH composites negatively affects the properties of the WPC. The measured MCs were all higher than those determined in commercial WPCs, such as Geodeck boards, which have an MC of 1.7% (Klyosov 2007).

The densities were similar for PE-g-MA and dPE composites, while EVOH composites had a slightly lower, but comparable density. The similar densities were obtained because the WPCs were formulated based on weight. There were no significant differences ($p < 0.05$) between the species for the dPE composites and a few differences between the PE-g-MA and EVOH composites, as shown in Table 2.

The measured densities compare very well to the densities of commercial products, such as, eg, Boardwalk, Trex, Monarch, and Rhino Deck WPCs with densities of 0.91-0.96 g/cm^3 (Klyosov 2007).

Table 2 shows the physical, mechanical properties, and adhesive forces of various WPCs from six species with three compatibilizers.

Tensile Strength

Figure 1b shows the tensile strength of composites made with LDPE, different compatibilizers, and different wood species.

The EVOH composites showed a good tensile strength of about 10 MPa in composites containing Pine and Eucalyptus. All other composites had significantly lower tensile strength, with only about 2 MPa in the Beefwood composite. This shows that EVOH as compatibilizer is highly sensitive to its binding partners and does not work well on all wood species. This can be explained by the fact that EVOH does not interact with all parts of the polymer and therefore counteracts the positive reinforcement effect of the fibers, as described by Basson (2013). Furthermore, EVOH only facilitates interactions between the ethylene-rich areas of the LDPE and wood (Drummond et al 2000). The tensile strength was further decreased by the high MC of EVOH composites. The tensile strength corresponds to the results obtained in the CFM analysis, where the adhesive forces detected between EVOH and wood were very variable with the wood species.

The composites containing PE-g-MA as compatibilizer had significantly a higher tensile strength between 12 and 16 MPa, with less variation and sensitivity toward the wood species. The dPE compatibilizer produced the highest tensile strength results of around 15-16 MPa for all wood species. This is an indication that the dPE compatibilizer is equally compatible with all the wood species, which is again in good agreement with the adhesive force results obtained by CFM (Ndlovu et al 2013).

ANOVA presented in Table 2 showed significant differences ($p < 0.05$) between tensile strength of most the wood species for EVOH composites. WPCs containing PE-g-MA showed the least differences, only Pine and Long-leaved wattle and Long-leaved wattle and Port Jackson were significantly different. Wood species in dPE composites did not show significantly different tensile strength.

The tensile strength of the WPCs determined in this study compares well with commercial WPCs, eg, products of TimberTech, GeoDeck, Trex, EverX, and Timberlast which have tensile strength values of 8-13 MPa (Klyosov 2007).

Relationship between Microscopic and Macroscopic Properties

To determine the relationship between physical and mechanical properties of WPCs, a linear

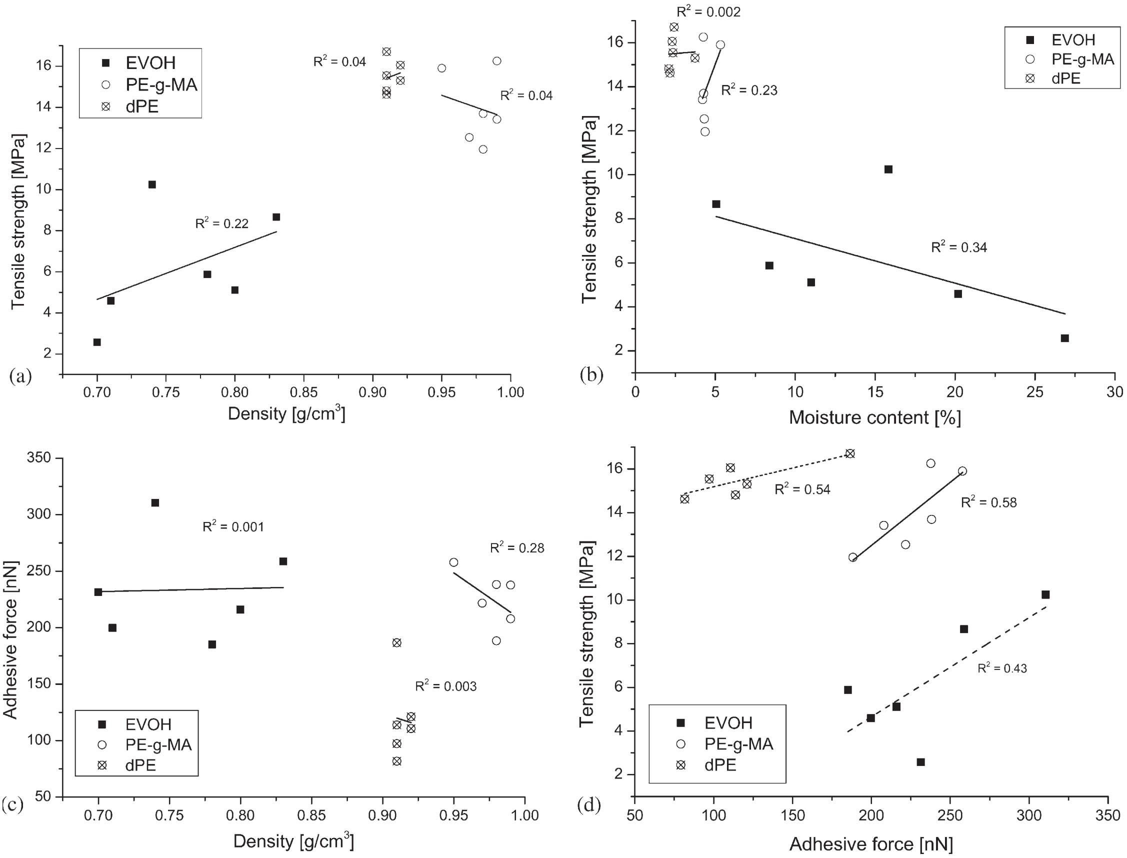

Figure 2. Relationship between (a) density and tensile strength of WPCs, (b) MC and tensile strength (c) density and adhesive force between compatibilizer coated tips and wood surfaces, and (d) tensile strength and adhesive force between compatibilizer coated tips and wood surfaces.

regression model was fitted and the results are presented in Fig 2.

Figure 2a shows that the density accounted for 22% of the tensile strength for the EVOH composites, and only 4% for PE-g-MA and dPE composites, respectively. This shows that the prediction rate between density and tensile strength is low for all composites, but especially for PE-g-MA and dPE WPCs.

The model between MC and tensile strength of the WPCs fitted well for two of the compatibilizers with R^2 of 0.34 for EVOH and 0.23 for PE-g-MA, however, for dPE R^2 was only 0.002. It can be seen that a lower MC correlated to better the tensile strength. The relationship between MC and tensile strength is shown in Fig 2b.

The density contributed hardly to the adhesive force, for EVOH (0.1%) and dPE (0.3%) composites, while it accounted for 28% of the adhesive force in PE-g-MA compositess. It can be seen in Fig 2c that for EVOH composites a higher density leads to a higher adhesive force, whereas for PE-g-MA and dPE a higher density leads to lower adhesive force.

Fig 2d shows the relationship between the tensile strength of WPCs and the adhesive force. The determined R^2 values were 0.43 for EVOH, 0.54 for dPE, and 0.58 for PE-g-MA composites. This means that the tensile strength can be explained by the adhesive forces acting between compatibilizer and wood to the extent of about 50%.

Figure 2 shows that the relationship between some of the variables is low, yet important conclusions can be drawn from the statistically significant ($p < 0.5$) differences that were observed.

The highest adhesive force interaction with the EVOH coated tip was observed on Pine wood followed by Eucalyptus, a softwood, and a hardwood. All acacias and the Beefwood resulted in lower adhesive forces. The tensile strength changed more significantly ($p < 0.05$) with the wood species. The highest value was observed in the Pine composite and the lowest in the Beefwood composite. The MC was very high for most of the WPCs containing EVOH as compatibilizer and the density differed between the species.

The PE-g-MA coated tip showed less difference in adhesive forces on the different wood species than the EVOH coated tip, with a slight decrease in adhesive force for some of the hardwoods. The tensile strength of composites containing PE-g-MA was generally much higher with few significant ($p < 0.05$) differences detected between the wood species. The adhesive force and the tensile strength of PE-g-MA composites did not follow the same trend, but the lowest adhesive force and the lowest tensile strength were determined in composites made from Long-leaved wattle and the highest adhesive force and tensile strength in the composite made from Pine. The MC and density were similar for all the WPCs containing PE-g-MA as compatibilizer with few differences among them.

The dPE coated tip showed a lower adhesive force with some variations on all the wood species, which can be explained by chemical and anatomical effects of the wood species. Likewise, the tensile strength of all WPCs containing dPE as compatibilizer was similar with little variation. The composites containing dPE had the lowest adhesive forces determined by CFM, but the highest tensile strength in the composites. This can be explained by the fact that dPE binds well to the matrix and more importantly shows only a small variation on the wood surfaces (independent of cell type or surface chemistry), whereas the large variation of the EVOH compatibilizer proved that there were binding sites with high adhesion, but also sites with no affinity at all as a result of the heterogeneous nature of the wood surface. This heterogeneous nature of the wood surface leads to variations in interfacial interactions that may have impacted negatively on the mechanical performance of the composites (Petinakis et al 2014).

CONCLUSIONS

The performance of WPCs containing EVOH, PE-g-MA, and dPE and different wood species in LDPE matrix was investigated on a micro- and macroscopic scale. The high MC of EVOH composites negatively affected and lowered tensile strength of the final WPC. The EVOH composites were found to have good tensile strength with Pine and Eucalyptus wood, however, EVOH proved to be very sensitive to the wood species and did not perform well with the other wood species. Composites containing PE-g-MA had higher tensile strength and the results varied less with the wood species. Composites containing dPE as compatibilizer had a high tensile strength for all investigated species and the values were comparable to the WPCs containing PE-g-MA. The densities and tensile strengths of this study compare well with some commercial WPCs. The results are difficult to relate, as many factors, such as the wood species, MC, density, compatibilizer, and processing method affect the performance of the final product. However, the microscopic properties significantly affect the macroscopic properties of the WPCs.

In conclusion, the study shows that the studied invasive wood species may be incorporated into WPCs if the correct compatibilizer is chosen. dPE proved to be the best choice, as it had the lowest sensitivity to the wood species and yielded WPCs with good mechanical strength. Furthermore, it is an inexpensive compatibilizer that can potentially be obtained from waste materials, just like the polymer matrix.

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