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PRODUCTION OF WOOD PLASTIC COMPOSITES AS A SUSTAINABLE SOLUTION FOR THE POST-HARVEST AGRICULTURE WASTE AND PLASTIC WASTE

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Abstract

Pollution caused by burning the post-harvest agriculture waste and plastic waste in is a very serious problem that needs a solution. The amount of agricultural waste in Egypt ranges from 30 to 35 million tons a year. Out of this amount, only 11 million tons are used as animal feed and organic manure and the rest is burned. Egypt also produces 5.4 million tons of plastics yearly, only 20% of which is recycled. The rest is either burned resulting in highly toxic dioxins or dumped in water sources causing endanger to aquatic life. Egypt does not produce wood and imports more than three billion dollars' worth of wood yearly, including wood plastic composites (WPC). WPC is a composite material widely used in decking, fencing, garden furniture, cladding, and kitchen cabinets and made of wood fiber, thermoplastics, and additives. This work investigates the sustainable sources to produce WPC from different types of agriculture and plastic wastes. To produce WPC of high quality, the processing, physical, and mechanical testing were carried out on the produced WPC. Three types of post-harvest waste were experimented, orange tree trimmings, cotton stems, and casuarina tree trimmings. Both virgin and recycled High Density Polyethylene (vHDPE & rHDPE respectively) plastic were experimented. Both Maleic Anhydride grafted polyethylene (MAPE) and silane coupling agents were also experimented. Results show that, the compound that had the best WPC properties had the following recipe: orange wood at 50% by weight with 0.11 mesh size, rHDPE at 50%, MAPE coupling agent at 5%.

Keywords Agriculture waste, plastic waste, WPC, sustainability.

INTRODUCTION

Egypt produces 5.4 million tons of plastics every year, making it the biggest plastic polluter in the Arab world. A recent report by the Worldwide Fund for Nature (WWF) revealed that Egypt dumps 250,000 tons of plastic waste in the Mediterranean [1]. Agriculture waste has also been a major source of pollution in Egypt. The amount of agricultural waste ranges from 30 to 35 million tons a year. Only 7 million tons are used as animal feed, and 4 million tons are used as organic manure. The problem of agricultural waste arises after the harvest of summer crops because the farmer is in a rush to cultivate his land, therefore, he gets rid of the wastes usually by burning them, causing the emission of poisonous gases into the air, and reduction of the microbial activities in the soil [2].

As Egypt does not produce wood, it depends totally on the imports of wood with an amount of approximately three billion dollars a year, including WPC imports. This puts a burden on the economy and the foreign currency demand and calls for an effective economic solution.

WPC is considered one of the solutions to environmental problems caused by plastic and agricultural waste. As well as the economic problem of wood imports. It should be an effective strategy to benefit from these wastes leading to valuation of such materials.

The first wood plastic composite (WPC) was produced in 1983 by American Woodstock, an automotive interior company based in Sheboygan, Wisconsin [3]. Polypropylene and wood flour with equal percentages were mixed and extruded to produce a flat sheet, which was then formed into various shapes for automotive interior purposes. WPC has many advantages over both wood and plastic. Compared to wood, WPC is mold resistant and recyclable. It does not generate cracks easily. The plastic constituent of WPC enables the production of complex shapes using various forming technologies. In addition, different additives can be added to WPC to enhance its physical and mechanical properties. Compared to plastic, WPC can be sawed, bonded, and fixed with nails and screws. The cost of the product is low compared to the same plastic or wood product, and the surface hardness of WPCs is higher than plastic. The toughness of WPC is low compared to plastic. Compared to wood, bending strength is lower and creep performance is poorer [4], and WPC it is difficult to paint [5].

Also, WPC has an advantage over formaldehyde-based particle boards as it does not contain formaldehyde, which causes many diseases [6]. WPCs can be produced using different abundant agriculture byproducts such as radiate pine [7], coconut coir, bagasse, pineapple leaves [8], chili stems [9], cornstalk [10], albezia richardiana (silk tree), Prainea limpato [11], Cunninghamia Lanceeolate (Chinese fir), Pinus Taiwanensis (Taiwan Red Pine), Trema Orientalis (charcoal-tree), and Phyllostachys Makinoi (evergreen bamboo) [12]. Recent research indicates that wood type influences the characteristics of the resulting WPC. For example, WPCs made with eastern red cedar and cherry have comparatively high resistance to rod, swelling, and water absorption [13]. In addition to different wood species, natural fiber can also be included in fiber-plastic composites. Examples include bast fibers (flax, hemp, jute, kenaf, and ramie), rice hulls, leaf fibers (sisal, pineapple, and abaca), seed fibers (cotton), fruit fibers (coconut coir), and stalk fibers (straw of various kinds) [14]. The use of some of these fibers could add additional steps to the production process due to their high silica content and cuticle wax [15].

Thermoplastic polymers melt and flow at high temperatures and harden when cooled. Thermoplastics are used as matrix materials for wood particles. The processing temperature of the thermoplastic used in WPCs must be less than the thermal degradation temperature of wood (~ 200oC). Low Density Polyethylene (LDPE), High Density Polyethylene (HDPE), Polypropylene (PP), Polystyrene (PS), and Polyvinyl Chloride (PVC) are suitable plastics for use in WPCs in virgin and recycled forms [16]-17].

There are many types of additives used in the WPC industry. Lubricants help the molten WPC move through the processing equipment [14], [18]. Coupling agents improve the interaction between the wood and the non-polar polymers. Wood is hydrophilic, while thermoplastic is hydrophobic. This chemical incompatibility makes it very difficult to bond wood to polymers. A coupling agent helps overcome this incompatibility [14]. The most used coupling agents in the WPC industry are copolymers of maleic anhydride, such as maleated polypropylene (MAPP) and maleated polyethylene (MAPE) [19].

Fillers, such as talc powder, are added to reduce the cost of materials and to improve durability and stiffness [14]. Biocides are used to protect the wood component of the WPC from fungal and insect attack. Zinc borate is the most used biocide added to WPC [14]-[20]. Zink biocide was found to be effective when used to treat WPCs made from wood flour and HDPE. It controls fungal growth and discoloration. It attains the best result at a 1% (w/w) loading level [21].

Fire retardants are used to reduce the tendency of WPC to burn [14]. Decabromodiphenyl oxide, magnesium hydroxide, zinc borate, melamine phosphate, and ammonium polyphosphate are used as flame retardants in WPC composites [22]. Ultraviolet (UV) causes WPCs to discolor and lose mechanical strength gradually. Stabilizers like hindered amine light stabilizers and ultraviolet absorbers help to overcome this durability issue [23]. Toughening agents are used to improve the reduced impact strength caused by adding wood fibers to polymer matrices. The biodegradable plastic Polyhydroxyalcanoate can be used to produce biodegradable WPC and styrene-butadiene-styrene can be used as a toughening agent [24]-[25].

Wood percentage, wood particle size, wood type, plastic type, plastic percentage, additive type, and additive percentage are factors that affect the mechanical and physical properties of the produced WPC. When wood percentage increases, flexural strength increases until wood percentage reaches its optimum level. After that level, the flexural strength decreases with the increase in wood percentage [26]. Some experiments were conducted to find the optimum value of the wood percentage. According to the results of these experiments, the optimum levels of wood percentage are between 40% [27] and 50% [26]. The Micro-hardness increases with an increase in wood percentage [26]. All research agrees that water absorption increases with increasing wood percentage [27]-[28]. Increasing the wood percentage in WPC reduces the impact strength [26]. When the particle size of the wood flour used to produce WPC increases, water absorption and surface roughness increase [7]. The modulus of rapture increases with the increase in wood particle size, while the modulus of elasticity and tensile strength decrease [7, 8]. Flexural strength, impact strength, and micro-hardness increase when coupling agent percentage increases until coupling agent percentage reaches a certain level, then begin to decrease after that level [26]. According to the experimental results, the optimum levels of coupling agent percentage is between 3% [26] and 7% [29].

MATERIALS AND METHODS

2.1. Materials

Three types of woods were experimented, orange tree wood trimmings, cotton wood after harvest stems, and casuarina tree wood trimmings. All wood types were obtained from Abo-hommos fields, Albehera, Egypt. vHDPE and rHDPE were experimented as plastic matrix. vHDPE obtained from local market of Alexandria city from Sidpec company. The grades was injection molding grade HD5740UA with a melt flow index (MFI) of 4 g/10 min, and density of 957 kg/m3. The rHDPE was obtained from a local recycler and had a MFI of 0.5 g/10 min and a denisty of 976 kg/m3. Maleic Anhydride grafted Polyethylene (MAPE) and Silane were experimented as coupling agents. MAPE was obtained from COACE Chemical Company Limited, Xiamen, China, grade W1H, PE-g-MAH, white granules. Si-69 silane of Evonik Industries AG company was used that had a density of 1.10 g/m3 and was obtained from the local market.

2.2. Methods

First, Orange branches trimmings, cotton stems (post-harvest residue), casuarina branches (results of the pruning process), were dried in the sun for about one month. After that, Branches of orange and casuarina trees were cut into small pieces using the electric saw CENTRAL MACHINERY®

1/3 HP, 9-inch benchtop band saw while cotton stems were cut by hand. Wood pieces were then grinded into wood flour using MB® Commercial Grain attrition mill. Wood flour was sieved and classified into coarse particles (between 20 and 50 mesh) and fine particles (between 100 and 200 mesh) using a VEVOR® Automatic Sieve Shaker. The average size of the coarse particles was 0.57 mm, while the average size of the fine particles was 0.11 mm.

Moisture in wood particles can create voids, which adversely affect the mechanical properties of the final product. Therefore, wood flour was dried using LBB2-12 DESPATCH® LBB Lab Oven 12.1 Forced Convection Oven at a temperature of 80°C for 24 hours. This was done to control the moisture content at a typical value between 2 to 8 percent.

2.3. Mixing and Compounding

Compounding was done using HAPRO® 10 HP laboratory two roll mill to produce a homogenous compound. The rotor size was 160 mm diameter × 350 mm length. The compounding was done at a temperature of 180°C and speed of 25 rpm. The compound was then compressed using a 1000KN, 5HP, HAPRO® laboratory plastic and rubber electric heating hot platen press at a temperature of 180°C and a pressure of 2.5 MPa for 3 minutes to produce testing sheets of dimensions 20x20 cm. The sheets were then cooled using water cooling and kept at room temperature for 24 hours before cutting into the standard testing samples.

RESULTS AND DISCUSSION

3.1. Preliminary Comparison of Wood Types

To compare the performance of the different wood types in order to expand the experiments and optimize the formulations, the three wood types were compounded at the same loading of 50% wood (which is typical for the WPC industry), with same mesh size of 0.57 mm. Same plastic type was used (rHDPE as an environmental objective) at 50% by weight (the 100% was calculated based on the amount of wood plus the amount of plastic). Same coupling agent was used (MAPE, mostly used for PE) and same loading of the coupling agent at 5% (typical industry value, calculated as a percentage from the wood + plastic). The wood flour, plastic, and coupling agent were mixed on the two roll mill according to the formulations shown in Table 1. Tensile, bending, and water absorption tests were done on samples taken from every formulation in Table 1.

Table 1. WPC Formulations for different wood types

Wood			Plastic		Coupling Agent	
Type	%	Mesh Size (mm)	Type	%	Type	%
Orange	50	0.57	rHDPE	50	MAPE	5
Cotton	50	0.57	rHDPE	50	MAPE	5
Casuarin	50	0.57	rHDPE	50	MAPE	5

3.2. Testing

- Tensile Test: A 50KN, AGS-X® Precision Universal tensile testing machine was used for the tensile testing. The test was performed according to ASTM-D7031 (Standard Guide for Evaluating Mechanical and Physical Properties of Wood-Plastic Composite Products). Three specimens were tested for each composition. Test specimens were cut using a type 'C' die cutter. The overall specimen length is 165mm x 19mm x 3.2mm with a gage length of 50mm. The tensile test specimen for a 60% rHDPE sample is shown in Figure 1.

Figure 1. Tensile test specimen

- Bending Test: A Universal testing machine INSPEKT® table 50KN was used for bending tests of the samples. The bending test was performed according to ASTM-D790 (Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics). Three specimens were tested for each composition. The specimen was 127mm x 12.7mm x 3.2mm and had a span of 51.2mm. The test specimen for a 40% vHDPE sample is shown in Figure 2.

Figure 2. Bending test specimen

- Water Absorption Test: The water absorption test was performed according to ASTM-D1037 to determine the moisture absorption and thickness swell properties of WPCs. The specimen was 76.2 mm × 25.4 mm × 3.2 mm. The specimens were dried in an oven at 50oC for 24 hours and then placed in a desiccator to cool down. Immediately after cooling, the specimens were weighed. The specimens were then immersed in distilled water at 23oC for 24 hours. The specimens were removed, patted dry with a lint-free cloth, and weighed. For statistical purposes, three specimens were tested for each composition. Water absorption is calculated using equation (1).

$$Water\ Absorption\ (\%) = \frac{W_{24}-W_0}{W_0} x100 \tag{1}$$

$W_{24}$is the sample weight after 24 hours of immersion in distilled water at 23°C.

W_0 is the initial weight.

Table 2. Results for tensile, bending, and water absorption tests for different wood types

Wood Type	Average UTS (MPa)	Bending strength (MPa)	Water absorption (%)
Orange	20.5	14.6	4
Cotton	19.6	12.9	7
Casuarina	12.8	11.1	7

Table 2 shows the test values of the Ultimate Tensile Strength (UTS), Bending/Flexural Strength (BS), and Percentage of Water Absorption (PWA) for the three types of wood.

Figure 3 compares the mechanical performance of the samples made from different types of wood during tensile and bending tests and the water absorption test results.

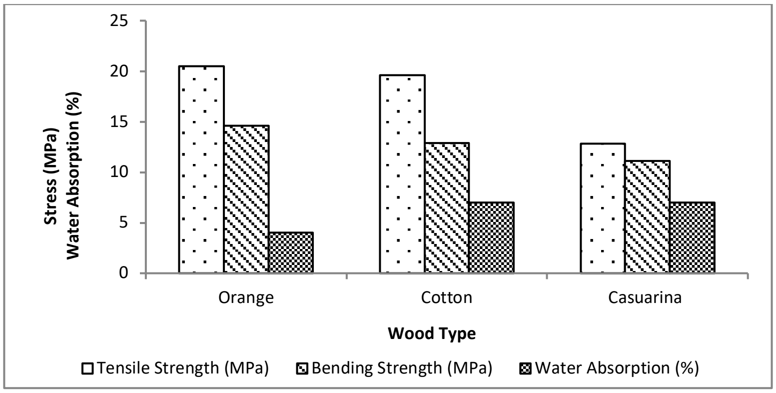

Figure3. UTS, bending strength, and water absorption for different wood types

3.3. Effect of Wood Type on WPC Properties

The effect of wood type is studied by comparing the results of the three different formulations that are all identical except for the wood type. WPC containing orange wood powder was found to have the maximum UTS and maximum BS compared to the cotton and the casuarina wood. It also has the lowest PWA among all three woods. The UTS for the orange wood formulation is higher by 4.6% than the cotton and by 60% than the casuarina. For the BS, the orange was higher by 13% than the cotton and 31.5% than the casuarina. The orange wood had the lowest PWA at 4%, which means that it was lower that both the cotton and casuarina woods by 75%.

This result is confirming the research done on orange wood for engineering applications [30], where the performance of the orange wood was comparable to the Oak wood. This is due to the hemicellulose and cellulose contents of the orange tree wood, which are 29.3% and 40.5% respectively [31]-[32], compared to both the cotton stem that has a 19.3% hemicellulose, and 32.1% cellulose content [33] and the casuarina tree wood that has a 21.5% hemicellulose, and 40.4% cellulose content [34]-[36].

On the molecular level, cellulose is the main structural polymer in plant cell walls and thus the primary source of the high strength and stiffness of wood and other plant tissues [37]. This fact illustrates why the orange compound exhibited the highest UTS and bending strength followed by the cotton stems and finally the casuarina tree wood.

The results also revealed that WPC produced from orange tree wood exhibited the lowest level of water absorption. The higher lignin content in orange tree wood compared to cotton stem and casuarina tree wood results in the lower water absorption by the orange tree wood. Lignin, a complex polymer, is hydrophobic and acts as a barrier, reducing the ability of water to penetrate the wood cell walls [38]-[39]. As a hydrophobic polymer, Lignin strengthens plant cell walls as it crosslinks the polysaccharides in cell walls, which can make it harder for water to be absorbed. Therefore, the current results make the orange wood a very good candidate for WPC applications. The following sections will optimize the formulation for orange wood-based WPC to formulate a recipe that can give the mechanical and physical performance possible.

3.4. Optimizing the Formulation for the Orange Wood WPC

From the above results it was clear that, the orange pruning/trimmings has the best mechanical and water absorption properties among the other woods/post-harvest residues experimented. To have an optimum formulation for the orange wood that can lead to better quality characteristics for the applications of WPC, the researchers used the Design of Experiments (DoE) tool to test the following formulations shown in Table 3 to optimize the following variables: wood percentage, wood particle size, plastic type, coupling agent type, and coupling agent percentage. In every group of experiments/formulations only one parameter was varied while the other parameters were fixed to judge the effect of the varied parameter.

Table 3. Formulations for optimizing orange wood WPC recipe

Formulation No.	Wood			Plastic		Coupling Agent	
	Type	%	Mesh Size (mm)	Type	%	Type	%
1	Orange	40	0.57	rHDPE	60	MAPE	5
2	Orange	50	0.57	rHDPE	50	MAPE	5
3	Orange	60	0.57	rHDPE	40	MAPE	5
4	Orange	50	0.11	rHDPE	50	MAPE	5
5	Orange	50	0.57	vHDPE	50	MAPE	5
6	Orange	50	0.57	rHDPE	50	MAPE	0
7	Orange	50	0.57	rHDPE	50	MAPE	2
8	Orange	50	0.57	rHDPE	50	Silane	5

1. Effect of Wood Percentage with Recycled Plastic: formulations number 1, 2 and 3 represent different wood percentages from 40%-60% and hence different rHDPE percentages from 60%-40%.

2. Effect of Wood Particle Size: formulations number 4 and 5 represent different particle sizes 0.11 mm and 0.57 mm.

3. Effect of Plastic Type: formulations number 2 and 5 represent different plastic types; rHDPE and vHDPE.

4. Effect of Coupling Agent Type: formulations number 2 and 8 represent different coupling agents; MAPE and Silane.

5. Effect of Coupling Agent Percentage: formulations number 2, 7, and 6 represent different MAPE coupling agent percentages of 5%, 2%, and 0%, respectively.

The tensile, bending, and water absorption test results for the formulations in Table 3 are shown in Table 4.

Table 4. Results of the tensile, bending, and water absorption tests for the DoE experiments

Formulation no.	Average UTS (MPa)	Bending strength (MPa)	Water absorption (%)
1	13.7	7.2	3
2	20.5	14.6	4
3	15.3	11.9	8
4	21.5	15.1	6
5	19.5	12.0	6
6	8.7	7.5	12
7	17.2	12.4	7
8	14.9	15.7	5

3.4.1. Effect of Wood Percentage on WPC Properties

The effect of wood percentage is studied by comparing the results of three different formulations, which are formulations no. 1, 2, and 3 by studying the performance of the WPC compounds with wood percentages of 40%, 50%, and 60% respectively. Figure 4 compares the mechanical performance of the samples made with different wood loading during tensile and bending tests and the water absorption test results as well.

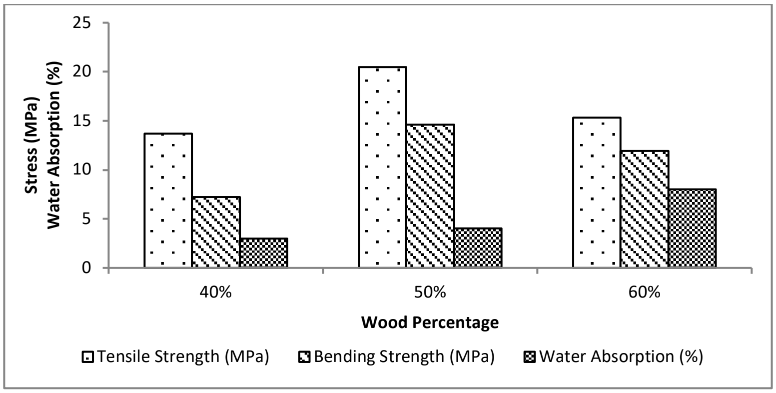

Figure 4. UTS, flexural strength, and water absorption for different wood loading

The results showed that tensile strength and bending strength increased by almost 50% and 102% (more than doubled) respectively with the increase of wood percentage from 40% to 50% then decreased by about 25% and 18.4% respectively when the wood percentage goes from 50% to 60%. Increasing the wood content from 40% to 50% increased the reinforcement of the polymer matrix and hence the UTS. The higher increase of the wood content to 60% causes inadequate bonding between the wood fibers and the plastic matrix, resulting in reduced tensile and bending strength. This occurs due to the limited surface area of plastic matrix available for effective bonding with wood fiber. Tensile strength dropped as wood content increased [40]. As the percentage of wood flour increased and as a result of the reduction of polymer percentage, the stress transfer from polymer to fiber decreased [41]. Despite coupling agents improving the consistency between the components, the incompatibility between wood and polymer materials is evident [42]. A significant loss in mechanical characteristics was another effect of the aggregation of wood fiber with a greater wood flour content [43].

Regarding the water absorption, the PWA increased by 33%, then 100% going from wood percentage of 40% to 50% then from 50% to 60% respectively. The water absorption increased with the increase of wood percentage as a result of the hydrophilic nature of wood fibers [44].

3.4.2. Effect of Wood Particle Size on WPC Properties

The effect of wood particle size is studied by comparing the results of two different formulations no. 2 and no. 4. The only difference between these compounds is the wood particle size. Two wood particle sizes: large particle size (between 20 and 50 mesh sieves) and small particle size (between 100 and 200 mesh sieves) were compared. The average particle size of the large particles is 0.57 mm, while the average particle size of the small particles is 0.11 mm. The comparison between these particle sizes is shown in Figure 5.

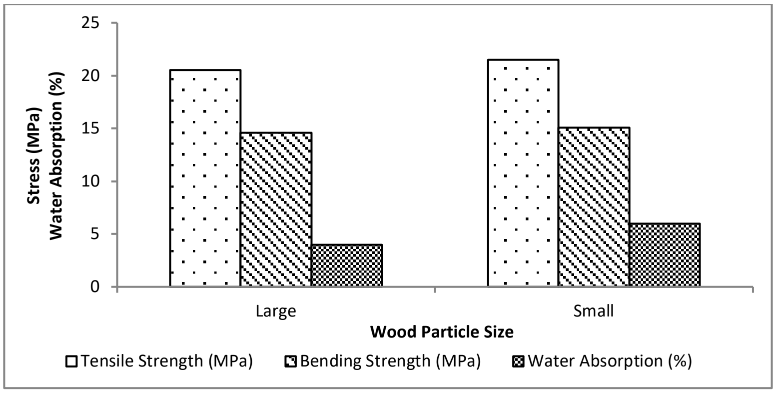

Figure 5. UTS, flexural strength, and water absorption for different wood particle size

The results showed that tensile and bending strength of WPC increased by about 5% and 3.5% respectively with the decrease of wood particle size. That is because of the higher surface area of the small particle size which leads to better interfacial bonding between the wood fibers and the plastic matrix, resulting in enhanced mechanical properties [45]. Additionally, smaller wood particles result in better dispersion and more uniform distribution within the plastic polymer matrix, contributing to improved mechanical properties [45]. The results also revealed that WPC produced from smaller wood particle size had higher water absorption. The higher surface area of smaller particle size accounts for more water absorption due to the hydrophilic nature of the wood fibers [44].

3.4.3. Effect of Plastic Type on WPC Properties

The effect of plastic type is studied by comparing the results of two different formulations no. 2, and no. 5. The only difference between these compounds is the plastic type. The plastic types are, rHDPEand vHDPE respectively. The comparison between these plastic types is shown in Figure 6. One of the objectives of this study is to utilize the plastic waste into a value-added product and at the same time protect the environment from the wrong practices. Practices like burning the plastic waste causing the release of toxins or improperly disposing it into the water resources and affecting the marine life. The results showed that, WPC produced from rHDPEhad higher tensile and flexural strength than the vHDPE (on the contrary of the expectations). The UTS of the vHDPE was higher by 5% than the vHDPE, while the BS was higher by 21.7%. The WAP was lower by 33% for the rHDPE. WPCs manufactured from rHDPE occasionally offer mechanical qualities that are comparative or superior to those made from vHDPE [46]. This can be attributed to the fillers and additives that are added to the HDPE during the production process to enhance the mechanical and physical properties of the final product.

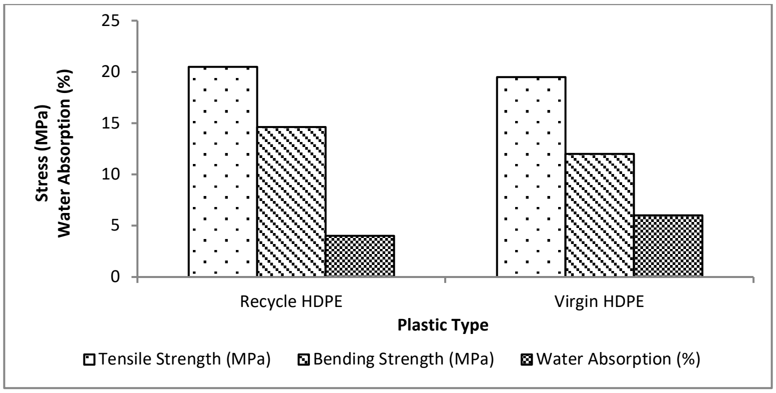

Figure 6. UTS, flexural strength, and water absorption for virgin and recycled HDPE

3.4.4. Effect of Coupling Agent Type on WPC Properties

The effect of coupling agent type is studied by comparing the results of two different formulations no. 2 and no. 8. The only difference between these compounds is the type of coupling agent. The comparison between these types is shown in Figure 7.

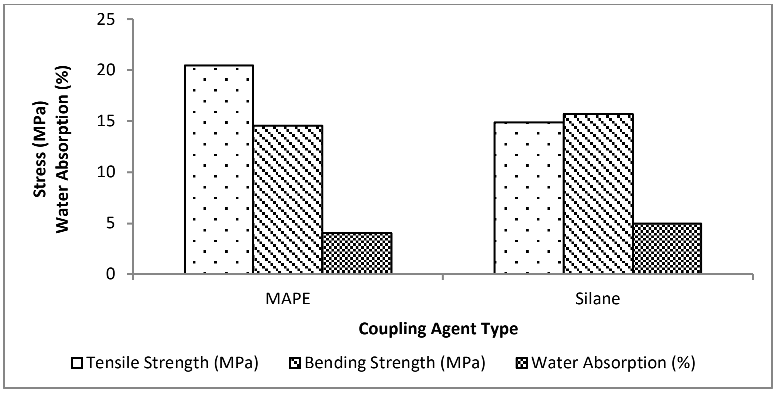

Figure 7. UTS, flexural strength, and water absorption for different coupling agents

Two coupling agents, MAPE and silane, were compared. Maleated polyethylene (MAPE) is a coupling agent that can be used to increase the compatibility and adhesion of polar and nonpolar constituents in composites. MAPE is applicable to wood-fiber/high density polyethylene (PE) composites, polypropylene (PP) composites [47]. Organosilicon compounds known as silane coupling agents serve as bridges between inorganic and organic components. At least two reactive functional groups - one that forms bonds with organic materials and the other with inorganic ones - are present in their molecules. The coupling process is completed when the two groups diffuse to the surface, with one end orienting towards the organic material and the other toward the inorganic substance [48]. Although both the wood and plastic are organic materials, the researchers wanted to explore the functionality of silane in WPC as it was an available material in the market and some research experimented compounding WPC with silane [49]. For instance, silane coupling agent can decrease water absorption, increase the dispersion of wood powder, and strengthen the binding between plastic and wood powder [50].

MAPE gave a higher UTS than silane by 37.5%. Silane compound had a higher BS than the MAPE compound by 7.5% and a higher WAP by 25% than the MAPE compound. A thorough investigation into the silane crosslinking of WPC and its impact on composite characteristics has demonstrated that silane crosslinking can strengthen the adhesion between the PE matrix and wood filler by creating a network of crosslinks and hydrogen bonds among other chemical linkages. The better wetting characteristics of the wood by the HDPE in presence of MAPE, makes it less prone to moisture absorption [51]-[53].

3.4.5. Effect of Coupling Agent Percentage on WPC Properties

According to the study of the effect of coupling agent type mentioned above, MAPE give better results than silane, regarding the UTS, BS and PWA. Based on this study, the researchers did a study to optimize the amount of MAPE to be added to the HDPE-WPC formulation that can result in the best mechanical and water absorption properties. The effect of coupling agent percentage is studied by comparing the results of three different formulations, which are formulations no. 8, no. 9, and no. 2. The only difference between these compositions is the coupling agent percentage. Three coupling agent percentages, which are 0% (no coupling agent), 2%, and 5%, respectively were compared. The comparison between these percentages is shown in Figure 8.

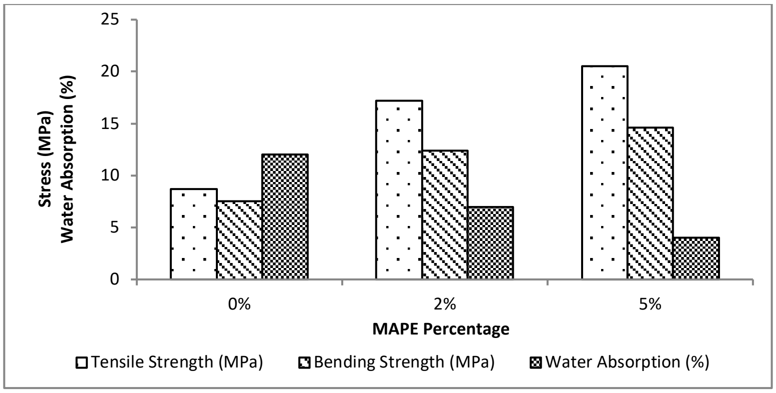

Figure 8. UTS, flexural strength, and water absorption for different coupling agent ratios

The 5% MAPE gave the maximum UTS, BS and the lowest WAP among the three compositions. The 5% MAPE has a higher UTS than the 2% and the 0% MAPE by 20.3 and 138% respectively. The 5% MAPE has also a higher BS than the 2% and the 0% MAPE by 17.7% and 94.7% respectively. It is clear that the addition of the coupling agent enhances the mechanical and water absorption performance of the WPC.

The coupling agent enhances greatly the inadequate mechanical performance (shown at the 0% coupling agent) as a result of the weak contact between a nonpolar polymer matrix (HDPE) and a hydrophilic strengthening phase (wood flour). Chemical reactions between the coupling agents and the constituents of the composite, i.e., covalent bonding with the hydroxyl group of the wood and crosslinking with HDPE molecules, improve the interfacial adhesion between the wood particles and the HDPE matrix [54].

Decreasing the PWA of the WPC compound with increasing the percentage of coupling agent is in agreement with the reported research [55] that suggested a formula relating water absorption to the percentage of coupling agent loading into WPC compound. The formula has a negative synergy coefficient for the coupling agent variable. The researchers [55] reported that, the presence of coupling agent decreased the water absorption, for example, increasing the coupling agent from 0 to 3% decreased water absorption by up to 65% due to enhancing the witting and encapsulation of the wood fibers by the plastic matrix.

CONCLUSIONS

The environmental problems associated with the disposal and burning of post-harvest residues and plastic waste can be solved by the production of WPC from these abundant materials. This solution will not only create an environmentally friendly and sustainable product but also it will valorize such wastes and produce products of market need, as well as reduce the need for the foreign currency used to import the WPC.

In this research the effects of wood particle type, percentage, and size, as well as the effect of plastic type, coupling agent type and percentage on the wood plastic composite (WPC) mechanical and water absorption properties were studied. Three different types of wood: orange tree, cotton stems and casuarina tree were tested. WPC with the orange tree wood gave the maximum tensile and bending strengths due to the higher cellulosic content of the orange wood. Orange wood had also the lowest water absorption. Three orange wood percentages 40%, 50%, and 60%, were compared, the highest tensile strength and maximum flexural strength were obtained at 50% wood percentage. Water absorption increased with the increase in wood percentage. rHDPE-based WPC had higher tensile strength and flexural strength than vHDPE-based WPC, which can be explained by the additives that may be added to the vHDPE during production process. MAPE and silane were used as coupling agents. MAPE gave higher tensile strength and lower water absorption than silane, while silane gave higher flexural strength. WPC produced with smaller size wood particles had higher tensile, flexural strength and water absorption than that produced with wood flour of larger size.

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