Physical and mechanical properties of five Indonesian wood treated with polystyrene

I Budiman1*, R Purnawati2, H Siruru3 and Y S Hadi4)

1Research Center for Biomaterials, Indonesian Institute of Sciences, Cibinong Science Center, Cibinong-Bogor, Indonesia
2Papua University, Manokwari, Papua Province, Indonesia
3Pattimura University, Ambon, Maluku Province, Indonesia
4Forest Product Department, Faculty of Forestry, IPB University, Bogor, Indonesia

*Email: budimanismail@gmail.com; ismail.budiman@lipi.go.id

Abstract. Five Indonesian wood include sengon (Falcataria moluccana), manii (Maesopsis eminii), pinus (Pinus merkusii), duabanga (Duabanga mollucana) and maniani (Flindersia pimenteliana) were treated with polystyrene. The purpose of this study was to determine the physical and mechanical properties of treated wood. Air-dried samples were placed under vacuum at 600 mmHg for 30 minutes, which was followed by immersion in monomer styrene and pressure at 10 kg/cm² used varied for 30, 60, and 90 minutes respectively. The wood samples were then wrapped in aluminium foil and placed in an oven at 103±2 °C for 24 hours. Furthermore, the aluminium foil was removed and the samples were weighed for polymer loading calculation. The test of impregnated wood conducted by refers to the British Standard BS 373:1957, comprised of moisture content, density, water absorption, shrinkage swelling, modulus of rupture, modulus of elasticity, and hardness. Results showed that wood treatment with polystyrene could improve the physical and mechanical properties of wood.

1. Introduction

The existence of industrial plantations in meeting the demand for wood for industry and society in Indonesia is currently higher, along with the decreasing quantity of natural forests. Planting of industrial forest plantations with fast-growing plants can meet most of the needs of the timber industry and the wider community. But there are obstacles in the use of fast-growing wood that is used for wood needs that require high strength. Some wood grown is planted in industrial plantations such as jabon (Anthocephalus cadamba Miq.), sengon (Falcataria moluccana), mangium (Acacia mangium Willd.), and gmelina (Gmelina arborea Linn.) which are harvested at less age of 10 years has disadvantages compared to mature wood in terms of physical properties, mechanical properties, and resistance to wood-damaging pests such as termites. One way to overcome the low physical and mechanical properties of fast-growing wood can be done by modifying wood by impregnating it using impregnation material, which can improve the physical and mechanical properties of wood [1].

Wood-polymer composites result from the polymerization of liquid monomers or oligomers already impregnated in the wood. Wood porous structure, composed of lignin, cellulose, and hemicellulose, is filled with a solid, plastic and fairly hard substance. In principle, WPCs should display superior
mechanical properties, dimensional stability, greater resistance to chemical and biological degradation, and less moisture absorption than non-impregnated wood. WPC production necessarily goes through two different phases: impregnation with a monomer/oligomer, followed by its polymerization inside the wood.

Previous research on wood impregnation used a variety of different materials, including water [1,2], the combination of citric acid with glycerol [3], tannin [4], methyl methacrylate [5,6], borax [7], benzoyl peroxide [5], and styrene or polystyrene [5,7–11]. Specifically, in research aimed at improving the physical and mechanical properties of wood, the use of different impregnation materials has different effects on the physical and mechanical properties of the wood. The use of methyl methacrylate as an impregnation material can significantly improve the physical and mechanical properties of wood [6]. Other studies suggest that the use of styrene, methyl methacrylate, and benzoyl peroxide as impregnation agents cannot significantly improve physical and mechanical properties of Eucalyptus grandis wood, but can significantly increase physical and mechanical properties of Pinus caribaea wood [1]. This shows that the increase in physical and mechanical properties of impregnated wood is influenced by the anatomy of the wood and its compatibility with the impregnation material [1]. Another factor that affects the physical and mechanical improvement of impregnated wood is the processing time. Some studies use different times to impregnate the material into the wood. The 30 minute impregnation time was carried out on the styrene impregnation process using a vacuum at 600 mm Hg for 30 minutes, followed by immersion in the styrene monomer with a pressure of 10 kg/cm² (7,11). Different things occur with soaking wood in a styrene solution at room temperature which takes up to 8 days [12].

In this research, the impregnation of the five types of wood that is sengon (Falcataria moluccana), manii (Maesopsis eminii), pinus (Pinus merkusii), duabanga (Duabanga mollucana) and maniani (Flindersia pimenteliana) was conducted using styrene equipped with tert-butyl perbenzoat (TBPB ), with variations in the time of impregnation for 30, 60, and 90 minutes. The purpose of this study was to determine the effect of impregnation on the physical and mechanical properties of the wood, as well as to investigate the interaction between wood species and the impregnation time on the physical and mechanical properties of wood.

2. Materials and Methods

2.1. Wood specimen preparation

Wood from sengon, manii, pinus obtained from Bogor, West Java, while duabanga and maniani from Maluku Province. The size of test specimens was 2 x 2 x 2 cm for physical properties test (moisture content and density), 28 x 2 x 2 cm for bending test (Modulus of rupture/MOR and modulus of elasticity/MOE), and 10 x 2 x 2 cm for hardness test. The air-dried specimens were weighed prior to styrene impregnation. Styrene liquid and catalysts were purchased from CV. Abdi Abadi (Bogor, West Java, Indonesia). Impregnation of the wood with polystyrene was conducted by placing air-dried specimens under vacuum at 600 mmHg for 30 minutes, followed by immersion in monomer styrene at 10 kg/cm², with varied time for 30, 60 and 90 minutes, after which they were brought to 1 atmospheric pressure. The wood samples were then wrapped with aluminium foil and placed in an oven at 103±2 °C for 24 hours. The aluminium foil was removed and each sample was weighed for polymer loading calculation. Four samples of each species and each time of immersion, yielding a total of 60 samples.

2.2. Physical and Mechanical Testing

Method of physical and mechanical testing of polystyrene wood was conducted by the British Standard BS 373:1957 (methods of testing small clear specimens of timber). Physical testing including density and moisture content, and for mechanical testing including modulus of rupture (MOR), modulus of elasticity (MOE), and hardness.

2.3. Statistical Analysis

To know the interaction between species and impregnation time, the data were analyzed by using a 5x3 factorial in a completely randomized design. The first factor was a wood species, namely sengon, manii,
pinus, duabanga, and maniani, and the second factor was impregnation time, namely 30, 60, and 90 minutes. Further analysis for each factor was conducted if the factor was significantly different.

3. Result and Discussion

The results of the study consisted of the physical properties of wood before and after impregnation using styrene and TBPB catalysts, which consisted of density and moisture content, supplemented by the amount of polymer loading that occurred in the wood. Besides, the mechanical properties of wood before and after impregnation are obtained, consisting of modulus of rupture (MOR), modulus of elasticity (MOE), and hardness.

3.1 Polymer loading and physical properties of wood

The values of polymer loading, density, moisture content of untreated and treated wood are shown in Table 1. The highest average loading polymer value was obtained by duabanga wood with an impregnation time of 90 minutes which was 28.469%. Whereas the lowest polymer loading value was obtained by maniani wood with an impregnation time of 30 minutes which was 0.869%. Compared to the other types, the lowest polymer loading value for all times was performed by maniani wood. During the impregnation process, styrene enters the wood cavity in the form of lumen or voids by replacing water and air that was previously in the wood cavity because it is pushed by the pressure applied to the reactor. The retention of the impregnated material in the cell wall is not always due to the formation of chemical bonds between the impregnated material and the cell wall polymer [13]. Furthermore, styrene will be polymerized to form hard polystyrene due to the giving heat to the reactor. Therefore, the percentage value of polymer loading of wood is influenced by the anatomical structure and wood density. The average value of untreated wood density from the lowest to the highest is 3.192 g/cm³, sengon (0.271 g/cm³), pinus (0.438 g/cm³), and maniani (0.499 g/cm³) (Table 1). The impregnation process using styrene monomers in wood can increase the density of all wood used. This increase in wood density results from the inclusion of styrene monomers in wood cavities (lumen and voids), and the polymerization of styrene to polystyrene due to the high temperatures applied to the wood from the reactor used. This styrene polymerization results in increased wood density. This increase is in line with the large percentage of styrene entering the wood. The highest increase in density was obtained by pinus wood with an average increase in percentage between 26.94-55.48%, while the lowest density increase was obtained by manii with an average increase in density of 0.82-2.17%. The increase in the density of *Pinus merkusii* wood is almost the same as the increase in density in Southern pine wood which rises from 0.487 g/cm³ to a density of 0.792 g/cm³, or the percentage increase in density reaches 62% [12]. The average moisture content of untreated wood from the lowest to the highest is as follows duabanga (14.980%), maniani (16.181%), manii (16.190%), pinus (16.516%), and sengon (16.796%). The value of wood moisture content is reduced considerably after an impregnation process using styrene, with a decrease of 41.69% (maniani wood at 60 minutes of impregnation), and 70.53% (manii at 60 minutes of impregnation). The decrease in moisture content in impregnated wood is caused by the degradation of water and air during the impregnation process on wood and replaced by the presence of styrene.

### Table 1. Density and moisture content, and polymer loading of treated wood

| Species   | Impregnation time (min) | Polymer loading (%) | Density (g/cm³) | Moisture content (%) |
|-----------|-------------------------|---------------------|----------------|----------------------|
| Duabanga  | 0                       | -                   | 0.238 ± 0.023  | 14.980 ± 0.634       |
|           | 30                      | 6.402 ± 3.417       | 0.298 ± 0.048  | 7.690 ± 0.379        |
|           | 60                      | 5.547 ± 1.153       | 0.275 ± 0.036  | 8.409 ± 0.132        |
|           | 90                      | 28.469 ± 7.08       | 0.327 ± 0.028  | 7.307 ± 0.132        |
3.2 Mechanical properties of wood

The values of modulus of rupture (MOR), modulus of elasticity (MOE), and hardness of untreated and treated wood are shown in Table 2. The mechanical properties of impregnated wood are better than untreated wood. This occurs because the impregnated wood has a higher density than the untreated wood. This higher density resulting from the polymerization of styrene into polystyrene in the wood cavities, caused by the applying of heat and a catalyst in the impregnation process.

The MOR value average of untreated wood starting from the lowest to the highest are as follows sengon wood (25.801 MPa), duabanga (26.045 MPa), manii (48.084 MPa), pinus (59.368 MPa), and maniani (88.044 MPa). The MOR average value of wood increased after the impregnation process using styrene. This increase occurs along with an increase in the density of impregnated wood. The percentage increase in the average value of MOR is as follows sengon (16.65-28.94%), duabanga (54.31-108.16%), manii (1.01-5.72%), pinus (39.01-71.75%), and maniani (18.51-32.29%).

**Table 2.** Modulus of rupture, modulus of elasticity, and hardness of wood

| Species   | Impregnation time (min) | MOR (MPa) | MOE (GPa) | Hardness (MPa) |
|-----------|-------------------------|-----------|-----------|----------------|
| Duabanga  | 0                       | 26.045 ± 5.14 | 4.684 ± 0.887 | 9.721 ± 3.241 |
|           | 30                      | 40.190 ± 18.366 | 5.942 ± 0.935 | 15.621 ± 0.748 |
|           | 60                      | 54.216 ± 1.689 | 6.701 ± 0.454 | 14.369 ± 2.724 |
|           | 90                      | 41.652 ± 17.861 | 6.516 ± 0.397 | 13.428 ± 1.013 |
| Sengon    | 0                       | 25.801 ± 5.622 | 3.957 ± 0.410 | 10.018 ± 3.979 |
|           | 30                      | 33.269 ± 6.284 | 4.489 ± 0.567 | 11.083 ± 2.823 |
Similar to MOR, the average value of lumber MOE increased after the impregnation process using styrene, along with the increasing density of the wood. The average value of MOE of untreated wood ranging from lowest to highest was obtained by sengon wood (3.957 GPa), duabanga (4.684 GPa), manii (6.174 GPa), pinus (7.588 GPa), and maniani (9.082 GPa). The percentage increase in the average value of MOE is as follows sengon (2.27-13.44%), duabanga (26.86-43.06%), manii (2.04-15.47%), pinus (22.61-34.96%), and maniani (10.37-16.76) %).

The average hardness value of untreated wood starting from the lowest to the highest was obtained by duabanga wood (9.721 MPa), sengon (10.018 MPa), manii (17.026 MPa), pinus (30.534 MPa), and maniani (35.525 MPa). The average value of wood hardness increases after the impregnation process using styrene. This increase in hardness occurs along with the increased density of impregnation wood. The large increase in the hardness average value in a row as follows duabanga (38.13-60.69%), sengon (1.43-21.09%), manii (14.38-36.92%), pinus (66.02-87.35%), and maniani (2.16-7.94) %. Impregnated pinus wood has a higher hardness value compared to impregnated maniani wood. This shows that the effect of increased density due to the impregnation of styrene in pinus wood was greater than in maniani wood.

3.3 Statistical analysis
Analysis of variance (ANOVA) of the relationship between independent variables (wood species and impregnation time), in its effect on the response, in this case, the physical and mechanical properties, was carried out with the aim to determine the interaction between the two independent variables with the response (Table 3). The results showed that there was an interaction between wood species and impregnation time of the physical and mechanical properties of wood, except for MOR and MOE. This shows that the different types of wood and different impregnation times simultaneously have a significant effect on the polymer loading, density, moisture content, and hardness of impregnated wood. For MOR, the different types of wood and the time of impregnation each have a significant influence on the value of the MOR. This is different from MOE where the value is only influenced by the difference in the type of wood impregnated. Analysis of variance results is shown in Table 3.
Table 3. Analysis of variance results (F test)

| Respond        | Species | Impregnation period | Interaction |
|----------------|---------|---------------------|-------------|
| Polymer loading| 34.14** | 6.15*               | 20.13**     |
| Density        | 159.01**| 10.73**             | 4.47**      |
| Moisture content| 22.67** | 1133.28**         | 16.67**     |
| MOR            | 73.69** | 5.13*               | 1.65ns      |
| MOE            | 33.75** | 2.35ns              | 0.56ns      |
| Hardness       | 117.57**| 8.09**              | 2.73*       |

Notes: *significant effect ; **very significant

The pattern of interaction between wood species with the impregnation time in their effect on polymer loading is significant as found in Figure 1. The effect of impregnation time on polymer loading is different for each wood species. The impregnation time pattern in duabanga wood is quadratic, meaning that it reaches the minimum value at the 60 minutes of impregnation time and rises to the 90 minutes impregnation. The impregnation time pattern in maniani is flat, indicating that there is no equal effect for all the impregnation time differences in polymer loading. The impregnation time pattern in manii and pinus wood are quadratic with a maximum value at 60 minutes impregnation. The impregnation time pattern in sengon is exponential, where the longer the impregnation time will cause the smaller polymer loading value.

The pattern of interaction between wood species and impregnation time in their effect on density is significant, as found in Figure 2. The effect of impregnation time on wood density is different for each wood species. The impregnation time pattern in duabanga is cubic, meaning that there are two turning points where there is an increase from the impregnation time of 0 minutes to 30 minutes, hence the density decreases towards the 60 minutes, and rises again to the 90 minutes impregnation time. The impregnation time pattern in maniani and manii is flat, showing that there is no equal effect for all impregnation time differences in wood density. The impregnation time pattern in pinus is linear, in which the longer impregnation time will lead to higher density. The impregnation time pattern in sengon is quadratic, which reaches a maximum density at an impregnation time of 30 minutes.

![Figure 1. Interaction plot of polymer loading](image)
The interaction pattern between wood species and the time of impregnation in their effect on moisture content is significant as found in Figure 3. The effect of impregnation time on moisture content differs between wood species. The impregnation pattern in duabanga wood is cubic, meaning that there are two turning points where there the moisture content decrease from the impregnation time of 0 minutes to 30 minutes, then rises to the 60 minutes, and down again until the 90 minute impregnation time. The impregnation time pattern in manii and sengon are quadratic with a minimum of moisture content at 60 minutes of impregnation time. The impregnation time pattern in pinus and maniani is exponential, in which the longer impregnation time will lead to a decrease in the average moisture content.

The interaction pattern between wood species and the time of impregnation in their effect on MOR and MOE is not as significant as in Figure 4 and Figure 5. Although there are interactions in some species and the time of impregnation, they are not significant.
The pattern of interaction between wood species and impregnation time in their effect on hardness is significant as found in Figure 6. The effect of impregnation time on the value of the hardness differs between wood species. The impregnation pattern in pinus, maniani, manii, and sengon is cubic, meaning that there are two turning points where an increase from 0 to 30 minutes impregnation time, then the hardness decreases to the 60 minutes impregnation time, and rise again until the 90 minutes impregnation time. The impregnation time pattern in duabanga is quadratic, with a maximum value of hardness at an impregnation time of 30 minutes.
4. Conclusion
The impregnation process using styrene monomers and tert-butyl perbenzoate catalyst in five different wood species succeeded in improving the physical and mechanical properties of the wood. Meanwhile, there is a significant interaction between the differences in wood species and the impregnation time of the polymer loading, density, moisture content, and hardness. Moreover, it can be concluded that the low-density wood tends to be easier to be given impregnation treatment.

Author contributions. All authors contributed equally to this work and discussed the results and implications and commented on the manuscript at all stages.

References
[1] Stolf DO and Lahr FAR 1992 Mater. Res. 7 617.
[2] Zhao Y, Wang Z, Iida I and Guo J 2018 J. Wood Sci. 64 556
[3] Zhao Y, Zhao X, Iida I and Guo J 2019 J. Wood Sci. 65 28
[4] Berube MA, Schorr D, Ball RJ, Landry V and 2018 J. Polym. Envir. 26 979
[5] Tondi G, Thevenon MF, Mies B, Standfest G, Petutschngg A and Wieland S 2013 Wood Sci. Technol. 47 615–26
[6] Hadi YS, Rahayu IS and Danu S 2013 J. Indian Acad. Wood Sci. 10 80
[7] Hadi YS, Massijaya MY, Hermawan D and Arinana A 2015 J. Indian Acad. Wood Sci. 12 80
[8] Devi RR, Ali I and Maji TK 2003 Biores. Technol. 88 188
[9] Devi RR, Maji TK and Banerjee AN 2004 J. Appl. Polym. Sci. 93 1938–45
[10] Devi RR and Maji TK 2006 Indian J. Eng. Mater. Sci. 13 149–54
[11] Hadi YS, Massijaya MY and Arinana A 2016 Insects 7 6–11
[12] Chao WY and Lee AWC 2003 Holzforschung 57 336
[13] Hill CS 2006 Wood Modification: chemical, thermal and other processes (Chichester: John Wiley & Sons, Ltd)