Physico-Mechanical Behavior and Recovery of Wood-Plastic Composite (WPC) Based on Recycled High Density Polyethylene (HDPE)

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Abstract

In this paper, we have investigated the stability, mechanical properties, and the microstructure of wood–plastic composites, which were fabricated using recycled high-density polyethylene (HDPE) with pine wood flour used as fillers. Composite panels were obtained using hot-press molding. The tensile and flexural properties of the composites based on recycled HDPE revealed the strength properties of the composites can be improved by increasing the polymer content, also the composite formulation significantly improved the morphology and the stability. Scanning Electron Microscope (SEM) was used to characterize the morphology of the wood particulate/HDPE interface. It was clearly proved from the results that wood-plastic composite (WPC) based on recycled high density polyethylene (HDPE) can be successfully utilized to fabricate stable and strong WPCs.

Keywords: Composites; Wood; Polyethylene; Tensile; Flexural; Mechanical; Strength; Morphology; Recycled

Introduction

The growing demand for forest products in Morocco is particularly harmful for ecosystems, which are subject to acute climatic constraints and whose soils are slowly replenishing, to overcome this problem and reduce the environmental impact. Reforestation since the sixties, among these softwood species, in particular the maritime pine (Pinus pinaster) which constitute important socio-economic resources, with a total reforested area of 54,000 ha [1].

Previous studies on the physical and mechanical properties of these reforested plantations, particularly in the Maâmora forest in Morocco, have revealed that this wood is of poor quality because of its high resin content and the presence of many defects and knots… which reduces its use on an industrial scale, only 300,000 m3/year of industrial wood is produced annually by the forest [2] (mine posts, traditional sawing, formwork and crating…) [3] comparing with 600,000 m3/year produced as fuelwood [2].

Since the wood of the Moroccan maritime pine is rich at the national level, and needs to be regenerated at the age of maturation, and since this wood has no relevant application on an industrial scale, and that the current world production of plastic is around 100 million tonnes per year [4], which threatens the ecosystems of our planet, it is expected to value them in composite materials called wood-plastic composites (WPC), these composites represent an emerging class of materials that have gained increasing degrees of acceptance because of their favorable performance characteristics such as improved stiffness, density, lower abrasiveness, better processing capacity, favorable cost of wood and plastic and a significant reduction in environmental impact [5-9]. The field of application of (WPC) is diverse; it is used in furniture, floor covering, on walls and ceilings, stair treads, sliding doors, bulletin boards and other Industrial Products [10-13].

In Morocco, and despite the efforts made to ban non-degradable plastic bags for agri-food packaging in 2016 by the new law 77-15, plastic still persists in various forms (bottle of mineral or sparkling water, milk, detergents, trays, jars of yoghurt, plastic tableware, packaging of industrial products, manufacture of plastic furniture,…), these products are generally made of high density polyethylene. Studies have shown that recycled high density polyethylene (HDPE) obtained from plastic waste (milk bottles) is 31% to 34% cheaper than virgin high density polyethylene (HDPE) [14], which leads to a reduction in the price of the product, on the other hand the (HDPE) from the milk bottles are not widely different from those of the virgin resin and can be used by different application [15].

This study involves the use of maritime pine wood (Pinus pinaster) produced by the Maâmora forest in the region of Mechra el Ketan in Morocco and the high density polyethylene extracted from bottles and jars of recycled dairy products (rHDPE) for the production of composites based on wood-plastic panels (WPC).

Experimental Section

Starting materials

The maritime pine wood waste is obtained from the sawmill at the Forest Research Center in Rabat (CRF). The sawdust was dried at 103°C for 24 hours at a water content of about 2 to 3%, and then milled using a grinder adapted to the hardness of the materials to grind and the fineness of the desired powder. The sieved in this study and of the order of 0.5 mm. Experience has shown that the granules obtained after grinding are between 0.1 and 0.5 mm. The pellets of (rHDPE) were purchased from a local recycling plant which originated mainly from the dairy product wastes; they were thoroughly washed with water and dried at 65°C for 12 hours.

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Preparation of the composites

The mixture of the wood flour and the (HDPEr) was made with a local mixer at a mixing speed of 55 tr/min for a duration of 5 min in order to obtain a homogeneous mixture [16], the mat obtained is poured into a metal mold with a dimension of 20 cm². The pressing cycle was carried out by a press (STETON Hydraulic). Presque pressing was carried out for several cycles (3 to 4 times) to balance the particles within the mold, then at a temperature of T=180°C and a pressure of P=5 MPa, a pressing of the mat was carried out respectively for 8 min at hot and 6 min at cold [17].

The final size of the composite panel was 200 × 200 × 4.5 (thickness) mm.

The panels obtained were conditioned at a temperature of 23 ± 2°C and at a relative humidity of 50 ± 5% for at least 40 hours according to ASTM D618-99 [18]. The formulations of wood-plastic composites are given in Table 1.

Note. The W and HDPEr codes were used for wood flour, and recycled high-density polyethylene respectively.

Dimensional stability tests

According to ASTM D570-98 [19], a water absorption study was conducted on the various wood-plastic panels (WPC), the specimens were immersed in water for 2 h and 24 h at a temperature of 23 ± 1°C. The measurements and the weight of the test pieces were measured 20 minutes after removing them from the water.

The moisture measurement was carried out by weighing the mass loss of a specimen between its initial state and its state after oven drying at 105°C. for 24 hours; it is expressed by the following relation:

\[ H\% = \frac{M_h - M_0}{M_0} \times 100 \]

With:
- \( M_h \): The mass of the specimen in the wet state.
- \( M_0 \): The mass of the specimen in the anhydrous state.

For a given moisture content, the density of the composite cannot be constant, in fact it varies depending on the humidity, for this it is expressed at a given moisture content H%. The density of the composite in the anhydrous state was measured by the following relation:

\[ D_0 = \frac{M_0}{V_0} \]

With:
- \( M_0 \): the mass of the specimen in the anhydrous state.
- \( V_0 \): the volume of the specimen in the anhydrous state.

Linear swelling is the relative increase in the size (length) of the sample in the three directions (Radial (R), tangential (T), and longitudinal (L)) as the moisture of the wood increases; it has been measured by the following relation:

\[ G_i = \frac{L_i - L_i^0}{L_i^0} \times 100 \]

With:
- \( L_i \): Dimension (length).
- \( L_i^0 \): R, T or L.
- \( S \): saturated state.
- \( 0 \): anhydrous state at 105°C.

Morphological studies of wood-plastic composites

The scanning electron microscope is equipped with a secondary electron detector, a backscattered electron detector and requiring a secondary vacuum in the observation chamber (10-6 mbar). We performed SEM on 30 × 4 × 3 mm³ specimens to visualize the wood/plastic interface and conclude about the homogeneity of the obtained composites panels.

The fracture surfaces of the flexural test specimens were characterized with high-resolution field emission scanning electron microscopy (FESEM). The FESEM was operated at an accelerating voltage of 1 kV and emission current of 47 A. Fracture surfaces were sputter-coated with gold of approximately 50 nm in thickness. Specimens were analyzed at magnifications of 100.

Tensile and flexural tests

Mechanical properties of WPCs in terms of flexural and tensile tests were performed using Universal Testing Machine (Instron, model 8112) according to ASTM D790 and D638, respectively. The specimens were tested at crosshead speed of 3 and 1.6 mm/min for flexural and tensile tests, respectively at room temperature. The dimensions of the test specimen were according to the respective ASTM standards. All the reported values for the tests were the average values of 5 specimens.

Results and Discussions

Moisture absorption and thickness swelling

Results of composite density, moisture absorption and thickness swelling are summarized in Table 2. It was found that the density of the composites is increasing by the increases of the wood content in the Polyethylene host matrix. This suggests that higher density implies reduced porosity of the WPC composites which means that the composites express stronger interfacial compatibility. We note also that the water absorption is increases with increasing wood content within the composite, the behavior is almost the same for both the 2 h and the 24 h water immersion tests, with the addition the wood content, more water residence sites appears, thus more water amount is absorbed. Moreover, the composites with higher plastic content have less water absorption sites and thus lower water absorption. It’s clear that the water absorption corresponding values for the composites with 50 wt.% wood are lower compared to those with higher density. Thus by taking into consideration the density and water absorption, it’s deduced that this specimen is interesting and might be considered as optimal material.

The thickness swelling (TS) of the WP composites follows similar trend of the water absorption. The TS values for the 2 h water immersion vary from 0.29% to 1.5%, and these values are increased after 24 h immersion, varying from 0.44% to 2.9%. It’s noteworthy that samples made with lower content of wood have lower thickness swelling, in good agreement with moisture absorption findings.

Table 1: Wood-plastic composite formulations (% by weight).

| Composite Samples | HDPE in % | Wood in % |
|-------------------|-----------|-----------|
| HDPEr 70W30       | 30        | 70        |
| HDPEr 60W40       | 40        | 60        |
| HDPEr 50W50       | 50        | 50        |
| HDPEr 40W60       | 60        | 40        |
| HDPEr 30W70       | 70        | 30        |
Micro-structural examination of wood/plastic interface

The microstructure of the wood/HDPE composite in the initial state (after incorporation) is observed using a scanning electron microscope shown in Figure 1, the HDPE matrix is recognized (dark), and the wood particulate (in light gray) that are clearly visible, as well as pores produced during the fabrication process. The SEM micrographs are exhibiting different microstructures of different Wood-plastic composite formulations ranging from 30 wt% to 70 wt% wood content.

The HDPE-wood flour composites at a filler loading of 30 wt.% is shown in Figure 1 in which numerous cavities are observed. The presence of these cavities confirms that the interfacial bonding between the wood filler and the matrix polymer is poor and weak. In addition, localized bunch of wood and patches of HDPE matrix are seen, which indicates the poor dispersion of fillers within HDPE matrix.

When wood content is increased, the polymer matrix is no longer continuously distributed and many wood fibers are in direct contact with one another, resulting in poor bonding at adhesion at the interface.

It’s noteworthy that pores are progressively raised by increasing the wood content in the plastic matrix which explains the reduced density of WPC containing lower HDPE, this behavior is in great concordance with density results.

Figure 2 shows the micrograph of fracture surface of composite filled with 50 wt.% wood flour. The SEM image shows that there are no clear gap between wood floors and HDPE matrix, indicating the good interface bonding.

Stress-strain evaluation

The tensile test was carried out by introducing a specimen into a universal traction machine. This machine consists of a flat base and hydraulic piston having a linear motion perpendicular to the same base. Moreover, jaws (hydraulic or manual) are located on the piston as well as on the base. These are installed so that their axes are collinear with that of the piston. Then, once the specimen is inserted in the jaws, the piston is moved vertically and the axial force required for this movement is recorded. In addition, strain gauges are glued on the specimen to measure the deformations involved in the calculation of mechanical properties. These mechanical properties are generally calculated as follows:

First, the axial stress $\sigma$, in the test piece is obtained by dividing the axial force measured by the area of the useful section of the specimen at the beginning of the test. Secondly, the elastic modulus in tension is calculated by dividing the axial stress by the deformation measured by the gauge. Finally, the stress at break is usually identified as the maximum stress which is recorded during the entire test. The Figure 3 illustrates the stress-strain curves of the above described fabricated composites with different compositions. It’s exhibiting the mechanical behavior of WPC panels. It’s to be noted that the resistance to stress is enhanced with decreasing the incorporated wood powder content in the polymer host matrix, such improvement is probably due to polymer wood bonding which stiffer the obtained composite, this hypothesis is confirmed by previous studies [19-22], indeed the highest response to stress is assigned to the composition rHDPE 70W30 where the applied stress is of 17.44 MPa whereas the lower response corresponds to the composition rHDPE 30W70, it was depicted from the drawn curves that the composite panel with composition rHDPE 50W50 express medium response at about 10 MP. It’s noteworthy that the applied stress increases with increasing the wood powder content within the polyethylene matrix from 30 to 70 wt.%. Also some researchers have found that the neat reused polyethylene matrix expressed the higher strain value compared to other fabricated rHDPE-wood composites [23]. It’s noteworthy that the strain values decrease with increasing the wood powder content. This is explained by the decrease of plasticity of the obtained composites when the wood fillers are augmented, in good agreement with literature data [24]. The strain behavior of the obtained composites suggest that while incorporating wood powder within the plastic matrix, discontinuity structures occurred which is found to be influencing the mechanical behavior of the material as depicted in the Figure 1, we observe that the lower wood content implies higher strain of the fabricated composite this is in good concordance with several performed stress-strain studies [25].

### Table 2: Absorption of water and swelling of the thickness of wood-plastic composites.

| Composite       | Density kg/m³ | Moisture absorption (%) | Thickness swelling (%) |
|-----------------|---------------|-------------------------|------------------------|
|                 | 2 h           | 24 h                    | 2 h                    | 24 h                     |
| rHDPE 70W30     | 962           | 0.4                     | 0.97                   | 0.29                     | 0.44                   |
| rHDPE 60W40     | 980           | 0.96                    | 2.2                    | 0.57                     | 1.62                   |
| rHDPE 50W50     | 998           | 1.8                     | 3.9                    | 0.8                      | 1.9                    |
| rHDPE 40W60     | 1021          | 2.25                    | 4.1                    | 1.2                      | 2.3                    |
| rHDPE 30W70     | 1053          | 2.9                     | 5.2                    | 1.5                      | 2.9                    |

Flexural investigations

Flexural investigations have been carried out on the performed
of recycled plastic achieve good stability properties due to improved interfacial bonding. The mechanical properties of the composites were performed in term of tensile and flexural studies, it was deduced that the composites made with lower wood content show lower stiffness however the composite of containing 50% of reused plastic have moderated tensile and flexural strength. Thus it’s noteworthy that this composite is likely to be most useful material due to its improved stability and mechanical properties.

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Conclusion
In this work, WPCs were made from recycled HDPE with Pinus wood flour. The dimensional stability and mechanical properties, which are important properties in product utilization and the microstructure of the interface of wood flour content and plastic, were investigated.

Following conclusions are drawn from the current work:

The composites made with hot-press have very low water absorption and thickness swelling increase with the wood content, the composites of 50 wt.% composite in order to evaluate the wood powder content influence. As illustrated in Figure 4 we can notice that the strength impact is higher when the wood powder content is incorporated up to 70% when the load is at maximal value. However the displacement is narrowed. This is in good agreement with some previous conducted flexural tests on recycled polyethylene-wood composites [26]. This finding suggests that the flexural behavior of the obtained composites is confirming the response to stress, nevertheless it in the displacement point of view it’s in contrast.

![Figure 3: Tensile stress-strain curves of HDPE-wood composites.](image-url)

![Figure 4: Load-displacement curves of HDPE-wood flour composites.](image-url)
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