

The impact of water exposure on the mechanical properties of a wood-plastic composite

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Abstract. Processed and unprocessed polypropylene samples reinforced with various proportions of pine and beech wood were manufactured using pressure molding and subjected to various mechanical tests. Increasing the percentage of wood particles regardless of the wood species was associated with increased density and hardness of the wood-plastic composite, while tensile strength, deformation at fracture, and elastic limit decreased with increasing particle size. Higher moisture contents were associated with increases in both tensile strength and elastic limit.

Keywords: Wood-plastic composite; Polypropylene; Black pine; European beech; Mechanical properties; Wood particles; Polymer; Moisture effects

Introduction

There has been a growing trend to use wood waste in various industrial sectors such as construction, agriculture, forestry, automotive, and others. This trend reduces waste, conserves valuable material resources, creates new materials, or can improve properties of already existing materials (Perišić et al 2024; Rezakalla and Dyachenko 2022).

An important use of various forms of wood waste (such as pellets or fibers) is as a polymer filler in the production of wood/plastic composites (WPC). Adding wood particles creates composites with the necessary mechanical and physical properties required for specific applications under specific working conditions (Perišić et al. 2024; Rezakalla and Dyachenko 2022). These materials tend to be much more resistant to moisture absorption than the parent wood.

Wang and Morrell (2004) found slow moisture uptake in long-term immersion of two commercial WPCs (Trex® and Strandex®), but significant accumulation in the outer 5 mm

layer at levels sufficient for fungal decay (Wang and Morrell 2004). Moisture mapping revealed that Strandex® absorbed water more slowly, with both brands showing moisture gradients capable of supporting fungal growth near the surface.

Wang and Morrell (2005) investigated the effects of moisture and temperature cycling on the durability and mechanical properties of wood-plastic composites (WPCs). Their study found that repeated wet-dry and freeze-thaw cycles degraded the material's strength and stiffness, while increasing water absorption and swelling. These results underscore the environmental vulnerabilities of WPCs and emphasize the need for enhanced material formulations to improve performance in outdoor applications.

Wang et al. (2020) investigated water absorption in wood-polypropylene composites with 15–45 wt% wood content and found that showing Fickian diffusion behavior accelerated at higher temperatures (23°C, 60°C, 80°C). Water absorption reduced mechanical properties, with 45% wood composites losing 32% tensile strength and 47% modulus of elasticity, while flexural strength showed similar degradation. Dynamic material analysis confirmed water's plasticizing effect, emphasizing the trade-off between wood content and moisture-induced property loss in WPCs.

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Kord (2011) examined the influence of different proportions of fixed-sized beech particles combined with polypropylene, using citric acid as a binder, on the hardness of samples manufactured through pressure molding. He concluded that increasing the percentage of wood was associated with increased hardness. This finding was further corroborated by Kaymakçi and Ayrilmiş (2013) who also reported that increased wood content was associated with increased water absorption and changes in thickness.

Lin et al. (2023) evaluated a polypropylene (PP)-based WPC prepared using twin-screw extrusion, and the effects of adding maleic anhydride (MAH) and wood flour on the properties of the WRC, prepared at ratios of 5, 6, 7, 8, 9, and 10% by weight of MAH. Increasing MAH was associated with an initial increase in tensile strength, but further additions resulted in declines, while water absorption decreased. Tensile strength also initially increased with increased wood flour, then declined, and water absorption increased by 62% when the wood flour content exceeded 10% by weight.

Cavus and Mengeloğlu (2020) examined the effect of particle size (0.074–0.841 mm) and 3% MPP on neat PP and recycled PP (rPP) wood-plastic composites containing 40% mahogany wood flour. Smaller wood particles enhanced density, stiffness (flexural/tensile modulus), and impact strength, while MAPP improved interfacial adhesion, boosting strength properties but reducing elongation. Scanning electron microscopy (SEM) revealed optimized particle-matrix bonding with MAPP, though rPP composites showed slightly reduced performance versus virgin PP.

Bhaskar et al. (2021) examined the influence of various types of polymer binders (PP, polyvinyl chloride, polyethylene vinyl acetate, and polyethylene naphthalate) on WPC properties. Polyvinyl acetate polymer had a significant impact on tensile strength, bending strength, and impact resistance properties.

These studies suggest the potential for adjusting WPC composition to minimize water absorption and thereby reduce any potential effects on mechanical properties. The objective of this study was to assess the influence of water exposure on the mechanical properties of WPCs.

Materials and methods

Material Preparation

Wood Particles

Black pine (*Pinus nigra* L.) particles (L = 300–800 µm) with a density of 0.45 g/cm³, and hardwood particles (L = 100–800 µm) from beech (*Fagus sylvatica* L) with a density of 0.65 g/

cm³ were obtained from a cutting and furniture finishing operation. Particle size distributions were determined by weighing a series of sieves with different diameters. The particles were added and the sieves were vibrated for 3 minutes, after which the amount of particles retained in each sieve was weighed (Figure 1).

Particles larger than 600 µm were removed, since previous studies have shown that moisture absorption increases with increasing particle size (Bhaskar et al. 2021; Abdul Rahman et al., 2023).

The particles were oven-dried at 100°C for 120 minutes and then placed in vacuum sealed bags to minimize moisture absorption. The bags were stored in a cool/dry location until needed.

Polymer granules

Primary polypropylene (PP) particles were obtained from SABIC PP 520 L (Saudi Basic Industries Corporation, Riyadh, Saudi Arabia) with the following characteristics: density: 0.910 g/cm³; melting point: 160°C; Shore D hardness: 70; tensile strength (ISO 527): 32 MPa; flexural modulus (ISO 178): 1300 MPa.

Particles from recycled plastic industry waste polymer plants (Re-PP) had the following characteristics: density: 0.910 g/cm³; melting point: 20 g/10 min; Shore D hardness: 70; tensile strength 25 MPa; flexural modulus 1300 MPa.

Coupling agent

Abietic acid was ground to a fine powder and used as a coupling agent for wood and polymers. This organic material had an average melting point of 140°C, density of 1.06 g/cm³, and was insoluble in water (Ataman Chemicals, Turkey).

Manufacturing of casting molds

The sample injection mold was designed using the ANSYX program, following specifications described in ASTM Standard D-638 (2003). The mold was then manufactured using a CNC machine and subsequently assembled.

Manufacturing of wood-plastic composites (WPC)

The materials were used to assess the effects of different wood/plastic ratios on WPC properties (Table 1).

Injection Process

The materials were thoroughly mixed before being introduced into the funnel of a Qingdao Tongsan extruder operated at 450 kPa for 10 s (Qingdao Tongsan Plastic Machinery Co, Ltd, China). The materials were held at 450 kPa for 4 s before being extruded through the system, with temperatures held at 170°C

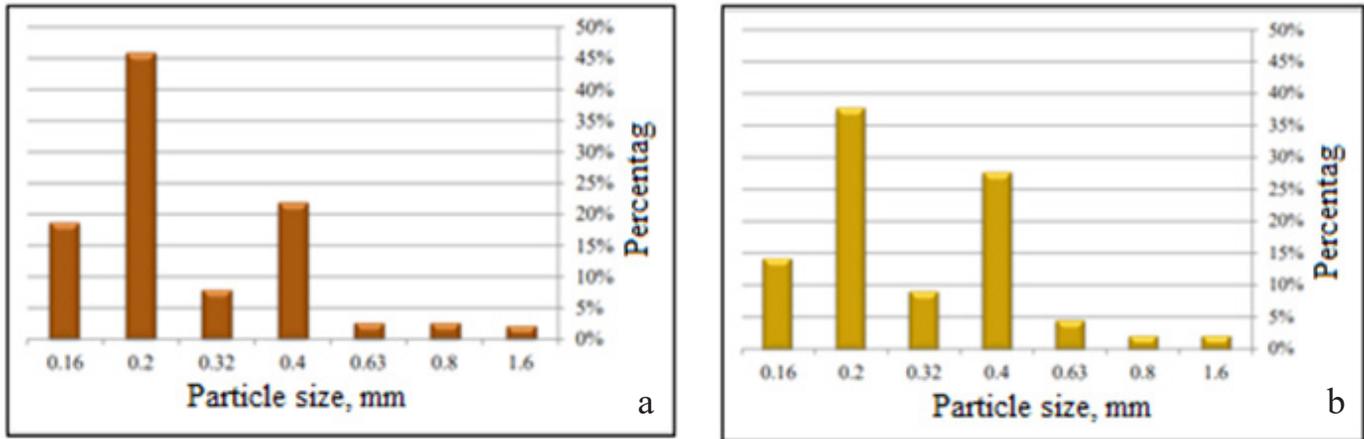


Figure 1 Wood Particle Size Distribution in (a) beech or (b) pine.

for the feed, and 190°C for zone 1, zone 2, and the nozzle. The samples were cooled for 15 seconds and then stored at $23 \pm 2^\circ\text{C}$ and $50 \pm 5\%$ RH until tested (Figure 2).

Experiments

Density determination test

Sample density was determined by weighing (nearest 0.005 g) and then determining volume by water displacement. Density tests were conducted on three samples of each material and averaged.

The influence of immersion time on density

WPC samples were weighed and immersed in distilled water according to ASTM Standard D-1037 (1999), with three samples taken for each reinforcement ratio. After the desired immersion time, the samples were removed, liquid water was wiped off, and the samples were weighed (nearest 0.001 g) and their dimensions measured. This process was repeated after 0.5, 1, 7, and 14 days, and the data were used to calculate density.

Hardness test

Hardness was assessed on three samples of each material according to ASTM Standard D-2240 (2003). Five readings were taken per sample using a Shore Type HD 3000 Durometer (Hildebrand Korskllldelumd, Germany) at a pressure force of 5000 g, with a measurement displacement of 2.5 mm, an indenter at 30° , and a measuring range of 10–90 (LABOMAT Equipment and Specialties, France).

Tensile test

The tensile strength was assessed according to ASTM Standard D-638 (2003) on a CY -6120 Tensile tester with a 50 kN load cell (Chun Yen Testing Machines Co., Ltd., Taiwan). Tensile tests were conducted on three samples of each material, and the average value of the results was taken after calculating

Table 1. Proportions of components used to manufacture wood-plastic composites.

Sample code	Wood particles, Wt%	Polymer, Wt%	
		Virgin (%)	Recycled (%)
PP15/Pine	15	83	—
PP30/Pine	30	68	—
PP45/Pine	45	53	—
PP15/Beech	15	83	—
PP35/Beech	30	68	—
PP45/Beech	45	53	—
RePP15/Pine	15	—	83
RePP30/Pine	30	—	68
RePP45/Pine	45	—	53

2% mass/mass of coupling agent was added to all mixtures.

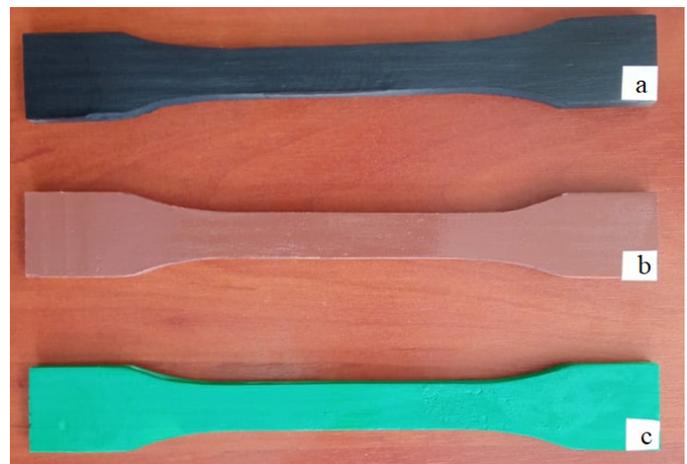


Figure 2. Samples of wood-plastic composite containing (a) pine, (b) beech, or (c) recycled PP with pine.

the deviation and confidence. (Example: for the sample PP/15 pine, average $\mu = 22.6$ MPa, standard deviation $\sigma \approx 1.14$ MPa $\rightarrow 22.6 \pm 1.0$ MPa (95% confidence)).

Results and discussion

Density

Density increased 9.35% with the addition of 45% pine and 10.45% with the addition of 45% beech (Figure 3). This density increase was somewhat lower at low reinforcement ratios, as it was only 0.6% for 15% pine wood and 1.15% for beech wood fiber reinforcement. Increased density of the WPC reflects the compression of the denser wood cell wall (Maldas et al. 1989).

Production processes that use high pressure, such as injection molding at 5 bar, exert pressure on the cell walls, leading to increased density of wood particles and, consequently, increased WPC density (Amos et al. 2012; DeArmitt 2017).

There was a marked increase in density of the recycled polypropylene, starting at 2.6% with the addition of 15% pine and reaching 13% with the addition of 45% pine. Recycled polypropylene generally had a higher density than virgin polypropylene due to the presence of materials added during earlier production.

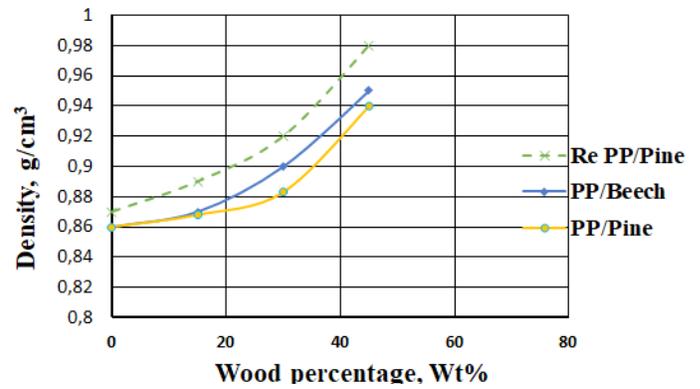


Figure 3. Effect of different proportions of pine or beech particles on density of the resulting WPC.

The influence of immersion time on density

Water absorption increased as the percentage of wood particles increased (Figure 4). Water absorption in composite materials is primarily associated with cellulose and hemicellulose because they contain a large number of easily accessible hydroxyl groups. Since wood naturally has a high water-absorption capacity, an increase in the ratio of wood particles results in a corresponding increase in water absorption of the WPC. It is important to note that the polypropylene exhibits almost

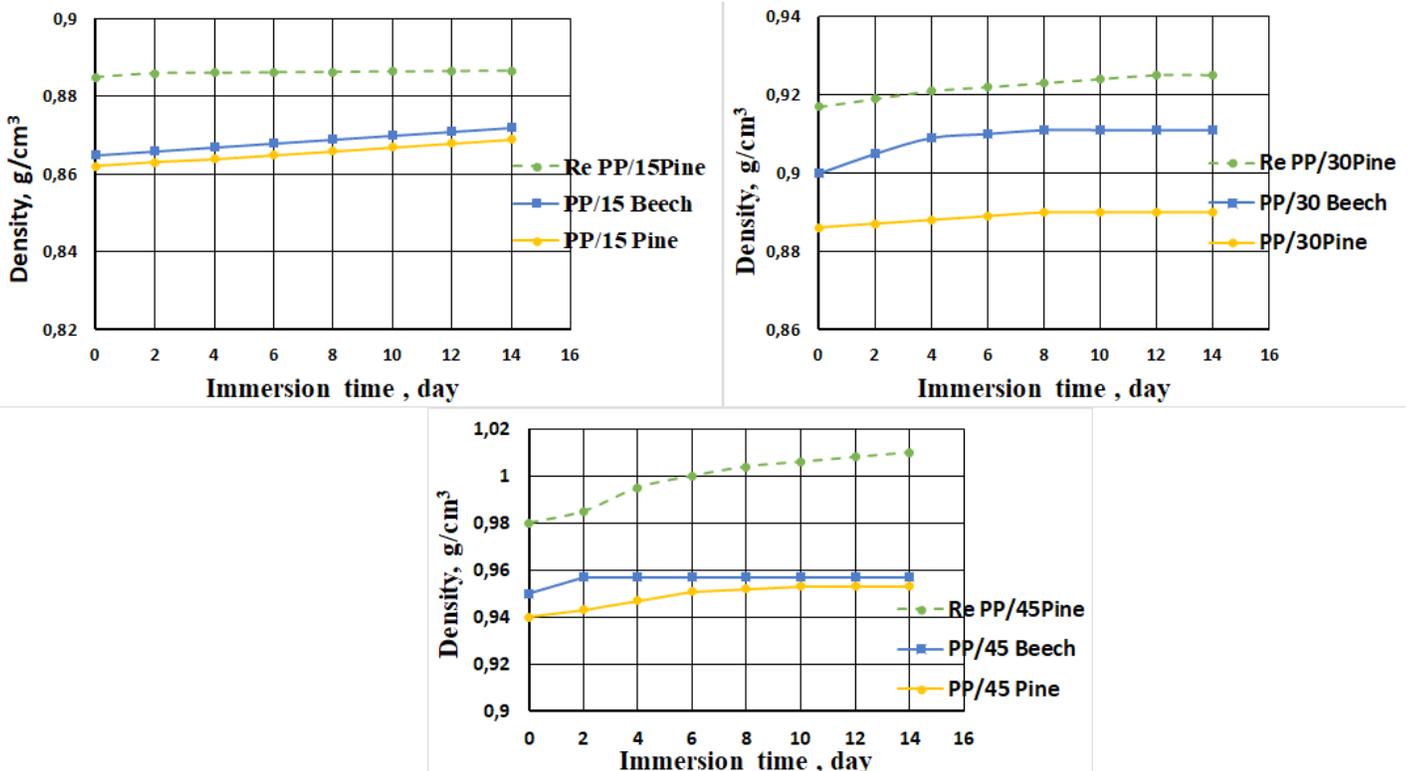


Figure 4. Effect of water immersion on density of WPCs with different ratios of wood particles and polypropylene.

negligible water absorption compared to wood during the specified immersion time, which aligns with the findings of previous research (Kord 2011; Cavus and Mengeloğlu 2020).

The RePP45/Pine samples had a greater water absorption capacity, as their density increased by 3.2%, while the PP15/Beech samples were less water-absorbent, with their density increasing by only 0.12%.

Influence of reinforcement percentage on hardness

WPC hardness increased with increased wood particle level for both wood species. The increase was 21% when reinforced with 45 wt.% pine wood particles and 22.6% when reinforced with 48 wt.% beech wood particles. A similar result was observed when comparing virgin and recycled PP. Hardness increased by 21% with 45 wt.% pine wood particles using virgin PP, and by 14% when using recycled PP (Figure 5).

There was no difference in hardness in WPC samples immersed for 14 days (Table 2).

Hardness increased linearly with increasing WPC density, with the derivative of hardness, with respect to density, being greater than zero, indicating a linear function (Figure 6).

Tensile test

The tension tests were used to derive mechanical behavior curves (Figure 7). Tensile strength, fracture strain, and yield strength all decreased with increased wood content, while modulus of elasticity increased. Increased MOE with increased wood content reflects that ability of wood to stiffen the PP, but these materials disrupt the PP, reducing tensile strength (Figure 8) (Gnatowski 2002).

Influence of the recycled polymer on tensile properties

Overall, mechanical properties were higher when using primary PP compared to recycled PP at the same wood level

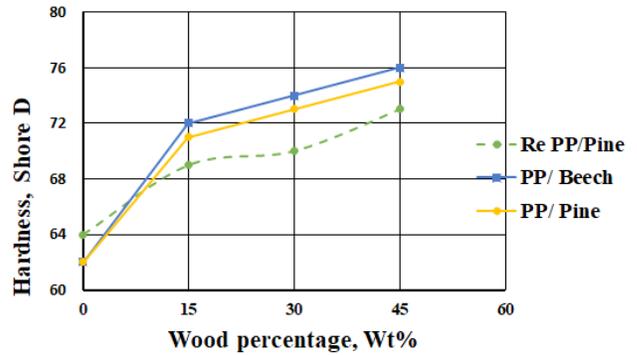


Figure 5. Effect of increasing wood levels on hardness of WPCs prepared using virgin or recycled PP.

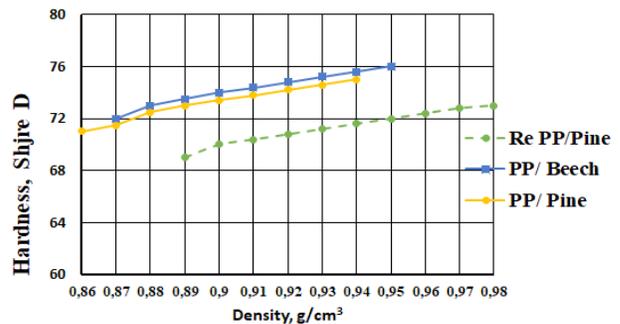


Figure 6. Relationship between density and hardness of WPCs containing different ratios of wood.

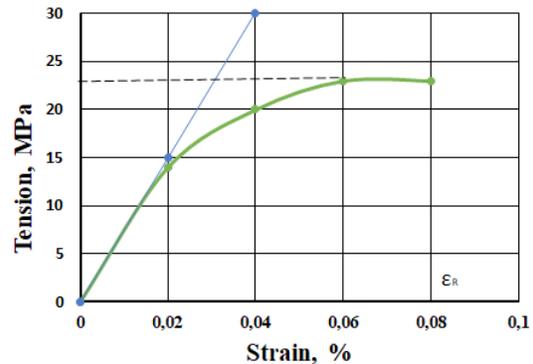


Figure 7. Example of a stress-strain curve of a wood-plastic composite reinforced with 15% pine.

Table 2. Change in WPC hardness over time samples immersed in water for up to 14 days.

Sample code	Hardness (Shore D)				
	Pre-immersion	0.5 day	1 day	7 days	14 days
PP15/Pine	71	70	69	70	70
PP30/Pine	73	73	72	72	73
PP45/Pine	75	75	75	74	74
PP15/Beech	72	72	71	72	71
PP30/Beech	74	74	74	74	74
PP45/Beech	76	75	75	75	75
Re PP15/Pine	69	69	69	69	69
Re PP30/Pine	70	70	71	70	70
Re PP45/Pine	73	72	72	71	71

Values represent means of 3 replicates per material and time (ASTM D-1037)

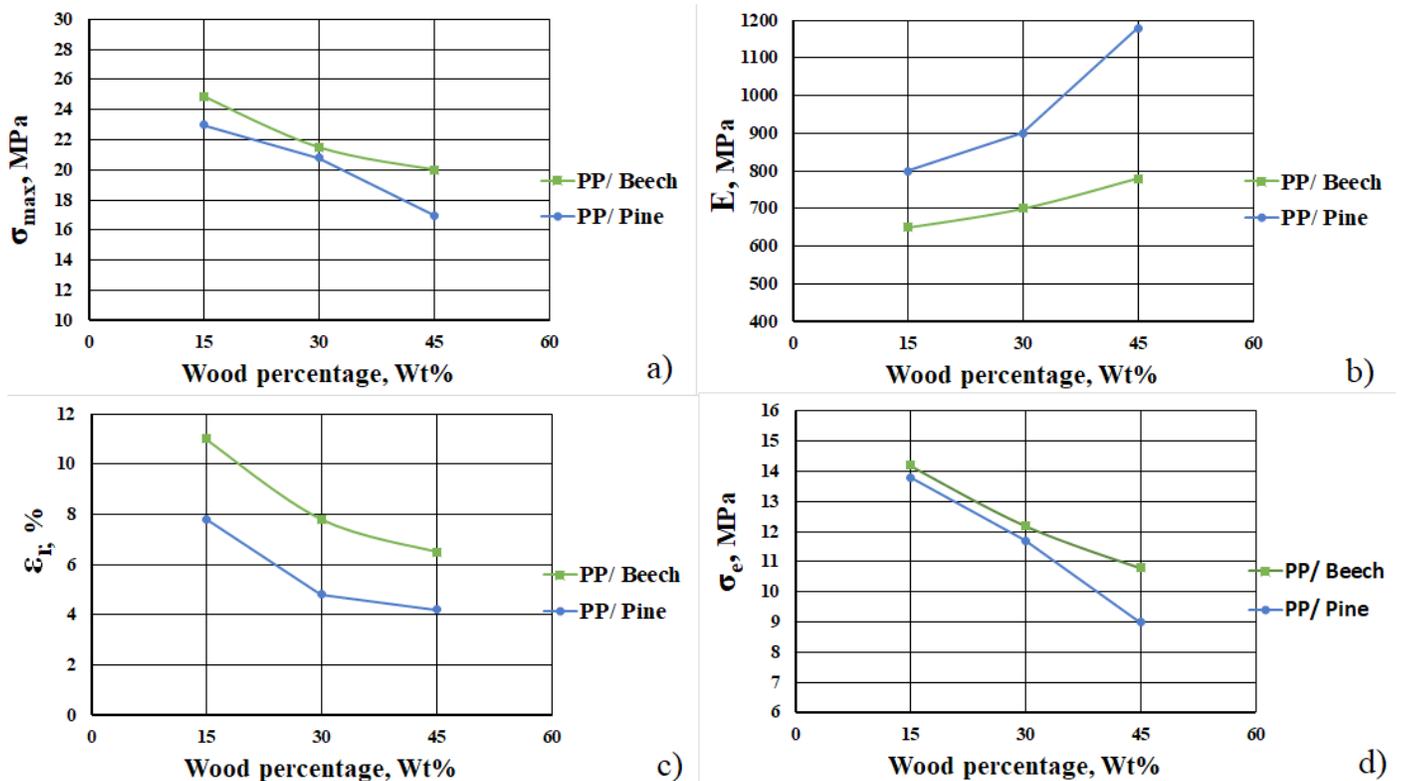


Figure 8. Effect of increased proportions of wood particles in a WPC on (a) tensile strength, (b) modulus of elasticity, (c) fracture strain, and (d) yield strength for WPC at different blending ratios of pine and beech wood particles.

(Figure 9). This could be attributed to impurities present in the recycled polymer, which negatively affect the adhesion between components and weakened the interfacial surfaces, aligning with the findings of previous research (Kord et al. 2011). Additionally, differences in the structures of primary and recycled polypropylene may also play a role.

The influence of immersion time on tensile mechanical properties

Maximum stress and yield stress both increased with immersion time, while MOE initially declined then increased slightly over time (Figure 10).

From Figure 10a, it can be observed that, at the beginning of the immersion, the maximum stress decreased in magnitude. The resistance of composite materials reflects the quality of the interfacial surfaces between components, which allows for the transfer of stress from the binder material to the support. The strength of this bond contributes to improved resistance. However, during immersion, water was absorbed by the wood, leading to distortions at the interface or failure of the bond between the polymer and the wood, resulting in degradation of the surface and a decrease in resistance. As the immersion time increased and exceeded 2 days, the wood continued to

absorb more water, causing the particles to swell and fill the voids in their structure, which hindered the sliding of polymer chain molecules and ultimately increased the tensile strength.

MOE tended to decrease at the start of immersion and then increased slightly with additional immersion time (Figure 10b). The initial declines may be due to hydrogen bonding between water molecules and wood fibers. However, in the presence of moisture, these bonds break, forming new hydrogen bonds with water molecules, which leads to a decrease in mechanical properties. Subsequent swelling of wood particles within the PP matrix may account for the slight increase in MOE with longer immersion times.

Increased moisture content at the start of immersion led to increased elongation, due to slippage between water and wood, resulting in a weakening of the bond between the polymer and the wood (Figure 10b). However, the elongation values for all reinforcement ratios decreased when the immersion time reached approximately 1 day. This decrease was associated with the swelling of the wood and the filling of voids in the interfacial surfaces between the polymer and the wood. The higher the wood particle content, the lower the elongation at failure. However, elongation again increased after 2 days of immersion.

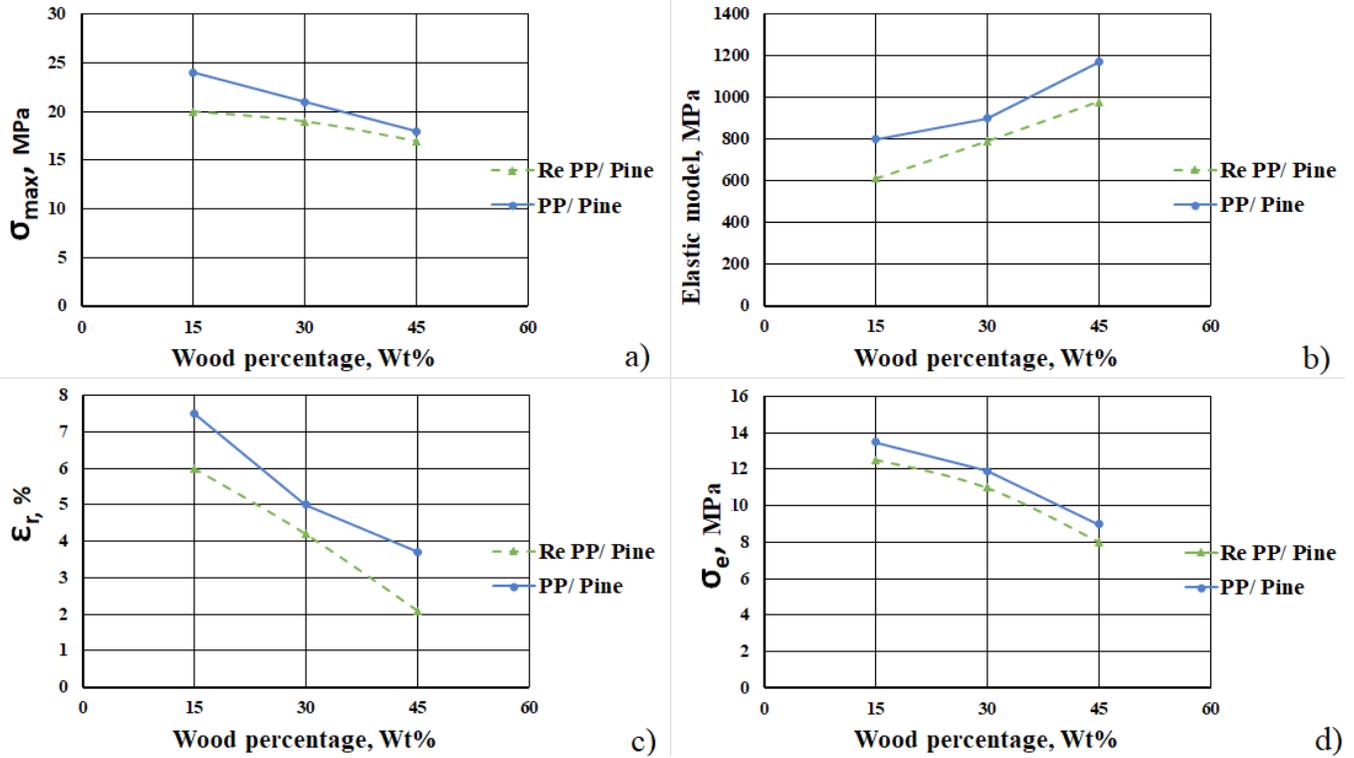


Figure 9. Effect of the use of virgin or recycled polypropylene on (a) tensile strength, (b) modulus of elasticity, (c) fracture strain, and (d) yield strength in tension of WPCs with different ratios of pine.

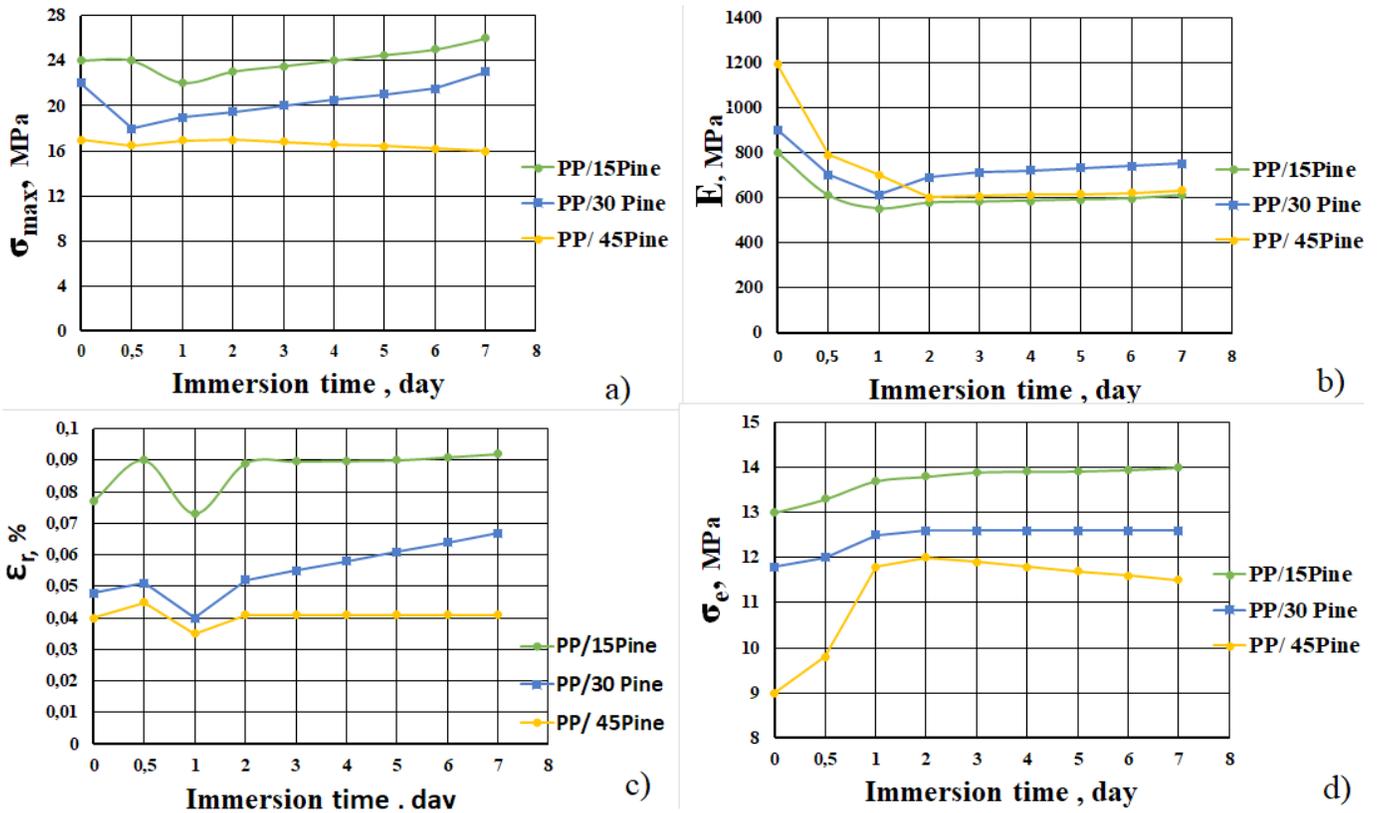


Figure 10. Effect of water immersion time on (a) maximum stress, (b) modulus of elasticity, (c) fracture strain, and (d) yield strength for WPCs made from primary and recycled PP with different ratios of pine particles.

Conclusions

Wood plastic composite hardness and density improved with increasing wood filler percentage, with the hardness of reinforcing materials directly impacting final product performance. A 2-week immersion had minimal effect on hardness, regardless of specific component ratios or material combinations.

Particle size analysis revealed that larger particles adversely affected several key properties, including ultimate strength, failure deformation characteristics, and elastic limit performance. Conversely, stiffness measurements showed consistent enhancement with greater wood content across all tested formulations.

Failure deformation and elastic limit increased at lower moisture levels, while tensile strength and elastic modulus decreased. High moisture environments produced the opposite effect, elevating both tensile strength and elastic limit.

Recycled PP composites exhibited similar performance trends to virgin material counterparts, but the properties were reduced, possibly because the parent materials in the recycle products had extra additives.

These findings provide valuable insights for optimizing WPC formulations to meet specific engineering requirements. The consistent, predictable relationships observed between processing parameters and final product characteristics offer manufacturers reliable guidelines for material development and application-specific tuning of composite properties. The comprehensive results establish a foundation for further research into advanced WPCs and their practical implementations.

Recommendations

Further investigate the optimal ratios of wood particles to plastic in order to enhance specific mechanical properties such as tensile strength, elasticity, and hardness.

Study the effects of different types of binding materials and their impact on the bonding quality of wood-plastic composite components.

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