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Sustainable WPC Production: A Novel Method Using Recycled High-Density Polyethylene and Wood Veneer

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Abstract: This research work is focused on the development of an alternative method for manufacturing Wood Plastic Composite (WPC) panels based on Wood Veneers (WVs) and High-Density Polyethylene (HDPE) through compression molding, which enhances the physical properties, particularly, water absorption and moisture content. The aim of the present research was to develop alternative panels to replace commercial ones, which are heavily affected by hot, humid climates. In this context, the study began with the design process, which consisted of the collection and processing of primary material, production of the additional components necessary for the manufacturing process, determination of the WV ratio, and preparation of the samples. Thereafter, physical and mechanical tests were carried out on WPC, HDPE (control), commercial gypsum boards (GBs), plywood (PW), and medium density fiberboard (MDF) samples. The results indicate that the method applied to manufacture the WPC samples improved physical properties, achieving a water uptake of less than 4% in both proportions of replacement tested, in contrast to commercial panels, which reached values between 10% and 40%. In addition, a greater load capacity was achieved for lower thick elements.

Keywords: compression molding; wood plastic composite; wood veneer; recycled plastic; lightweight panels; manufacture

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1. Introduction

In the construction industry, there is a notable and ever-growing interest in lightweight wall systems and lightweight steel framing (LSF), which are commonly applied in buildings where walls are not considered as loading elements but as partition walls in interiors; these systems are composed of galvanized steel frames with fixed lightweight panels in the framework, which are manufactured from gypsum, cement, or wood [1]. However, LSF systems are prone to decreased durability due to exposure to warm, humid local weather where moisture has a key role [2]; excessive moisture results in mold formation in localized points and significantly reduces the serviceability of the envelope as a whole [3], leading to the degradation of the matrix and thus affecting physical and mechanical properties.

Hence, the relevance of developing more resilient composite panels with matrices designed to withstand such harsh environmental conditions, while effectively minimizing the negative impact on physical-mechanical properties, is a key aspect. Significant effort has been devoted to developing composite materials in order to manufacture polymers apt for a wide range of applications and able to comply with quality standards [4]; replacing plastic fibers with wood fibers in polymer-based composites leads to a more eco-efficient construction method [5]. In this context, WPC is crucial from a building serviceability viewpoint and, in addition, acts as a carbon sink, providing additional eco-systemic value [6].

Waste generated by the plastic industry, as well as that from the production of wooden furniture coatings, has been revalued thanks to new technological advances aimed at the manufacture and development of compound materials and alternative products; thus, recycling has been established as an innovative alternative to aid in tackling environmental issues, while the adoption of WPC in the construction industry has positioned itself as a viable alternative to face environmental challenges [7], mainly due to the associated economic and environmental impact of manufacturing composite-reinforcing materials and the newly growing need of more eco-efficient plastics [8]. A wide range of applications benefit from the performance and features of WPCs, as is the case of any semi-structural element in the construction industry. These include envelopes, lightweight covers, and paneling, which make the most of the thermic and general performance of WPCs, in contrast to conventional plastics [9]. Nonetheless, the development of WPC panels is a challenge for the construction industry [10], given their hydrophilic nature [11]. During the mixing and extrusion process, wood particles lay exposed in the surface of the composite, resulting in an increased porosity. The cavities between wood and plastic are entry points for microbial agents, which are highly water-dependent in order to thrive, and this bacterial growth leads to material degradation (Figure 1a). Hence, concern is devoted to the elimination of these degradation agents of a microbial nature. Evidently, humidity and moisture are two key points to be considered when designing and manufacturing WPCs [12]. Schirp et al. (2008) mention that water absorption and humidity are two key points to consider when designing and manufacturing WPC. Therefore, one of the ways to protect wood from humidity is by chemically modifying the wood for hydrophobization, but this process increases production costs due to the use of additives. Furthermore, the authors also propose coating the composite with the same plastic matrix to protect it from degradation [13]. Today, the usual methods are continued when using WPC, so similar results continue to be obtained in terms of water absorption and deterioration. According to Spear (2015), the use of larger fibers and the application of compression, with 0.6 mm being an appropriate balance between the strength and thickness of the strand, is sufficient to allow compression and avoid gaps at the ends, improving the mechanical properties and significantly minimizing the numbers of holes through which water can enter [14]. In this way, the forming pressure and pressing cycle duration can be reduced in compression molding with a simpler and less expensive tooling set [10], which could promote new construction applications [5].

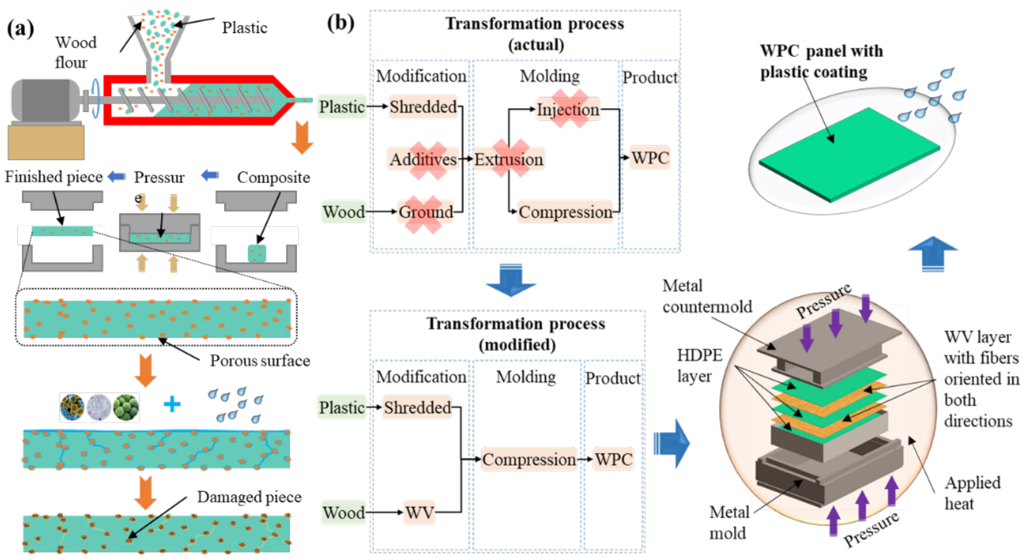

Figure 1. Diagram showing the development of traditional WPC panels versus a proposed modification: (**a**) WPC deterioration; (**b**) substitution of current method for the transformation and production process.

On the other hand, dimensional stability is crucial in the overall performance of natural fiber-based composites, affecting water uptake, moisture content and density [15]. The objective of this study was to develop WPC panels, based on recycled materials, with different WV/HDPE ratios (20/80 and 40/60% vol.), to which an alternative manufacturing process was applied. Figure 1 shows this alternative process, which excludes the use of wooden flour as well as additional additives and procedures, such as WPC extrusion and injection, replacing them with WV wastes and recycled plastic, to which a molding variant was applied. Compression with a hot plate was performed, in which the fusion of the sample was completed before pressing (not at the same time, as is usually done), with the intention of simplifying the manufacturing process and, at the same time, improving the hydrophobic properties (Figure 1b). We evaluated the physical and mechanical properties in accordance with relevant standards.

2. Results and Discussion

2.1. Development of WPC Panels

Figure 2a illustrates how temperature influences sample homogenization between HDPE/WPC; there were three important phases: the first one (I) is from t = 0 min to t = ~6.5 min, where an abrupt temperature shift took place from T = 25 °C to T = 135 ± 3 °C, right after the air extraction commenced, which continued until the second phase (ii), which ended at t = 30 min and T = 200 °C, during which the temperature was steadily rising. In phase (II), once the top of the mold had partially descended, the air extrusion could be considered as finalized, and the HDPE started its settling phase. The HDPE settling phase was achieved once the fusion temperature had been reached: 135 °C ± 5 °C; from then on, the softening of the material started. At this point, viscosity started to decrease; the temperature for this softening oscillated between T = 140 °C and T = 280 °C [16]. Melting of HDPE during the third phase (III), at $T_{constant}$ = 200 °C for t = 60 min, served the purpose of an even distribution of the material inside the mold, partially due to the pressure of the top mold descending until 90% of full closure, hence promoting a decrease in porosity of the sample. Pressing allowed for a full closure. Figure 2b shows the achieved sample with smooth surfaces (Figure 2b(i)) and sides; a transversal cut exposes the cross-section of the piece where the interlayering of materials can be appreciated (Figure 2b(ii)); also, a smooth, flat surface is observable on the horizontal axis (Figure 2b(iii)).

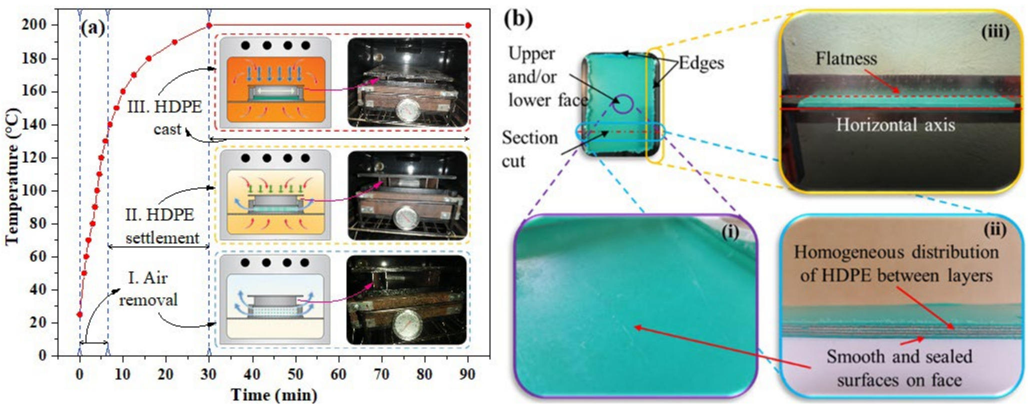

Figure 2. Effects of the application of temperature in a time interval in HDPE samples: (**a**) air extraction, settling, and melting; (**b**) final product: (i) smooth surfaces and sides; (ii) a transversal cut with the interlayering of materials, (iii) flat surface.

2.2. Density, Moisture Content, Water Absorption, and Thickness Swelling

The results of the density and moisture content tests are presented in Figure 3a. For HDPE 100%, WPC 20/80% and 40/60%, GB, MDF, and PW, the obtained values were 970.1 kg/m^3 and 0%, 858.3 kg/m^3 and 0.3%, 833.9 kg/m^3 and 0.7%, 618.7 kg/m^3 and 2.7%, 744.5 kg/m^3 and 6.07%, and 527.74 kg/m^3 and 6.71%, respectively. Apart from GB, a common effect was observed: as wood content increased, the density of the samples decreased, thus obtaining a lighter sample; however, moisture content increased, allowing for increased environmental pressure. Nonetheless, plastic/wood samples showed a minimal difference in density when compared with wood-based panels; a gradual decrease was observed, unlike the moisture content, where a steep increase was observable, which could be attributed to the hydrophobic nature of HPDE [17] with no moisture content. In this sense, it had major effects on the WPC results, with under 1% for moisture content, around six times lower than MDF and PW; hence, the composites are moisture-resistant, which leads to a prolonged service time regardless of the organic material used.

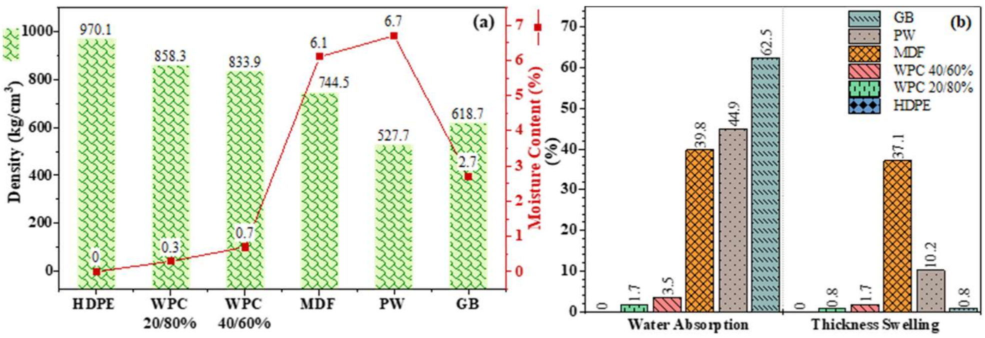

Figure 3. Physical tests: (**a**) density and moisture content; (**b**) water absorption and thickness swelling.

In addition, in Figure 3b, it may be observed that water absorption values are 0%, 1.7%, 3.5%, 62.5%, 39.8%, and 44.9% for HDPE 100%, WPC (20/80% and 40/60% vol.), GB, MDF, and PW, respectively, while thickness swelling values are 0%, 0.8%, 1.7%, 0.8%, 37.1%, and 10.2%, respectively. MDF and PW contain natural fibers of a hydrophilic nature, and in composites prone to elevated water uptake and moisture content, there is increasing swelling in all directions [18], affecting both the mass and volume of the samples. Since the PW 100% wood strains and WPC—where a 40% ratio was the highest—have a similar composition of wood content, it was estimated that they would present similar results in terms of mass and thickness; a decrease of ~17.97% water absorption and ~4.1% thickness was viable, with the two showing a 27.0% and 6.1% reduction, respectively.

The actual values obtained indicate a greater reduction: 41.4% and 8.6%, respectively, as shown in Table 1. Since HDPE presents minimum water absorption, WPC panels are more resistant to humid environments and sporadic direct contact with accidental water spillage, thus limiting volumetric changes due to water uptake and swelling.

Table 1. Comparison of the decrease in water absorption and swelling values for PW and WPC.

Test	PW	WPC 40/60% (Estimated)	WPC 40/60%	Difference WPC Estimated vs. PW (%)	Difference WPC vs. PW (%)
Water absorption	44.9	18.0	3.5	27.0	41.4
Thickness swelling (%)	10.2	4.1	1.7	6.1	8.6

It is important to note that dimensional stability is of utmost importance in composite panels; excluding MDF, all the other panels in the present study achieved satisfactory dimensional stability. However, the most important feature for the composite panels was the achievement of a reduced water absorption. In this context, commercial panels are the least convenient option, since, as was noted above, elevated water uptake and moisture content lead to microorganisms growing in the matrix and can affect their properties. In Figure 4, a cross-section of a WPC sample is shown; the WV is observable, and its surface presents many different size cavities, where HDPE is distributed evenly through temperature and pressure and fills these cavities (Figure 4a), giving it a distinct embossed surface (Figure 4b), where each HDPE layer on the top, bottom, and middle seals the area where water would have the greater area of contact. This limits entry points for water on the sides where the WV would be most exposed, and since the width is considerably small at 0.6 mm, this also contributes to lengthen the time it takes for water to penetrate the composite (Figure 4c). The results indicate that, for the same 24 h period, WPC 40/60%, which was the highest wood ratio, absorbs 36.3% and 41.4% less in comparison to MDF and PW, respectively.

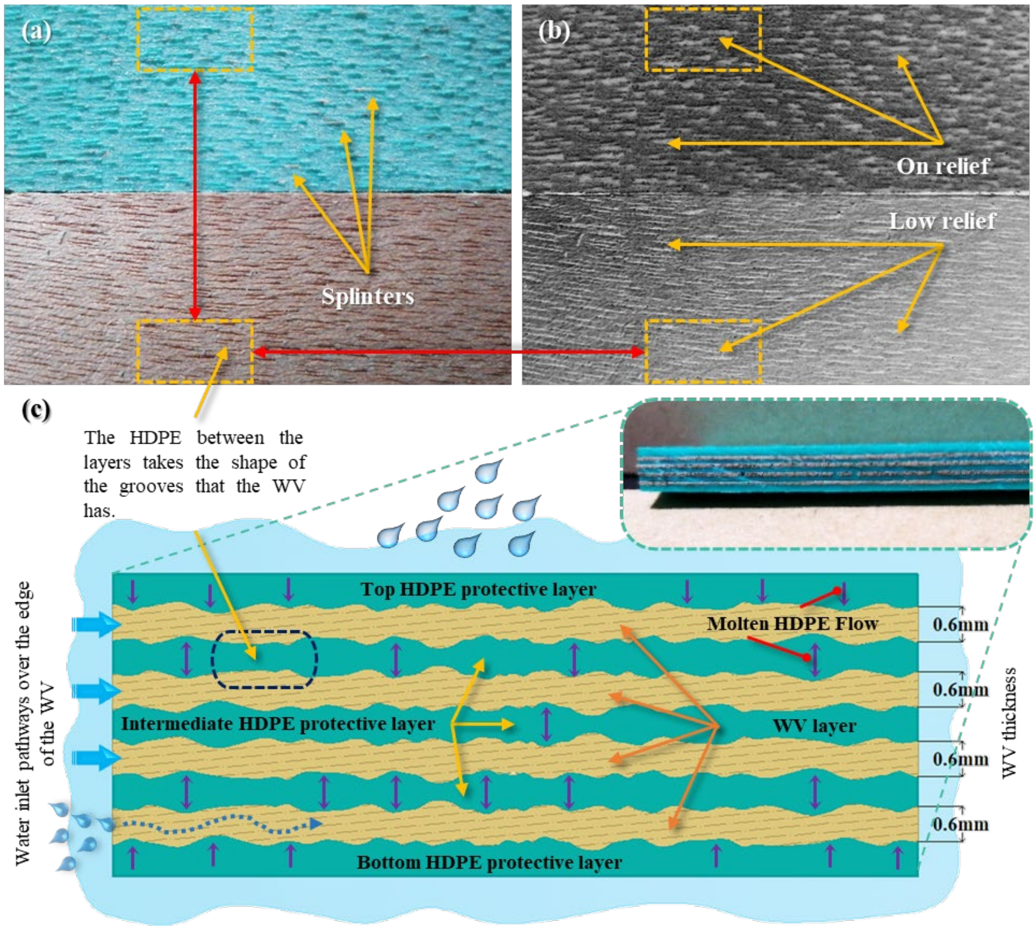

Figure 4. Resulting interface between the HDPE and WV layers of the WPC: (**a**) photograph of the intermediate faces; (**b**) black and white negative; (**c**) interface operation diagram.

2.3. Flexural Strength

The Three-Point Flexural Strength Test (Modulus of Rupture, MOR) gives a measure of a sample's strength before rupture. In that sense, a material can be denominated as resistant or sturdy; otherwise, it would be fragile or brittle. On the same note, the Modulus of Elasticity (MOE) measures the ability of a material to resist any stress applied to it without permanently deforming it; higher values represent stiffer materials, and lower values translate into more flexible materials. In Figure 5, GB panels achieved the highest MOE value of 1980.8 MPa; however, their MOR is typical of a brittle material, with 1 MPa. In contrast, MDF panels achieved the most balanced MOR-MOE values, with 23 MPa and 1916.3 MPa, respectively. PW panels demonstrated a stiffer behavior, with an MOE of 1796.8 MPa, but a considerably low loading capacity, with a MOR of 13.6 MPa. In the case of WPC panels of HDPE 100%, WPC_20/80% and WPC_40/60%, their MOR is higher than commercial panels, with 31.6 MPa, 37.1 MPa, and 44.5 MPa, respectively. Nonetheless, their MOE values fall under the commercial panels, with 1024.6 MPa, 1170.9 MPa, and 1384.5 MPa, respectively; this makes them more flexible panels than commercial ones, most likely due to their HDPE content. In the case of samples with WV WPC_20/80% and WPC_40/60%, an even increase in both properties is observed as the WV ratio increases, achieving higher values in terms of loading capabilities and rigidity. This behavior contradicts the findings of some authors who used rubberwood in different proportions mixed with HDPE as a polymeric matrix, achieving higher MOE values at the cost of lower MOR values [19].

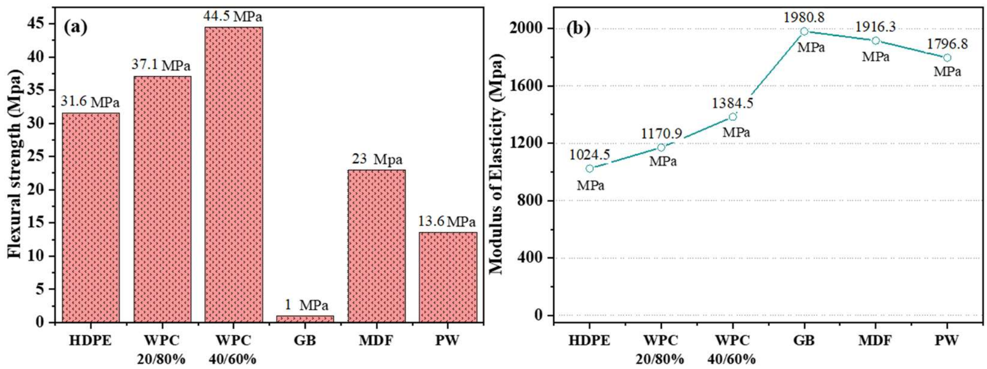

Figure 5. Flexural strength (**a**) and modulus of elasticity (**b**) in commercial panels.

The findings of the present study demonstrate that WPC 20/80% and WPC 40/60% panels developed physical properties that position them as a feasible option in hot, humid climates, such as 1.7% and 3.5% reduced water absorption, respectively, in contrast with commercial panels; also, their loading capacity (MOR) increased by 37.1 MPa and 44.5 MPa, respectively. The values obtained in this study were compared to those found in the related literature (shown in Table 2), where samples using Wood (W), Wood Flour (WF), Mesocarp Fiber (MF), and a variety of Polymers (Po) or Thermoplastics (TP) such as Polylactic Acid (PLA) and Polypropylene (PP) with similar ratios such as WPC 40/60%, were studied. Very similar results were obtained in the reviewed studies, with a noteworthy difference in MOE values, where WPC panels achieved increased flexibility values.

Table 2. Comparison of results obtained from WPC samples in relation to other authors. TM standards to be used according to the type of test and panel material.

Name	Density (kg/m^3)	Moisture Content (%)	Water Absorption (%)	Thickness Swelling (%)	Flexural Strength (MPa)	Modulus of Elasticity (MPa)	Reference
WF1/Po1 50/50%	-	-	~18	~3	~26	~2400	[20]
rPP/WF (60 mesh) 50/50%	1100	-	1.6	8.2	~40	~4600	[21]
PLA/MF 40/60%	~1062	-	~8	~2.3	~27	4400	[22]
Banana/coir fiber/PP 5/15/80%	-	-	1	-	28.1	598.3	[23]
S6_WF/TP 40/60%	~1080	~2.5	~2	~2.3	~12	3980	[24]
PP/WF 60/40% (1 xp)	1060	-	~4.5	<1	-	-	[25]
HDPE/rWF 60/35.8%	-	-	-	-	18.8	827.1	[19]
WPC 20/80%	858.3	0.3	1.7	0.8	37.1	1170.9	This study
WPC 40/60%	833.9	0.7	3.5	1.7	44.5	1384.5	This study

One of the most important elements in the present study was the process, which allowed for the manufacture of highly reliable materials without excessive resource depletion or complex additional processes, as is the case of wood refining and composite extrusion. The methodology shown in Figure 1b was proven to effectively produce functional composites.

3. Materials and Methods

3.1. Design and Elaboration of Panels

3.1.1. Materials

The HDPE used in this study was recovered from green chlorine containers. Some of its properties are as follows: density of 0.96 g/cm^3 and melt flow index (190 °C/2.16 kg) of 0.72 g/10 min. After collection, the labels were removed and washed to remove impurities; to obtain the granules (with dimensions of ~5 mm × ~2 mm × ~0.2 mm), an electric carpentry plane was used. Figure 6a shows the process to obtain HDPE in detail. Compression allows the modification of wood properties; this process flattens and decreases porosity through filling with other materials; a composite material in which this process is depicted is Oriented Strand Board (OSB) and plywood board with enhanced mechanical strength and tightness [26]. Commercial wood veneer (WV) of Caobilla is a commercial material provided by company located in Mexico. This material is the result of the loss generated by the company due to the marketing of the product, and it was been selected for the elaboration of the present study, with as-received dimensions of 122 cm × 244 cm × 0.6 mm, which were further reduced to enhance manipulation (Figure 6b).

Figure 6. (**a**) HDPE modification process and (**b**) WV cutting procedure.

3.1.2. Sample Sizing and Steel Mold Manufacture

Three sample pieces of HDPE (control, 1 pc) and WPC (2 pcs) are shown in Figure 7a, with dimensions of 30 mm × 150 mm × 6 mm for flexural strength and 25 mm × 75 mm × 6 mm for testing the physical properties of density and moisture content, as well as water absorption and swelling; each piece was replicated 4 times per test according to the standards mentioned in Tables 3 and 4.

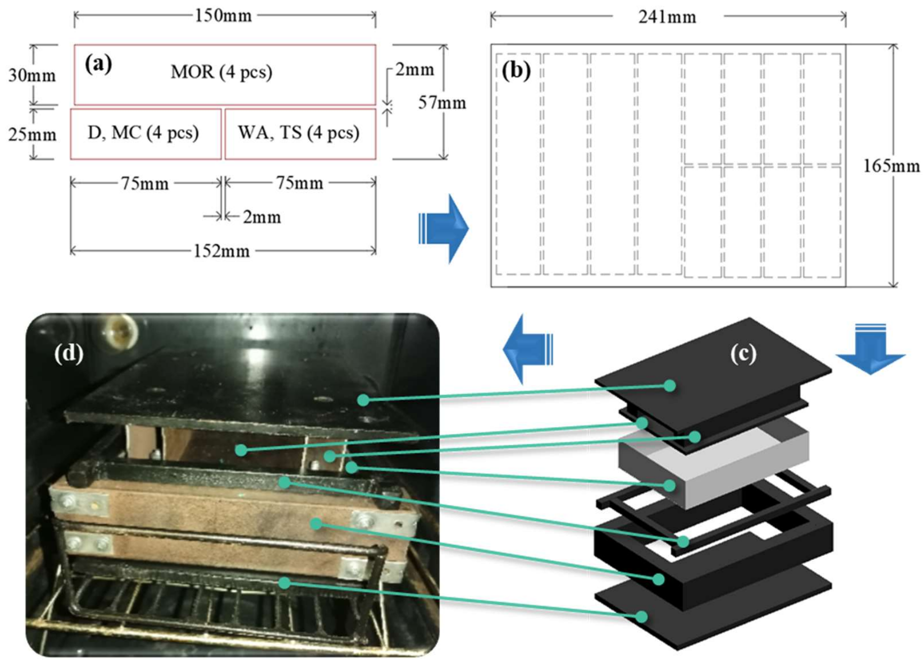

Figure 7. Manufacture of the mold and counter-mold: (**a**) test specimen measurements, (**b**) final sample measurement, (**c**) mold design, and (**d**) manufactured mold.

Table 3. ASTM standards to be used according to the type of test and panel material.

Panel Type	ASTM Standards			
	Flexural Strength	**Density**	**Moisture Content**	**Water Absorption and Thickness Swelling**
WPC (plastic–wood composite)	D 790 [27]	D 2395 [28]	D 4442 [29]	D 570 [30]
GB (gypsum board)	E 72 [31]	C 271 [32]	C 272 [33]	C 272
PW (plywood *Caobilla*, 3 layers interspersed)	D 1037 [34]	D 2395	D 1037	D 1037
MDF (medium-density fiberboard)	D 1037	D 2395	D 1037	D 1037

By wood-joining each piece-sample on its large end (75 mm) after each physical property test, an approximate length of the larger unit-sample used for the flexural strength tests was obtained, taking into consideration the width of the cutting edge of a saw disc (~2 mm); the number of set pieces were joined until the full length was obtained, considering the cutting width, for the unit-sample, as depicted in Figure 7b. Some commercial panels have different dimensions than the unit-sample, hence these were assessed separately according to the standards established for each one as specified in Table 4.

Table 4. ASTM standard dimensions for samples.

ASTM Standards		Sample Dimensions							
		E 72	**D790**	**D1037**	**C271**	**D2395**	**C272**	**D4442**	**D570**
Flexural strength	Total samples	4	4	4					
	L (mm)	370	150	190					
	W (mm)	75	30	50					
	T (mm)	12.7	6	4.1/5.8					
Density	Total samples			4	4	4			
	L (mm)			75	300	75			
	W (mm)			150	300	25			
	T (mm)			4.1/5.8	12.7	6			
Moisture content	Total samples			4			5	4	
	L (mm)			75			75	75	
	W (mm)			150			75	25	
	T (mm)			4.1/5.8			12.7	6	
Water absorption and thickness swelling	Total samples			4			5		4
	L (mm)			150			75		75
	W (mm)			150			75		25
	T (mm)			4.1/5.8			12.7		6

Length (L), Width (W), Thickness (T).

Once the unit-sample length and the number of piece-samples necessary to cover the full length were determined, a 3D model for the plastic melting process was developed (Figure 7c). A-36 steel was selected for the hot-compressing method, since a certain thickness for the metallic could was required (Figure 7d), which was in accordance with the sample thickness [35]. A-36 steel is resistant enough to enhance the hardness of the sample.

3.1.3. Manufacture of WPC Panels and Machining of Test Pieces

Once the material was processed and collected, the number of layers was determined according to the ratio of each sample, the density of HDPE, and the overall volume of the piece itself, as indicated in Table 5.

Figure 8 shows the procedure, further detailed in Figure 8a,b. Firstly, the material was placed in the mold in layers: HDPE was used for the first and last layers, and WV layers were placed in between the HDPE layers, alternating the orientation of each WV layer (Figure 8a(i)). Subsequently, the sample was cast in an oven at T = 200 °C for t = 90 min (Figure 8a(ii)). The prototype was kept under pressure using a homemade hydraulic press, for t = 20 h (Figure 8a(iii)). Finally, the sample was retrieved from the mold, and the edges were measured and adjusted to fit (Figure 8a(iv)). A circular sawing machine was used during the manufacturing process to obtain the final pieces for testing.

Table 5. Material calculation for the WPC samples.

Sample			Per Panel								Per Layer				Total Material to Be Used		
Name	Mat	%	L * (cm)	W * (cm)	T (cm)	A * (cm^2)	Vol (cm^3)	Vol. Mat per % (cm^3)	ρ *** (g/cm^3)	Wt (g)	T (cm)	Vol (cm^3)	No. Layers	Wt (g)	Panels **	HDPE (g)	WV Sheet ****
Control	HDPE	100	24.1	16.5	0.6	397.7	238.6	238.6	0.96	229.1	0.60	238.6	1.00	229.1	4.00	916.2	N/A
WPC 20/80%	HDPE WV	80 20	24.1	16.5	0.6	397.7	238.6	190.9 47.7	0.96 N/A	183.2 N/A	0.16 0.06	63.6 23.9	3.00 2.00	61.1 N/A	4.00	733.0 N/A	N/A 0.2
WPC 40/60%	HDPE WV	60 40	24.1	16.0	0.6	397.7	238.6	143.2 95.4	0.96 N/A	137.4 N/A	0.07 0.06	28.6 23.9	5.00 4.00	27.5 N/A	4.00	549.7 N/A	N/A 0.4

Length (L), Width (W), Thickness (T), Weight (Wt), Material (Mat), Density (ρ). * Same for each layer. ** One for ASTM test. *** The percentage calculation is by volume. The density is applied to determine the weight to be used in each layer at the time of panel manufacturing and the total weight required for all samples. The value used is according to what was found in the literature. **** (122 × 244 cm).

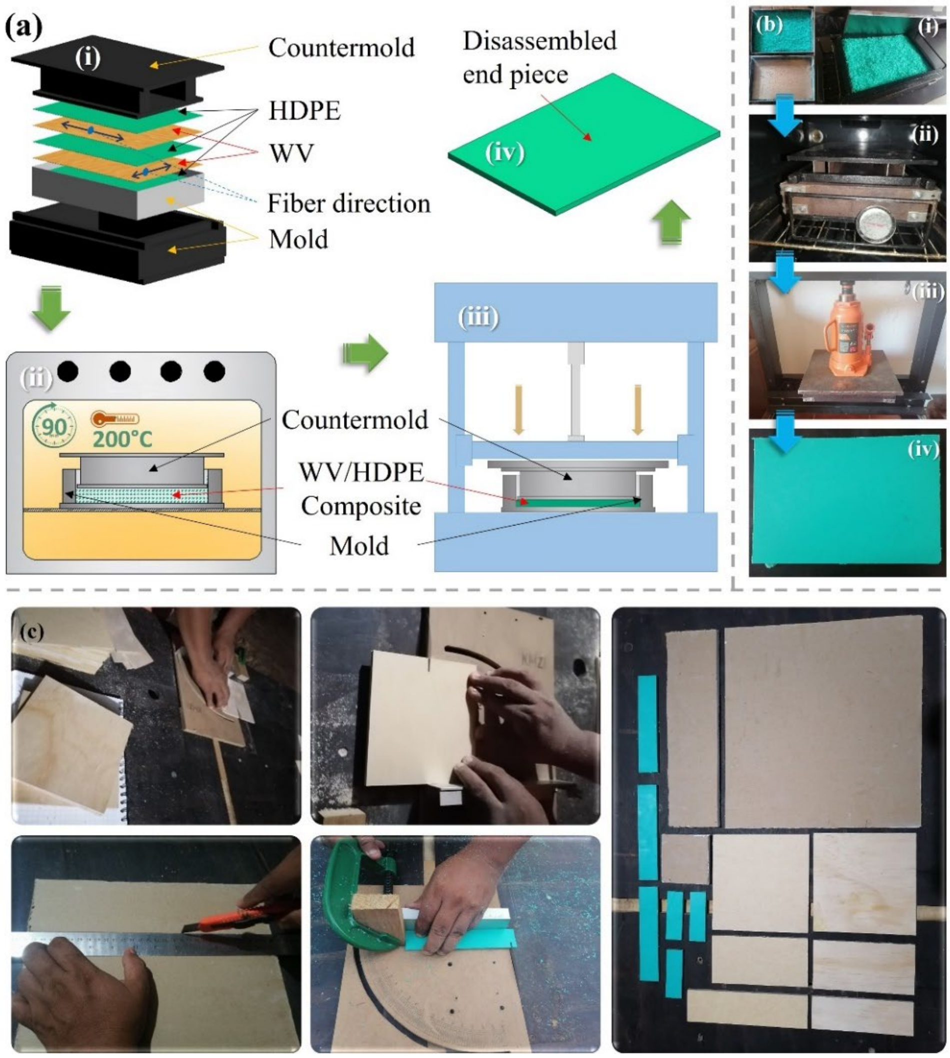

Figure 8. WPC panel manufacturing (**a**) process: (i) mold in layers with alternating the orientation, (ii) molding and heating process, (iii) mechanical pressing process and (iv) final sample; and (**b**) execution: material insertion (i), casting (ii), pressing (iii), final piece extraction (iv); and (**c**) machining.

3.2. Physical-Mechanical Tests

Density and Moisture Content, Water Absorption, and Thickness Swelling

Physical properties were assessed according to the standards detailed in Table 1 for each type of panel.

For density calculations, the following equation was used:

$$\rho = \frac{1000000\ m_s}{v_s} \tag{1}$$

where ρ = density, in kg/m^3; m_s = dry mass, in g; v_s = dry volume, in mm^3.

For moisture content (MC) calculations, the following equation was used:

$$MC = \frac{m_i - m_s}{m_s} \times 100 \tag{2}$$

where MC = moisture content, in %; m_i = initial mass, in g; m_s = dry mass, in g.

For water absorption (WA) and thickness swelling (TS) calculations, the following equations were used:

$$A_m = \frac{m_w - m_{i/s}}{m_{i/s}} \times 100 \tag{3}$$

$$A_v = \frac{v_w - v_{i/s}}{v_{i/s}} \times 100 \tag{4}$$

$$h = \frac{t_w - t_{i/s}}{t_{i/s}} \times 100 \tag{5}$$

where A_m = mass of water uptake, in %; A_v = volume of uptake water, in %; h = swelling, in %; m_i = initial mass, in g; m_s = dry mass, in g; m_w = wet mass, in g; v_i = initial volume, in g; v_s = dry volume, in g; v_w = wet volume, in g; t_i = initial thickness, in g; t_s = dry thickness, in g; t_w = wet thickness, in g.

3.3. Flexural Strength

The procedure for the flexural strength test was executed as determined according to the standard established in Table 3. Hence, the flexural strength of commercial panels was determined as follows:

$$\sigma_f = \frac{3PL}{2bd^2} \tag{6}$$

where σ_f = flexural strength, in MPa; P = load, in N; L = support span, in mm; b = sample width, in mm; d = sample thickness, in mm. For plastic-based panels, the following equation was used:

$$\sigma_f = \left(\frac{3PL}{2bd^2}\right)\left[1 + 6\left(\frac{D}{L}\right)^2 - 4\left(\frac{d}{L}\right)\left(\frac{D}{L}\right)\right] \tag{7}$$

where D = deflection at middle-line of sample, in mm; σ_f, P, L, b and d = same values as in Equation (6). The modulus of elasticity for plastic-based, wood-based (Equation (8)) and gypsum boards (Equation (9)) was obtained using the following equations:

$$E_B = \frac{PL^3}{4bd^3D} \tag{8}$$

$$E_B = \frac{5PL^3}{27bd^3D} \tag{9}$$

where E_B = modulus of elasticity, in MPa; P, L, b, d and D = same values from Equation (6).

4. Conclusions

In this study, wood veneer (WV) of 0.6 mm, as obtained commercially, was used instead of wood flour (WF). The results indicate that although WPC 20/80% samples presented the highest values for physical properties in terms of MOR, the sample appeared to have deformation issues. On the other hand, the WPC 40/60% sample had the highest ratio of wood content following the manufacturing process detailed in the present study; however, it obtained values of less than 4% for absorption, in contrast to commercial panels, which obtained values between 38% and 63%. In this sense, the WPC 40/60% sample resulted in the most feasible option for hot, humid climates because of its hydrophobic properties, obtaining a MOR value of 44 MPa and a MOE value of 1384.5 MPa. In addition, the ratio 40/60% proved to be a great option for flat or curved elements, as long as the distance between supports was short, and a more versatile panel than commercial ones.

Finally, using wood veneer as a primary material was crucial for the manufacturing process, since no wood refining/drying process was necessary to obtain certain particle size; instead, the revalorization of this residue allows minimizing waste from cut products from commercial production, directly impacting time and costs. In addition, by allowing the use of moderately contaminated Recycled Plastics (Pr) instead of virgin resin, this provides an additional market for Pr, helping to reduce the waste disposal burden [36]. Consequently, WPCs are potentially sustainable according to the application of the European framework directive on waste 2008/98/EC. This prioritizes alternative dismantling methods (EoL, End of Life), calling for a so-called waste management in hierarchy, which includes (a) prevention; (b) preparation for reuse; (c) recycling (without incineration); (d) other recovery (energy recovery); and (e) secure disposal. Materials that make up WPC can come from post-consumer sources, and the finished WPC product can be reused as a filler material within another secondary WPC product, repeating this process for several cycles, thus being compatible with the C2C (consumer to consumer) concept [37]. Although the influence of contaminated waste streams and types of filler and blended polymer on the properties of WPCs made from such recycled materials is not yet fully understood, and no collection systems exist for post-consumer WPC, internal recycling at production sites is identified as a promising option, as it reduces production costs and improves resource efficiency and cascading utilization [38].

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