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Characterization of Wood Plastic Composite Based on Virgin/Recycled Polypropylene and Teak Sawdust for Structural Applications

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ABSTRACT

The disposal of plastic waste has become a major environmental challenge worldwide. Converting this waste into new materials has attracted significant research interest due to its potential for sustainable resource utilization and diverse engineering applications. This study evaluates the physical and mechanical properties of composites reinforced with teak sawdust and manufactured using both virgin polypropylene (VPP) and recycled polypropylene (RPP). The performance of recycled polypropylene composites was compared with that of virgin polypropylene composites using identical testing standards and equipment to determine the suitability of recycled materials for building applications. The wood flour and polypropylene were compounded using a twin-screw extruder, and the wood–plastic composites (WPCs) were fabricated through compression molding. Mechanical, hygroscopic, and rheological properties were examined and compared. The results indicate that composites based on recycled polypropylene exhibit higher tensile and flexural strength but lower impact strength than those produced with virgin polypropylene. In addition, RPP composites demonstrated lower water absorption, reduced thickness swelling, a lower melt flow index, and greater hardness

compared to VPP composites. Scanning Electron Microscope (SEM) analysis revealed that the incorporation of maleated polypropylene (MAPP) enhanced the interfacial bonding between wood particles and the polymer matrix, leading to improved composite performance. Overall, the developed recycled polypropylene composites exhibited superior properties, making them promising materials for construction and building applications.

1.0 Introduction

Plastic waste has become a major environmental problem worldwide, and its safe disposal is a serious concern. Around 100 million tons of plastic waste are generated globally every year [1]. In India, about 39,031 tons of plastic waste are produced from domestic and industrial activities. Out of this, 40–80% is recycled, while the remaining waste is disposed of in landfills [2].

Similarly, a large amount of wood waste is generated during wood processing. Most of this waste is either sent to landfills or used as fuel for cooking [3]. These disposal methods release harmful gases and contribute to environmental pollution. One effective way to utilize both wood and plastic waste is by producing Wood Plastic Composites (WPCs). This approach reduces disposal costs and lowers the carbon footprint of plastic materials.

Wood Plastic Composites are materials made by combining wood particles with thermoplastics such as polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethylene (PE), and polyethylene terephthalate (PET). During recycling, polymers undergo changes in their mechanical, moisture-absorbing, and flow properties. As a result, recycled polymers can behave differently from virgin materials and may be considered new materials. Recycling of polymer increases tendency of polymer molecules to form covalent and ionic bonds, leading to greater cross-linking of polymer chains. This increases chain length and affects the density and viscosity of the material [4,5].

However, mixing wood particles with plastics is challenging because wood and plastic have very different chemical properties. This often results in weak bonding between the two materials, which can reduce the performance of WPCs [6]. To improve bonding, small amounts (0–5%) of coupling agents are added during manufacturing. Common coupling agents include MAPP, MAP, EPOLE, and E-43. These agents improve the adhesion between wood and plastic, thereby enhancing the mechanical, moisture-resistant, and flow properties of the composites [1,7].

The use of natural fibers and wood flour as reinforcement materials in plastics has increased significantly over the past few decades. Although many studies have investigated wood-fiber-reinforced plastics, relatively few have focused on WPCs made with recycled polymer matrices [8,9].Nafaji et al. (2006) reported that water absorption in WPCs follows Fick's law of diffusion. They found that WPCs made with recycled HDPE/PP matrices absorbed more water and had higher diffusion coefficients than those made with virgin polymers [10].

Adhikari et al. (2008) observed that WPCs produced with recycled HDPE showed water absorption and thickness swelling comparable to those made with virgin HDPE. They also found that adding MAPP reduced both water uptake and thickness swelling [11].

Nafaji et al. (2010) studied the effects of thermo-mechanical degradation on beech wood flour and polypropylene composites. Their results showed that composites made from recycled polypropylene (RPP) absorbed more water and exhibited greater thickness swelling than those made from virgin polypropylene (VPP). The addition of MAPP significantly reduced these effects [12].

Svetlana et al. (2011) investigated the mechanical and physical properties of WPCs made with virgin and recycled polypropylene. They found that recycled polypropylene composites had higher density, lower porosity, lower crystallinity, and better dimensional stability. They also reported lower water absorption and thickness swelling in recycled polypropylene composites compared to virgin polypropylene composites [13].

Bhasker et al. (2012) produced WPCs using recycled polypropylene and pine sawdust. Their results showed that recycled polypropylene composites had lower water absorption and thickness swelling than virgin polypropylene composites. The use of MAPP further improved these properties [14].Kurniawana et al. (2013) reported that reprocessing polypropylene positively affected both physical and mechanical properties. Reprocessing improved the mechanical performance while reducing water absorption and thickness swelling in WPCs [15].

Haq et al. (2015) studied composites made with virgin and recycled polypropylene reinforced with wood flour. They found that recycled polypropylene composites showed better mechanical strength, lower water absorption, and reduced thickness swelling compared to virgin polypropylene composites. The addition of MAPP further improved both mechanical and moisture-resistant properties [16].

In the present study, Wood Plastic Composites were prepared using virgin and recycled polypropylene along with teak wood sawdust. The effects of polymer type (virgin or recycled), wood content, and the

coupling agent MAPP on the mechanical, rheological, and hygroscopic properties of the composites were investigated.

Mechanical characterization included tensile, flexural, impact, and hardness tests. Water absorption and thickness swelling tests were conducted to evaluate dimensional stability. The melt flow index (MFI) of the compounded materials was measured to assess processing behavior. Scanning Electron Microscopy (SEM) was used to examine the fractured tensile surfaces and study the microstructure of the composites.

The main objective of this research is to explore the use of post-consumer recycled polypropylene and teak wood sawdust in developing strong, lightweight, eco-friendly, and cost-effective Wood Plastic Composites suitable for engineering applications.

2. Materials and Methods

2.1 Materials

2.1.1 Polymer

Virgin polypropylene (VPP) was procured from a local distributor of Repole, a unit of Reliance Petroleum, India. Recycled polypropylene (RPP) was obtained from a local recycling facility. The polymer granules were dried in an air-circulating oven at 65°C for 12 h to remove moisture before processing.

2.1.2 Wood Sawdust

Teak wood sawdust was used as the reinforcing filler in the composites. Fresh sawdust was collected from a local sawmill and dried in an air-circulating oven at 110°C for 24 h to eliminate moisture completely. The dried sawdust was sieved, and particles with sizes ranging from 200–250 μm were selected for composite fabrication.

2.1.3 Coupling Agent

Maleic anhydride grafted polypropylene (MAPP) was used as the coupling agent to improve the compatibility and adhesion between wood particles and the polypropylene matrix.

2.2 Composite Preparation

Virgin polypropylene, recycled polypropylene, and teak wood particles were compounded using a twin-screw extruder. The extruder was PLC-controlled and operated at four temperature zones of 160°C,

170°C, 180°C, and 190°C. The screw speed was maintained at 90 rpm, and the barrel pressure was 40 bar.

All formulations were prepared in 1 kg batches according to the compositions listed in Table 1. The extruded material was cooled in a water bath and then pelletized into small granules.

The pellets were further dried at 75°C for 4 h to remove residual moisture. Composite sheets were then manufactured by compression molding. The granules were placed in a mold of dimensions 180 mm × 150 mm × 3 mm and compressed at 200°C under a load of 5 tons for 4–5 min.

Figure 1. Manufacturing process of composites

Table 1. Formulation and specimen code-

Sr.No.	Composite code		Wood sawdust (%Weight)	Polypropylene (%Weight)	Coupling agent (%Weight)
	Virgin polypropylene	Recycled polypropylene			
1	V1	R1	00	00	00
2	V2	R2	20	80	00
3	V3	R3	30	70	00

4	V4	R4	40	60	00
5	V5	R5	50	50	00
6	V6	R6	50	47	03
7	V7	R7	50	45	05

2.3 Experimental Methods

2.3.1 Tensile Test

Tensile properties were evaluated according to ASTM D638-14 using a Tinius Olsen Universal Testing Machine equipped with a 10 kN load cell. Dumbbell-shaped specimens were cut from the composite sheets. Tests were conducted at a crosshead speed of 5 mm/min. Three specimens from each formulation were tested, and the average value was reported. All experiments were performed at room temperature (23 ± 2°C).

2.3.2 Flexural Test

Flexural strength was measured using a three-point bending test according to ASTM D790-03. The tests were performed at a crosshead speed of 2.8 mm/min using a 2.5 kN load cell. Specimens with dimensions of 76.2 mm × 25.4 mm × 3.2 mm were tested at 23 ± 2°C and 50 ± 5% relative humidity.

2.3.3 Impact Test

Impact strength was determined according to ASTM D256-10 using a Presto Impact Testing Machine. Specimens measuring 63.5 mm × 12.5 mm × 3.2 mm were prepared, and a 42° notch was introduced before testing.

2.3.4 Water Absorption Test

Water absorption was measured following ASTM D570-98. The specimens were first dried at 105°C for 24 h and cooled in a desiccator. They were then immersed in distilled water maintained at 23 ± 1°C. The specimens were weighed after 2 h and 24 h of immersion using a balance with an accuracy of 0.001 g. Water absorption was calculated using Equation (1).

2.3.5 Thickness Swelling Test

Thickness swelling was measured using a micrometer with an accuracy of 0.01 mm. The percentage thickness swelling was calculated using Equation (2).

2.3.6 Melt Flow Index Test

The melt flow index (MFI) was determined according to ASTM D1238-12. The test was performed at 230°C using a standard load of 2.16 kg. MFI was reported as the mass of polymer flowing through a capillary die in 10 min.

2.3.7 Hardness Test

Hardness measurements were conducted according to ASTM D2240 using a digital Shore-D hardness tester. Three readings were taken from different locations on each specimen, and the average value was reported.

2.3.8 Microstructural Analysis

The fracture surfaces of tensile-tested specimens were examined using a ZEISS Scanning Electron Microscope (SEM). Before analysis, the samples were coated with gold. Micrographs were obtained at magnifications of 300× and 500× under an accelerating voltage of 15 kV.

3. Results and Discussion

3.1Tensile test

The tensile strength of each formulation has been plotted in Figure.2. The tensile strength of polymer RPP and VPP are 34.18MPa and 35.40MPa respectively. The plots show that maximum tensile strength of VPP and RPP composites are 30.25MPa (V2) and 31.24MPa (R2) respectively. The minimum tensile strength of VPP and RPP composite was 24.45MPa (V5) and 25.88MPa (R5) respectively.

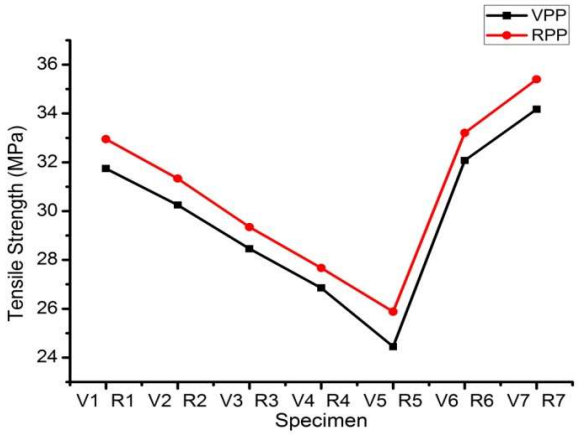

Figure 2. Tensile test of composites.

The increase of wood content in the polymer matrix reduces the strength of the composites from 30.25MPa (V2) to 24.45MPa (V5) and 31.34MPa (R2) to 25.88 MPa (R5).Incorporation of 3%wt MAPP in the matrix of the composite improves the tensile strength significantly as composite V6 (32.08MPa) and R6 (33.21MPa) have greater tensile strength than composites V5 (24.45MPa) and R5(25.88MPa). The increase of MAPP from 3%wt to 5%wt in the matrix increases the tensile strength 32.08 MPa (V6) to 34.18MPa(V7)and 33.21 MPa (R6) to 35.4 MPa (R7)[23]. The MAPP improved the interfacial bonding between wood particles and polymer which attributes to better tensile strength [11, 24,27].

3.2 Flexural strength test

Flexural strengths of the composites were recorded and plotted in Figure.3. The VPP and RPP polymer show the flexural strength of 48.50 and 50.59 MPa respectively. Virgin matrix based composite have maximum flexural strength 42.65MPa (V2) and minimum flexural strength 29.47MPa(V5). In the same way recycled matrix based composite have maximum flexural strength 44.23 MPa(R2) and minimum flexural strength 32.75MPa (R5). The observation reflects that increase of wood content in the matrix reduces the flexural strength of the composites. The flexural strength of virgin matrix based composites reduces from 42.65MPa (V2) to 29.47MPa (V5) and recycled matrix based composite reduce from 44.23 MPa (R2) to 32.75MPa (R5) due to the increase of wood content in the matrix. The brittleness of the composites increases as well as wood content increases in the polymer matrix. The results of flexural test confirmed that recycled polypropylene-based composite have higher flexural strength than virgin matrix based composite at the same composition [24].

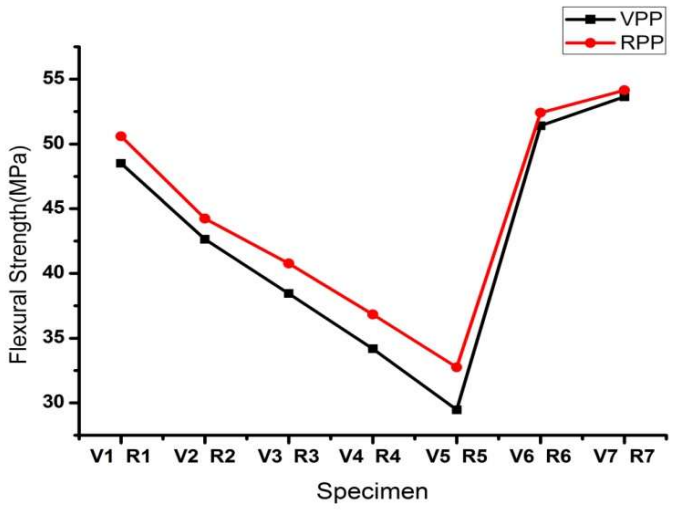

Figure 3. Flexural test of composites.

Flexural strength of VPP/RPP matrix based composites increased considerably by the addition of MAPP. The results show the flexural strength of V6 (51.41MPa) and R6 (52.41MPa) better than V5 (29.47MPa) and R5 (32.75MPa) after addition of 3%wt MAPP in the polymer. It has been observed that composites V7 (53.64MPa) and R7 (54.15MPa) show better strength than V6 (51.41 MPa) and R6(52.41 MPa) after addition of 5%wt MAPP in the polymer matrix. The MAPP increases the interfacial adhesion between wood and polymer, which show the positive effect on the flexural strength of the composite [25].

3.3 Impact test

The impact strength of the composite plotted in Figure 4. The plots refer that the impact strength of the composite made by virgin pp decreases continuously from 329.01 J/m (V2) to 168.33 J/m (V5) due to loading of wood content, similarly impact strength of recycled PP matrix composite decreases from 267.5 J/m (R2) to 132.89 J/m (R5).

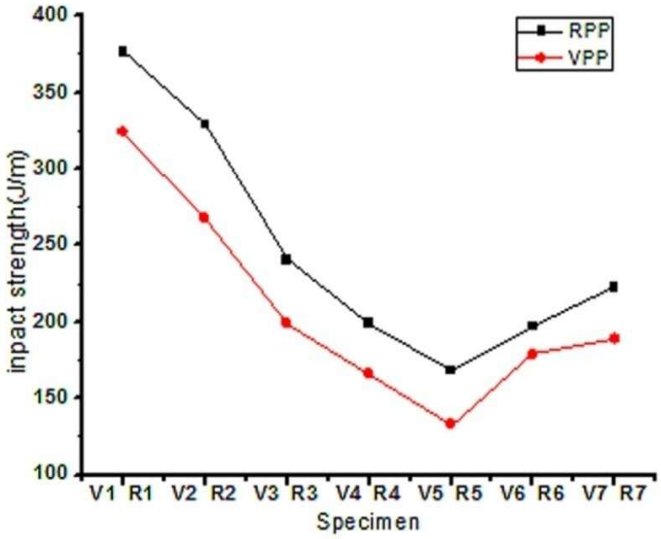

Figure 4. Impact test of composites.

It has been observed that VPP (376.54 J/m) has higher impact strength than RPP (323.76 J/m), likewise, VPP based composites have higher impact strength than RPP bases composites. Recycling of the polymer produces adverse effect on impact strength of the polymer. Impact strength of composites increases on addition of 3% MAPP in the matrix from V5 (168.33 J/m) to V6 (196.84 J/m) and R5 (132.89 J/m) to R6 (178.9 J/m). Composites V7 (222.5 J/m) and R7 (188.78 J/m) have better impact strength than V6

(196.84 J/m) and R6 (178.9 J/m), due to addition of 5%wt MAPP in the matrix. The coupling agent improves the impact strength of the composite significantly [25].

3.4 Hardness test

The results of hardness (Shore-D) test have been plotted in Figure 5. The hardness of VPP and RPP polymer was 60 and 62.1 respectively. The Figure shows that RPP matrix based composites have the maximum hardness of 70.7 and VPP matrix composite have the maximum hardness of 68.7. The minimum hardness of recycled and virgin PP matrix composites were 63.5 and 61.6. The hardness of the material increases with the increase of wood content in the polymer matrix [27].

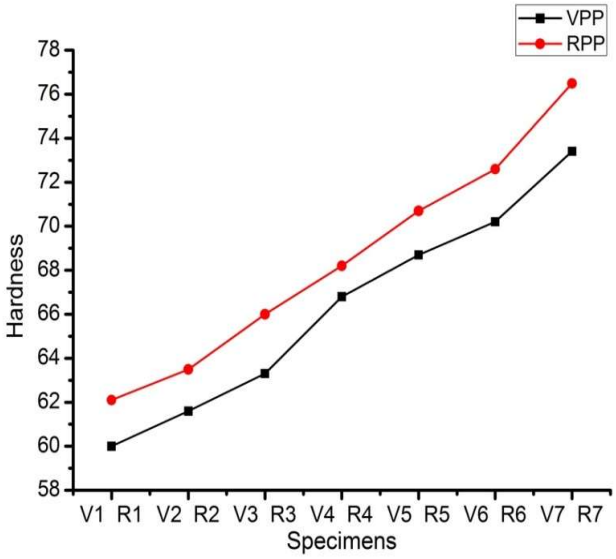

Figure 5. Hardness test of composites.

Addition of MAPP increases the hardness of composite having 3%wt MAPP in VPP(V6) and RPP(R6) matrix of hardness 70.2 and 72.6 respectively. The composite of VPP(V7) and RPP (R7) incorporated 5%wt MAPP have hardness 73.4 and76.5[28].

3.5 Melt flow index test

Melt flow index (MFI) of the compounded materials are plotted in Figure 6. The maximum MFI of virgin and recycled polypropylene are 13.5 g/10min (V1) and 10.32 g/10min (R1) respectively, RPP has lower melt flow index than VPP..

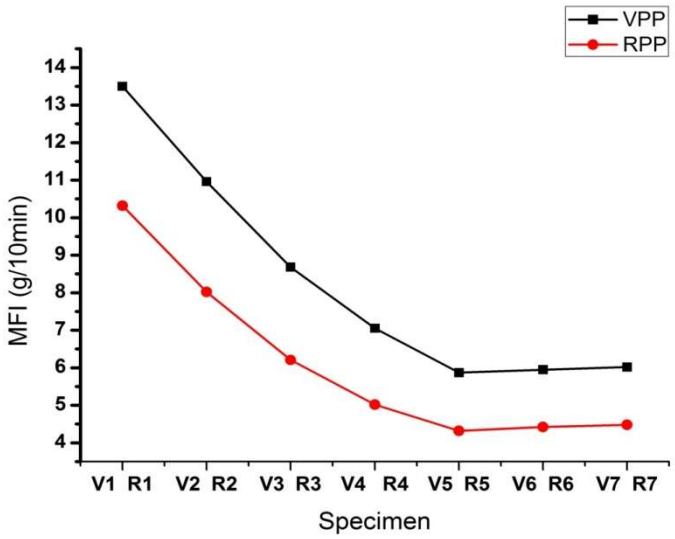

Figure 6. Melt flow index test of composites.

The minimum MFI of compounds V5 and R5 are 5.87 g/10min and 4.32 g/10min have been recorded. It has been illustrated that MFI of the VPP compounded material reduces from 10.96 g/10min (V2) to 5.87 g/10min (V5) and RPP compounded material reduces from 8.02 g/10min (R2) to 4.32(R5). The reduction in MFI of compounded material confirms that viscosity of the material increases as wood flour increases in the mixture. Addition of MAPP in the matrix increases the MFI of the compounds. The MFI increases from 5.87 g/10min (V5) to 5.95 g/10min (V6) in VPP compound and 4.32 g/10min (R5) to 4.42 g/10min (R6) in RPP compound by addition of 3%wt MAPP in the polymer. MFI increases from 5.87(V5) to 6.02 g/10min (V7) and 4.329 g/10min (R5) to 4.48 g/10min (R7) by addition of 5%wt MAPP in VPP and RPP compounds respectively. Cross-linking mechanism in the polymers takes place due to reprocessing of it. Cross-linking is a mechanism of making the covalent or ionic bond with another chain. Cross-linking of the polymers increases the density of the polymer. Due to cross-linking or molecular chain enlargement of the polymer the mobility of molecules decreases and viscosity increases which attributes to the reduction of MFI [23].

3.6 Water absorption test

The wood and plastics are not compatible with each other; therefore adhesion between wood and polymers is poor. This poor adhesion of wood and polymer promotes water absorption in WPCs. Water absorption in the WPCs occurs at the interface of wood and plastic. Water absorption test for all formulations of VPP and RPP matrix based composites with and without MAPP were conducted. The

percentages of water absorption by the composites have been calculated by using equation.1. The outcomes of 2h and 24 h experiment are given in the Figure 7. and Figure 8.

It has been observed that water uptake of the composites increased with the increase of wood filler in the composite. The VPP and RPP polymers show negligible water absorption during this investigation. The water absorbed by VPP and RPP during this experiment was 0.03% and 0.02% in 2h, similarly 0.06% and 0.05% for the 24h. The water absorption of VPP matrix composite varies from 0.09 to 1.65% for 2h test and from 0.28 to 5.17% for 24h period.

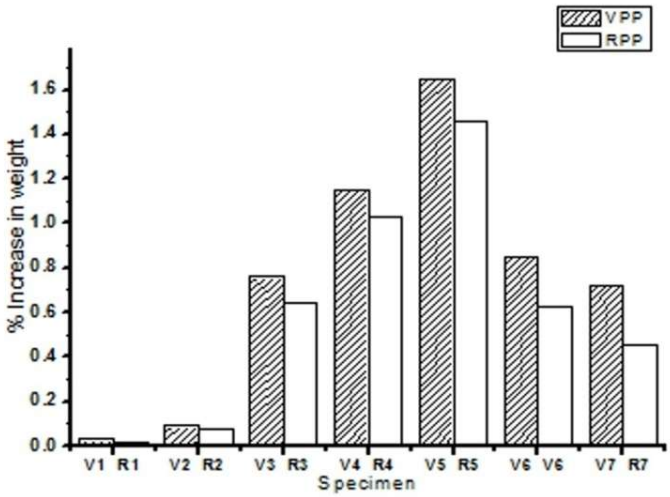

Figure 7. Water absorption test of composites for 2h.

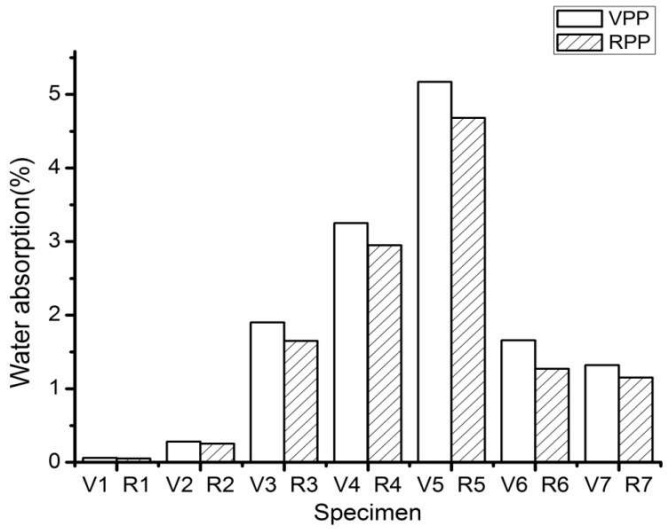

Figure 8. Water absorption test of composites for 24h.

Similarly, the water uptake by RPP matrix based composite in 2 h varies from 0.08 to 1.46% and for the 24h period from 0.25 to 4.68%. Water absorption is maximum for the composite produced by VPP with 50% of wood filler (V5). The RPP based composite show low water absorption than VPP based composite (R5) at the same wood content [11]. Addition of 3% or 5% MAPP in the polymer matrix reduces the water absorption significantly as shown in Figure(7&8).Reprocessing of polymer generates additional functional group and improves the adhesion between wood and plastic, which significantly reduces the water uptake of the composites [16].

Thickness of swell test

The thickness of swelling corresponds to water absorption of the composite due to poor encapsulation of wood flour by the polymer matrix. Thicknesses of the swell of all formulations are given in Figure 9 & 10. for 2h and 24h respectively. Initially, TS of the composite is high as water uptake by the composite is high.

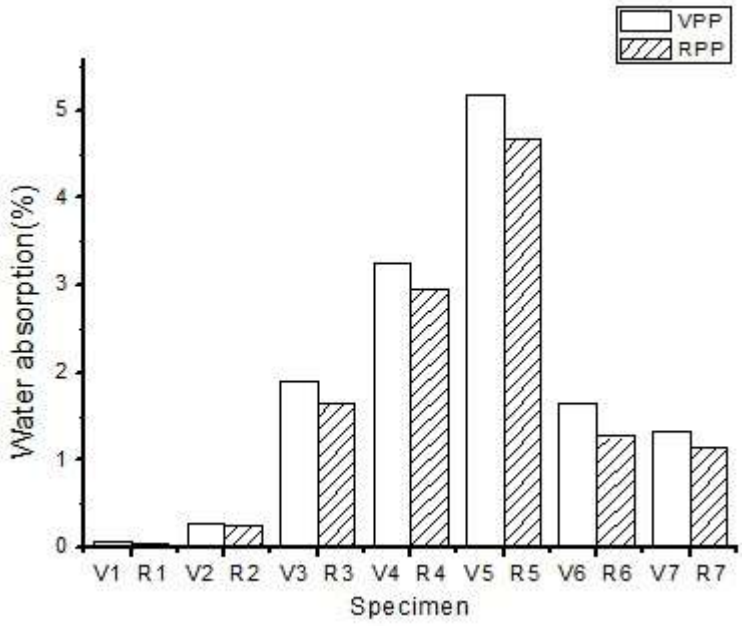

Figure 9. Thickness of swell test of composites 2h

Thickness swellings (TS) of the wood-PP composite were calculated by using the equation-2 in the experiment. The result confirms that 50:50 wt% wood flour–VPP composite (V5) show higher thickness of swelling, which corresponds to the highest water absorption. Thickness swelling of the composite increases with increase of wood content and follow the trend of water absorption. The thickness swelling in 2 h of the RPP matrix composite varies from 0.06 to 1.35% and VPP matrix composite from 0.05% to

1.48% (Figure 9.). Similarly in 24 h it varies from 0.21% to 4.35% for RPP matrix composite and 0.24% to 4.94% for VPP matrix composite (Figure 10.).

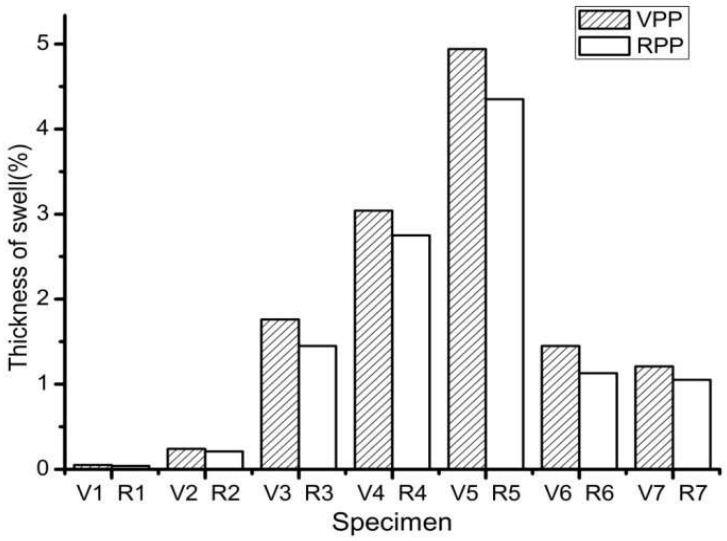

Figure 10. Thickness of swell test of composites 24h.

TS of the RPP matrix based composite (R5) is lower than VPP matrix bases composite (V5) in 2h (Figure 9.) and it reveal the similar trend in 24 h experiment (Figure 10).The experiment confirms that RPP matrix based composite exhibits low thickness of swell than VPP matrix based composite. TS of RPP and VPP matrix composite (R6,V6) reduce with incorporation of 3% of MAPP reduces the TS of RPP and VPP matrix composite from 1.35% (R5) to 0.61%(R6) and 1.48%(V5)to 0.68% (V6) for 2h test, similarly for 24hr test 4.35%(R5) to 1.13% (R6) and 4.94% (V5)to 1.45% (V6). In the case of 5% addition of MAPP in RPP and VPP composites, it reduces from 1.35 %(R5) to 0.57% (R7) and 1.48(V5) to 0.62% (V7) for 2h and 4.35%(R5) to 1.05%(R7) and 4.94%(V5) to1.21%(V7) for 24h respectively[11,26].

Microstructure characterization

The microstructure of the fractured tensile test specimen has been examined at 500X and 300 X magnifications. The image 11(a) and 11 (b) are the scans of composite V4 and R4 respectively at 300X magnification. It has been observed that wood particle is not properly encapsulated by the polymer in Figure 11 (a) at 300X magnification, which is responsible for higher water uptake.

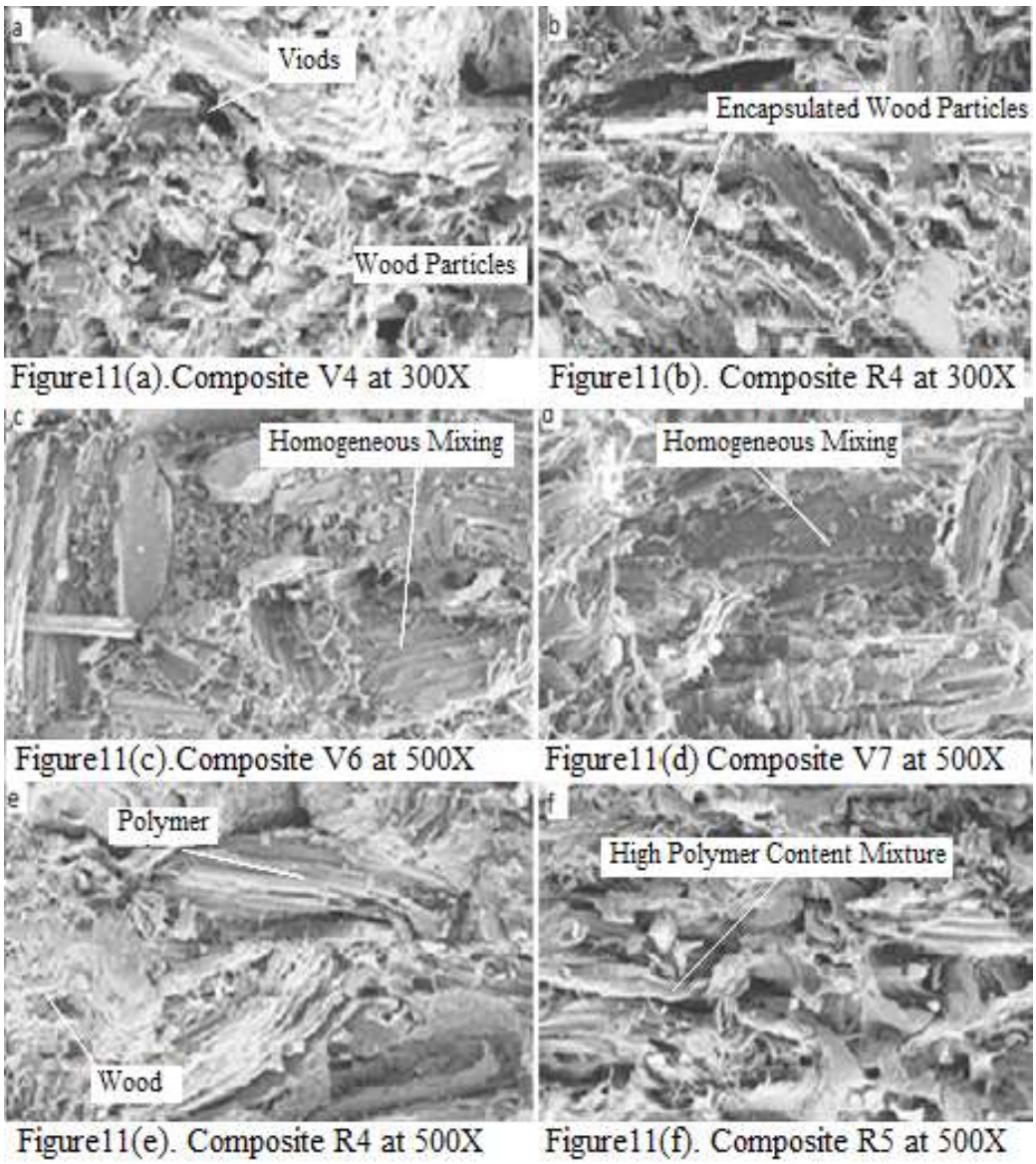

Figure 11. SEM scans of fracture surface

Voids are present in the scans, which were forms due to pulling of wood particle and light flairs show the flaw of the polymer composite. The presence of cluster and the small gap in the image confirm the inept adhesion of wood and polymer. This poor adhesion of wood and polymer exhibits poor mechanical, rheological and hygroscopic properties. The scan 11 (b) shows comparatively fine incorporation of wood and plastic in the composite. The distribution of the wood particle in the recycled matrix composite is uniform in compare to virgin PP matrix based composite in scans 11(a). The increment wood content in the matrix of the composite reduces the proper dispersion of it. The Figure.11 (e) R4 and 11 (f) R5 at 500X confirms the reduction in wood content increases the homogeneity of the composite. Proper dispersion of the wood particles in the composite enhances the mechanical, rheological and hygroscopic

properties of the composites. The incorporation of MAPP in the composite improves the adhesion properties of wood particles with polymer. Figures 11 (c) V6 and 11 (d) V7at 500X magnification confirms that coupling agent MAPP increase the interfacial bonding between wood and polymer by the formation of covalent bonds due to etherification mechanism. The improvement in the bonding of the wood and particle improve the mechanical rheological and hygroscopic properties of the composite.

4. Conclusions

This study investigated the mechanical, rheological, and hygroscopic properties of teak wood sawdust reinforced polypropylene composites prepared using virgin and recycled polypropylene.

The results showed that recycled polypropylene composites exhibited higher tensile strength, flexural strength, hardness, and improved dimensional stability compared to virgin polypropylene composites. However, their impact strength was slightly lower. Recycled polypropylene composites also demonstrated lower water absorption, thickness swelling, and melt flow index.

The addition of 3–5 wt.% MAPP significantly enhanced the overall performance of the composites by improving the interfacial bonding between wood particles and the polymer matrix. SEM analysis confirmed the improved compatibility and dispersion of wood particles in the presence of MAPP.Overall, recycled polypropylene reinforced with teak wood sawdust can be successfully used to develop lightweight, eco-friendly, and cost-effective wood–plastic composites with properties suitable for engineering and building applications.

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