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Microcellular Injection Molded Wood Fiber–PP Composites: Part II – Effect of Wood Fiber Length and Content on Cell Morphology and Physico-mechanical Properties

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ABSTRACT: Microcellular wood fiber reinforced PP composites, a new development using bio-fiber strengthened plastic, are prepared in an injection molding process. The microcellular composites with five different types of wood fibers (hard wood fiber, finer hard wood fiber, soft wood fiber, finer soft wood fiber, and long wood fiber) are examined. The influence of wood fiber content (30–60% by weight) on the microcellular properties is also investigated. Microcell morphology (cell size, shape, and distribution) is observed using optical light and scanning electron micrographs (SEMs).

The wood fiber length, geometry, and content strongly affected the microcellular structures of wood–PP composites. Composites with finer wood fibers possess better microcellular structures, and at a constant chemical foaming content, the higher percentage of wood fiber results in composites with smaller microcells. Due to the finer microcellular structures, finer wood fibers also result in improved physico-mechanical properties.

KEY WORDS: microcellular wood fiber–PP composites, fiber length and content, chemical foaming agent, injection molding, cell morphology.

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INTRODUCTION

Reinforced foamed polymeric materials offer a unique combination of low specific gravity, rigidity, and dimensional stability, and they exhibit excellent strength-to-weight ratios. The reinforced foam will also have higher heat capabilities, greater flexural strength, and better fatigue characteristics than a non-reinforced foam [1,2]. Incorporating the reinforcing filler actually improves the overall properties in two ways. The filler contributes to an increase in strength of the material and also acts as a nucleating agent to promote more uniform and complete cell formation.

Wood fiber as a reinforcing filler in plastic composites has been gaining acceptance because of advantages such as lower cost, improved stiffness, and better processibility compared to other fillers [3]. Incorporating a fine-celled structure into plastic–wood fiber composites can significantly reduce their weight. The foaming of wood fiber–plastic composites has enlarged the application of wood fiber–plastic composites by producing a number of benefits [4,5]. The growing markets call for high performance wood fiber–plastic composites with superior and unique properties to meet individual application requirements.

Still, concerning the length and geometry of cellulosic fibers, man-made fibers emerging from a spinneret are cylindrical with approximately constant diameter and specific area. This is not the case for cellulosic fibers that present many defects caused by twisting [6] in the stacking of the cellulose chains. These defects are apparent as 'knees' at the fiber surface and constitute points where the fiber may rupture more easily. In addition, an important parameter is the aspect ratio (length/diameter), which has an influence on the mechanical properties of the composite. The aspect ratios of wood, including its physical structure, mechanical properties, and density, change from species to species [7,8].

The influence of fiber length and geometry on physico-mechanical properties of non-foamed wood fiber reinforced PP composites was described in our previous study [9]. From the knowledge gained from those investigations, it was decided to investigate micro-cellular wood fiber–PP composites in injection molding process with different wood fibers (difference in length and geometry) and the cell morphology and physico-mechanical properties that resulted.

EXPERIMENTAL

Materials

Polypropylene (PP) [Stamylan P17M10 (melt flow index 10.5 g/10 min)] was provided as granules by DSM, Gelsenkirchen, Germany. A commercially available maleic anhydride–polypropylene copolymer (Licomont AR 504 FG, acid number 37–43 KOH mg/g) with 5 wt% to wood fiber was used as a compatibilizer. It was obtained from Clariant Corp., Frankfurt, Germany.

Hardwood fiber (HW) (Lignocel HBS 150-500) and soft wood fiber (SW) (Lignocel BK 40-90) with particle size of 150–500 μm, were supplied by J. Rettenmaier & Söhne GmbH+Co., Germany. Long wood fiber (LW) (particle size 4–25 mm) was obtained from Johnson Controls, Lüneburg, Germany. Finer hardwood fiber (FHW) (HAHO 150/30) with particle size of 180–300 μm and finer softwood fiber (FSW) (WEHO 500) with particle size of 75–300 μm were supplied by Jelu-werk Ludwigsmühle, Rosenberg, Germany.

To get foamed wood fiber reinforced composites, exothermic (Hydrocerol 530) and endothermic (BIH 20) chemical foaming agents (CFA) were used (Clariant Masterbatch GmbH & Co. OHG, Ahrensburg, Germany). The effective component was 50 and 20%, respectively, and the remainder was carrier polymer. The average gas yield was 120 mL/g for exothermic and 20 mL/g for endothermic CFA.

Processing and Foaming

Wood fibers with PP were mixed in a high speed mixer (Henschel Mixer, type HM40 KM120) with and without coupling agent. All wood fibers were dried at 80°C in an air circulating oven for 24 h (moisture content <1%) before mixing. The high speed mixer was preheated to 180°C, and the speed of the rotors was set to 2200 rpm, and the mixing time was 12–15 min. Cold agglomerate granules were then mixed with different CFAs. Before foaming in the injection mold, the mixed granules were dried at 80°C for 24 h. The specimens [200 × 90 × 4 mm in size] of different wood fibers foamed composites were prepared by an injection molding process at melting temperature about 150–180°C, mold temperature of 80–110°C and under an injection pressure of 20 kN/mm^2.

Measurements

The tensile and flexural tests (Zwick Machine, UPM 1446) were conducted at a test speed of 2 mm/min, according to EN ISO 527 and EN ISO 178, for all wood fiber–PP composites. All tests were investigated at a temperature of 23°C under a relative humidity of 50% and five to eight samples were used for each test. The densities of non-foamed and microfoamed specimens were measured according to DIN 53479. Fifteen replicates were conducted for each treatment. The microvoid content was calculated according to the standard ASTM D 2734-70 for foamed composites. In all experiments, values within a standard deviation of less than 10% were used to measure the mechanical properties.

SEM and Light Microscopy

The morphology of the wood fiber reinforced microcellular PP composites and the cell size, shape, and distribution of microcells in microfoamed composites were investigated using scanning electron microscopy (SEM) (VEGA TESCAN) and a light microscope. Cross sections of sanded and polished surfaces were studied with the light microscope. Fractured surfaces of flexural test samples were observed with SEM after coating with gold.

RESULTS AND DISCUSSION

Cell Morphology

The microcellular structure of HW and FHW fiber–PP composites is presented in Figure 1. The influence of wood fiber length on the structure and size of the microcells in a surface was observed by SEM micrographs. As shown, the wood fiber–PP microcellular structure is a three layer sandwich structure in the injection molding process. Figure 1 illustrates that there is a fine microcellular core in the middle area with compact outer hull. The finer and better cell size distribution appears to be greater with FHW fiber compared to HW fiber. The FHW fiber possesses round cells, whereas cells are oval with HW fiber (Figure 2) and the maximum cell size appears to be 100 μm. It seems that the small size of wood fiber particles gives more surface area, which provides more nucleation for the expansion of gas. It means that finer wood fibers are easier to use in foaming, and one can reduce the CFA content to get finer microcellular composites.

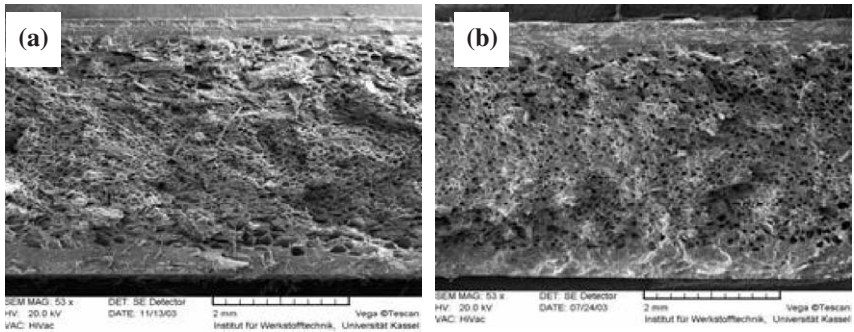

Figure 1. SEM micrographs of hard wood fiber–PP microcellular composites: (a) HW and (b) FHW, exothermic foaming agent 2 wt%, wood fiber content 30 wt%.

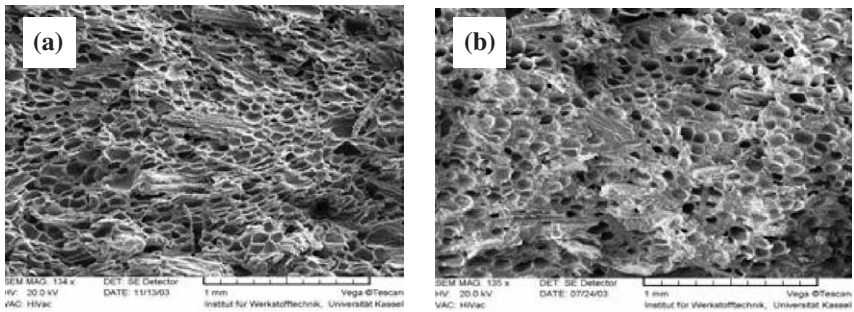

Figure 2. SEM micrographs of hard wood fiber–PP microcellular composites (higher magnification): (a) HW and (b) FHW, exothermic foaming agent 2 wt%, wood fiber content 30 wt%.

Figure 3 represents the influence of wood fiber particle size on the foaming agent content of HW fiber–PP microcellular composites. Figure 3(a) represents the HW fiber–PP microcellular composites with endothermic foaming agent (2 wt%), where it is seen that the number of cells are very few (it is nearly a non-foamed composite). But in Figure 3(b) with FHW fiber particles, it is clearly seen that microcells are distributed up to the boundary layer, and the number of cells are also increased. It is also notable that FHW fiber shows cell size bigger than standard HW fiber. It seems that a lower percentage of CFA content will be needed to get the finer structure. This foaming agent and its content of FHW fiber are better than standard HW fiber to achieve a finer microcellular structure.

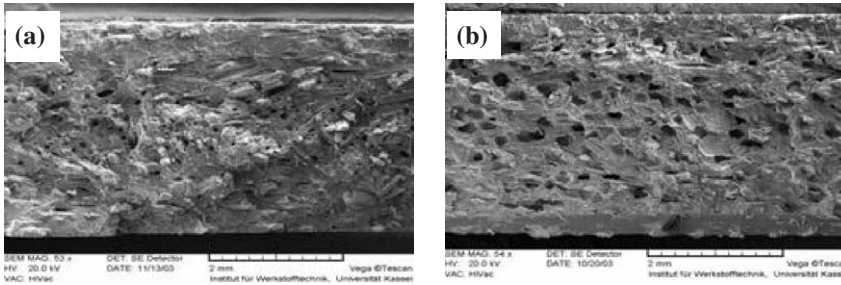

Figure 3. Influence of wood fiber length on the chemical foaming agent content: (a) HW fiber and (b) FHW fiber, endothermic foaming agent 2 wt%, wood fiber content 30 wt%.

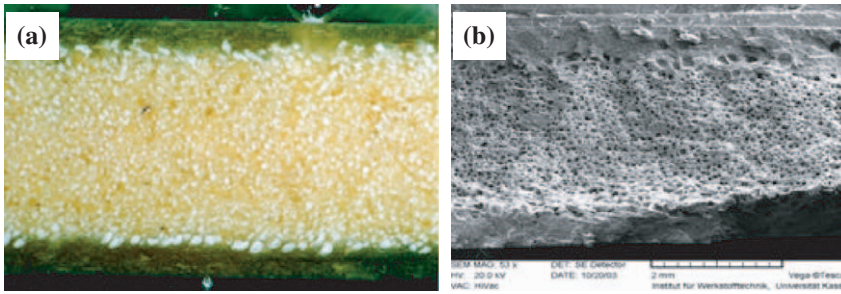

Figure 4. The microcellular structure of finer soft wood fiber–PP composites: (a) optical light micrograph and (b) SEM micrograph, exothermic foaming agent 2 wt%, wood fiber content 30 wt%.

The microcellular structure of FSW fiber–PP composites is illustrated in Figure 4. From the optical light and SEM micrographs, it can be clearly seen that cell size and shape is finer, similar, and distributed more uniformly compared to FHW fiber microcellular composites (Figure 1(b)). The maximum cell size is nearly 50 μm. Possibly the bulk density (170–230 g/L) of SW fibers which is lower than the bulk density of HW fibers (190–270 g/L) affects the structure.

The effect of wood fiber content on the microcellular composites is presented in Figure 5. Figure 5 illustrates the microcellular structures of LW fiber–PP composites with wood fiber of 40, 50, and 60 wt% content. With 40 wt% wood fiber content, the cells are comparatively bigger and fewer. With increasing wood fiber content, it is seen that with 50 wt% wood fiber content, the cells are much finer, and the number of cells increases. In the case of 60 wt% wood fiber content, the cells are finer but the of number of cells decreases. This indicates that increasing the wood fiber content enables the wood fiber to encapsulate the gas

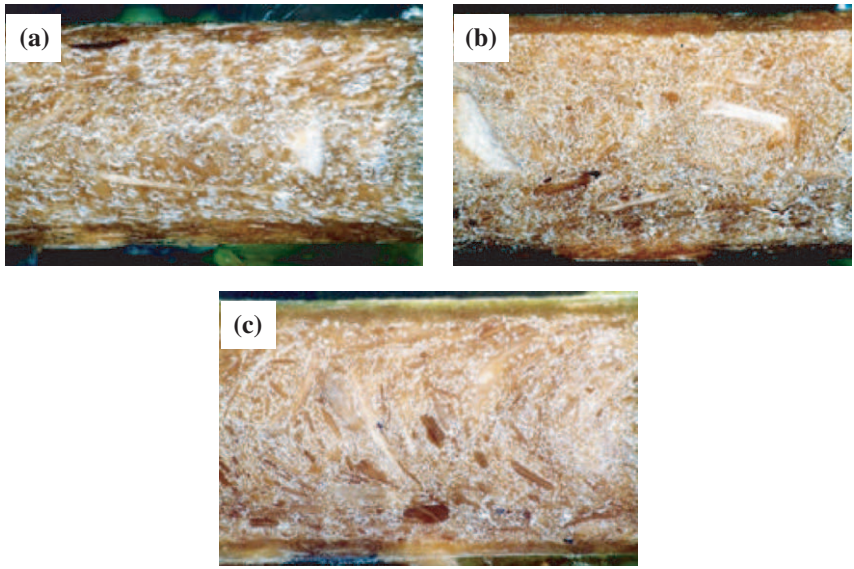

Figure 5. Light micrographs of long wood fiber–PP microcellular composites: (a) 40 wt%; (b) 50 wt%; and (c) 60 wt% wood fiber, exothermic foaming agent 4 wt% content.

molecule and cause the formation of finer cells. But when the wood fiber content is about 60 wt%, then LW fibers occupy the space and reduce the number of cells, which is observed in Figure 5(c). It is also observed that longer and bigger wood fibers do not interact with PP. This is seen as a separate cell size distribution.

Density

The density was measured for HW, FHW, SW, and FSW fiber–PP microcellular composites, and compared to non-foamed composites. This is summarized in Figure 6. The exothermic foaming agent was used at a 2 wt% content. The density of FSW fiber–PP microcellular composites was reduced the most and was around 25%.

Mechanical Properties

The specific tensile and flexural properties were also measured for HW, FHW, SW, and FSW fiber microcellular composites. Figure 7 shows the specific tensile strength for all types of wood fiber–PP microcellular composites compared with their non-foamed composites. Figure 7 also

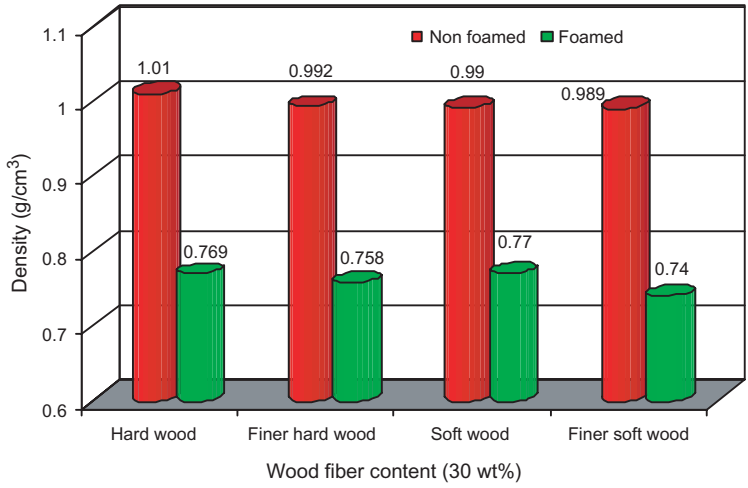

Figure 6. Influence of fiber type and length on the density of different wood fiber–PP composites (wood fiber content 30 wt%, exothermic foaming agent 2 wt% content).

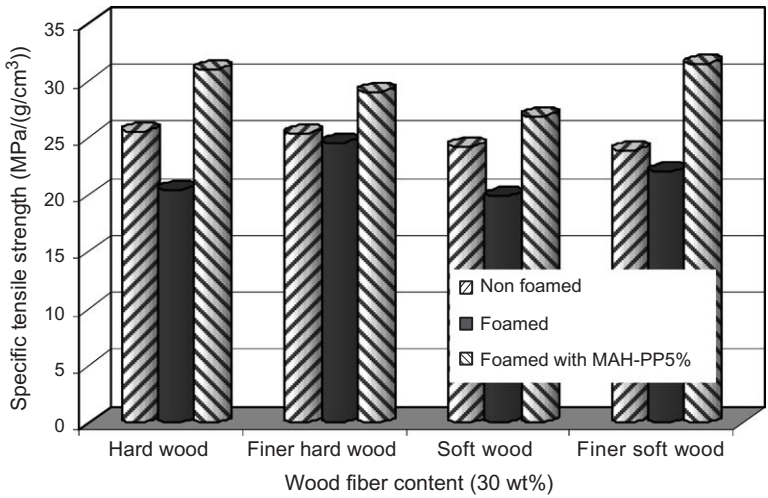

Figure 7. Specific tensile strength of different wood fiber–PP microcellular composites (wood fiber content 30 wt%, exothermic foaming agent 2 wt% content).

represents the influence of coupling agent MAH-PP5% content on the property. In all cases, wood fiber 30 wt% content was used. From the figure, it is seen that HW fiber–PP non-foamed composites show higher specific tensile strength than the others. As usual, due

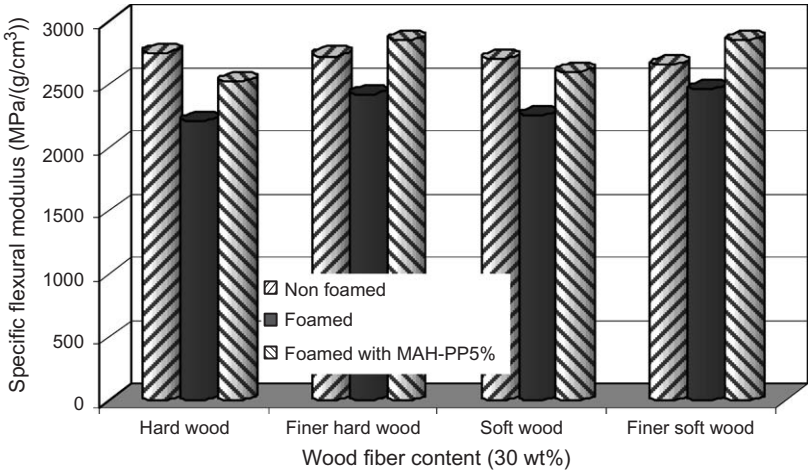

Figure 8. Specific flexural modulus of different wood fiber–PP microcellular composites (wood fiber content 30 wt%, exothermic foaming agent 2 wt% content).

to the microfoaming (without MAH-PP) the specific tensile strength was reduced in all cases. But in the case of FHW and FSW fiber–PP microcellular composites, the reducing tendency is not significant. All wood fiber–PP microcellular composites show higher strength with the addition of MAH-PP5% content. The microcellular composites with FSW fiber show the highest specific tensile strength due to their finest microcellular structure. In our previous experiment [10], it was already seen that coupling agent MAH-PP has a positive influence on the microcellular structure of the wood fiber reinforced PP composites; that means finer microcellular composites show higher mechanical properties.

The specific tensile modulus and also specific flexural strength of these wood fiber–PP microcellular composites followed the same trend as specific tensile strength as described here. The specific flexural modulus for these composites is presented in Figure 8. Figure 8 illustrates that for all types of wood fiber–PP solid and microcellular composites, specific flexural modulus is nearly the same. The FHW and FSW fiber–PP microcellular composites with the addition of MAH-PP5% show higher specific flexural modulus than their non-foamed composites, whereas for HW and SW fiber–PP microcellular composites, specific flexural modulus could not overcome that of their non-foamed composites.

The three-dimensional diagrams that represent the optimization of mechanical properties of HW fiber–PP microcellular composites were

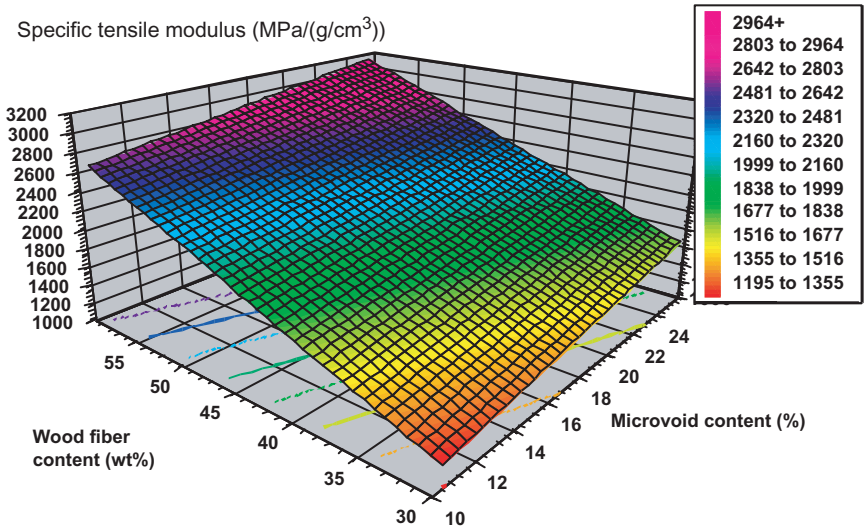

Figure 9. Three-dimensional diagram of specific tensile modulus with the effect of wood fiber and microvoid content (exothermic foaming agent content 3 wt%).

determined by the RESINT program [11,12]. The influence of wood fiber content (30–60 wt%) on the specific tensile modulus and flexural strength are presented. Figure 9 shows the three variables diagram of specific tensile modulus with a variation in wood fiber content and microvoid content. Figure 9 illustrates that with the increase in wood fiber and microvoid content, specific tensile modulus also increases linearly. Specific flexural strength decreases linearly with the increasing of wood fiber and microvoid content (Figure 10).

CONCLUSIONS

Five types of wood fiber (HW, FHW, SW, FSW, and LW fiber), at 30, 40, 50, and 60% each by weight were used to prepare microcellular wood fiber reinforced polypropylene composites. The effect of fiber type and length on the performance of microcellular wood fiber–PP composites was investigated. From this investigation, the following points can be drawn.

1. The wood fiber length, geometry, and content strongly affect the microcellular structures. Composites containing finer wood fibers possess better microcellular structures due to the small size of the wood particles, which provides more space for the expansion of gas.

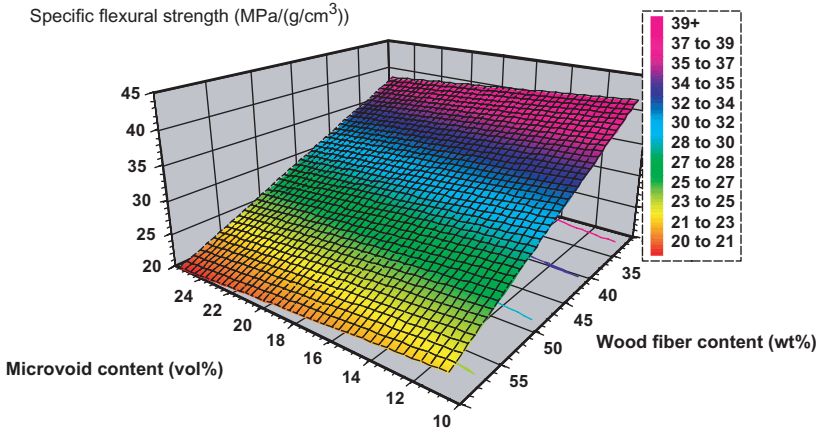

Figure 10. Three-dimensional diagram of specific flexural strength with the effect of wood fiber and microvoid content (exothermic foaming agent content 3 wt%).

2. Density was reduced in finer hard and soft wood fiber–PP microcellular composites, compared to non-foamed composites; the maximum density reduction was around 25%. The FSW fiber composites showed greater density reduction compared to the FHW fiber composites.
3. The FSW fiber microcellular composites showed higher mechanical properties with the addition of MAH-PP due to their finer microcellular structure.
4. With the three-dimensional diagram, the mechanical properties of the microcellular composites can be optimized considering the variation in wood fiber content, which represents the increasing or decreasing tendency of mechanical properties, as well as the influence of microvoid content.

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