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Full Length Research Article

Quality Evaluation of Fast-Growing Wood Impregnated with Nano-Silica Synthesized from Betung Bamboo Stems

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ABSTRACT

Sengon (*Paraserianthes falcataria* L. Nielsen.) and jabon (*Anthocephalus cadamba* Miq.) are fast-growing wood of low quality. This study aims to overcome the disadvantages of low-quality wood via impregnation using monoethylene glycol (MEG), and nano-silica synthesized from betung bamboo stems (*Dendrocalamus asper*). Nano-silica was obtained by the ultrasonication method, with the average size and zeta potential at 93 nm and -44.21 mV, respectively. This study used five different solutions: untreated, 50% MEG, MEG-Silica 0.5%, MEG-Silica 0.75%, and MEG-Silica 1%. The impregnation process began when a vacuum of 0.5 bar was applied for 60 minutes and continued with a pressure of 2.5 bar for 120 minutes. The results showed that sengon and jabon experienced an increase in quality as seen from the parameters of weight percent gain, specific gravity, modulus of elasticity, modulus of rupture, hardness, color brightness, and durability against dry wood and subterranean termites. Besides, the strength and durability classes of both kinds of wood also improved to III and IV, respectively, with the solution's concentration gradually increasing. Based on the results, MEG-Silica 1% is the most influential solution in improving the physical-mechanical properties and durability of sengon and jabon wood.

1. Introduction

Fast-growing wood is widely discussed as an alternative to natural forest wood. For example, sengon wood (*Paraserianthes falcataria* L. Nielsen) and jabon (*Anthocephalus cadamba* Miq.) are commonly found in community forests. Both species have short logging cycles, precisely under 10 years (Hadi et al. 2021). As a result, the wood has low specific gravity, thin cell walls, high moisture content, and a high portion of juvenile wood, resulting in poor qualities such as its strength and durability (Darmawan et al. 2015). Martawijaya et al. (2005) reported sengon and jabon wood strength classes, namely IV-V and III-IV, respectively, and their durability classes are IV-V and V. Therefore, the wood is unsuitable for construction purposes, such as columns, house ceilings, furniture, and others (Bowyer et al. 2007). These woods are currently utilized as plywood, carpentry wood, insulating boards, and crates (Anggraini et al. 2021). To overcome this problem,

it is necessary to use a technique called wood impregnation, which is environmentally friendly while improving the quality of the wood.

Wood impregnation is a process that enhances wood's durability and resistance to external factors. Traditional impregnation methods often use toxic substances, but the latest approaches focus on less harmful chemicals. These methods can still enhance wood properties while minimizing environmental impacts, namely by using bio-based products for wood impregnation (Wu et al. 2020). Some previous works have investigated the anti-degradation effect of wood impregnation using several natural bio-based materials, such as plants, oil, beeswax, and other non-toxic materials. This treatment is believed to increase wood's dimensional stability and prevent moisture from penetrating the wood (Calovi et al. 2024). In addition, wood impregnation is also known as the effort to make the wood more functional instead of having regular characteristics, including wood mechanical properties (Wang et al. 2019), termite and fungal resistance (Priadi et al. 2023), thermally stable and fire-retardancy (Lu et al. 2020), magnetic characteristics (Lou et al. 2018), and electrical properties (Rajulu and Mohanty 2016). Thus, this treatment is highly recommended to promote sengon and jabon utilization.

Generally, the impregnation method can be conducted by inserting chemicals into the wood microstructural area (Hill 2006; Teng et al. 2018). Many chemicals are often used in this treatment, i.e., methyl methacrylate (MMA), polyethylene glycol (PEG) (Zhang et al. 2022a), furfuryl alcohol (Wahyuningtyas et al. 2022), and monoethylene glycol (MEG) (Rahayu et al. 2020a). MEG is known as a liquid that is colorless, odorless, low volatility, and perfectly soluble in water molecules. Its molecular weight is 62.07 g/mol, which endures up to a pressure of 81 atmospheres and a temperature of 801°F. These characteristics make MEG a suitable impregnant material for wood (ATSDR 2020; Fikri et al. 2018). Dirna et al. (2020a) mentioned that combining MEG and silicon dioxide (SiO_2) can improve wood density and dimensional stability due to their even distribution inside the wood cavities. Silica can be extracted from inorganic substances like sand, clay, and rock (Hoang et al. 2022; Manurung et al. 2022; Zulfiqar et al. 2016). Meanwhile, organic substances containing silica are also extractable to produce bio-silica, namely corn cobs, husks, bagasse, and bamboo (Park et al. 2023; September et al. 2023; Yu et al. 2016).

Bamboo is the largest source of natural silica compared to other plants. The previous research stated that over 70% organic silica is contained in this plant (Rawat et al. 2018). Leksikowati and Rachmawati (2024) also reported that the SiO_2 content of *Gigantochloa apus* in the leaf and stem ashes was 76.88% and 48.43%, respectively. Yin et al. (2016) also reported that the silica content of the *Neosincalamus affinis* is around 34.99–38.67% of the inner to epidermis layer. The presence of silica in bamboo can be considered as a natural bio-mineralization (Zixuan et al. 2016). In addition, silica's role in bamboo is also related to the structural rigidity of its cell wall and resistance to disease and pests, so bamboo is widely applied as a construction material due to its excellent mechanical properties (Zhang et al. 2022b). The lack of innovation in bamboo stems leads to bamboo having low economic value, especially in competition with other construction materials such as wood, concrete, iron, and steel. Therefore, the present work utilizes bamboo stems as a material choice in the nano-silica synthesis for wood impregnation material, considering silica extraction from bamboo stems is rarely carried out, especially in betung bamboo (*Dendrocalamus asper*).

The benefits of nano-silica impregnation are reducing shrinkage and swelling of wood. Impregnated wood becomes denser, improving mechanical properties with strength and hardness increase, enhancing wood resistance to decay (Bak et al. 2018), and silica-treated wood is less

flammable (Yona et al. 2021). Nano-silica has been proven to improve wood quality due to its low viscosity, easy distribution, and ability to penetrate evenly into the wood (Papadopoulos et al. 2019). Bio-nano silica from rice husk has been applied to improve *Pinus elliottii* and increase wood durability (Nicacio et al. 2022). Betung bamboo leaves have been used to synthesize nano-silica and successfully incorporated into the jabon wood, resulting in a cross-link between wood polymer and nano-silica. This improves the wood's dimensional stability and crystallinity (Dirna et al. 2020a). Previously, MEG and nano-silica from betung bamboo sticks have been observed to enhance the sengon wood's physical properties and characteristics (Rahayu et al. 2020b). However, its mechanical and durability properties have not been evaluated. Hence, this study finds out about the effect of MEG and nano-silica on the physical, mechanical, and durability properties of sengon and jabon wood.

2. Materials and Methods

2.1. Sample Preparation

This study used a 30 cm diameter of 5-year-old defect-free sengon and jabon wood cut down from a community forest in Sukabumi, West Java. Depending on the test, as many as 50 wood samples were cut into different sizes using a chainsaw and table circular saw without diminishing sapwood-heartwood parts. The sections of wood logs used were ensured to be taken in the same part radially to reduce the heterogeneity of the resulting data. Each treatment required five repetitions to obtain the optimum results. The dimensions of sengon and jabon wood used are referred to test standards described in **Table 1** below.

Table 1. Dimensions of samples at various test parameters

No	Evaluation	Sample dimensions	Standard/reference
1	Color test	2 cm × 5 cm × 6 cm	Christie (2015)
2	Specific gravity	2 cm × 2 cm × 2 cm	BS-373
3	Modulus of elasticity (MOE) and modulus of rupture (MOR)	2.5 cm × 2.5 cm × 41 cm	ASTM D 143-22 (ASTM 2022)
4	Hardness	5 cm × 5 cm × 15 cm	ASTM D 143-22 (ASTM 2022)
5	Dry wood termite test	2.5 cm × 2.5 cm × 5 cm	SNI 01-7207 (BSN 2006)
6	Graveyard field test	2 cm × 2 cm × 41 cm	ASTM D 1758-06 (ASTM 2000)

2.2. Nano-Silica Preparation

Nano-silica was synthesized from betung bamboo stems through the ultrasonication method, as previously reported by Dirna et al. (2020b). 5-year-old betung bamboo (*Dendrocalamus asper*) was obtained from the Faculty of Forestry and Environment, IPB University. The diameter of betung bamboo was 6–9 cm with 15–20 cm of its thickness. This study used the mid-cortex (between the epidermal and inner cortex) of the betung bamboo stem's middle part. Bamboo stems were chopped, washed using water, sun-dried, and burned without fuel until they became charcoal. Then, charcoal was placed in a porcelain cup and burned in a furnace at 700°C for 6 hours to obtain silica ash. The reflux method was utilized to extract the silica ash, which resulted in the production of pure silica. A probe type of ultrasonicator (CGOLDENWALL, manufactured by Zhejiang,

China) was used to mix the silica with polyethylene glycol (PEG-6000) for 1 hour, followed by burning it in a furnace at a temperature of 600°C for 3 hours.

2.3. Particle Size and Zeta Potential Measurement

This measurement used a 100 mL solution containing demineralized water and 2.5 g nano-silica produced from the ultrasonication method. Then, it was stirred for 1 hour with a sonicator (Kim et al. 2014). The solution with a concentration of 2.5 wt./v% nano-silica was analyzed for particle size and zeta potential with PSA (Beckman Coulter LS 13 320 XR).

2.4. Impregnating Solution Preparation

The composition of the solutions used in this study was a mixture of MEG and water with a volume ratio of 1:1 and additional nano-silica with various concentrations, including 0.5%, 0.75%, and 1%. There were also the untreated and 50% MEG-treated wood for comparison. These solutions were mixed using a probe-type ultrasonicator (300W Ultrasonic Homogenizer Sonicator 5-200MLLab, manufactured by CGOLDENWALL, Zhejiang, China) for 2 hours with 40% amplitude.

2.5. Impregnation Process

Before starting the impregnation process, the wood samples were oven-dried at 103 ± 2°C until they reached a constant weight, then their weight and dimensions were written down. Once the wood samples were put into the impregnation tube, the solution was poured gradually until all the wood samples were completely submerged. A vacuum of 0.5 bar was applied for 1 hour to initiate the impregnation process, which continued with 2 hours of pressure of 1 bar. To facilitate the polymerization reaction, the wood samples were taken from the impregnation tube, wrapped in aluminum foil, and left at room temperature for 12 hours. The drying process was performed until they had a specific weight. Their weight and dimensions were noted once more.

2.6. Impregnated Wood Evaluation

2.6.1. Physical properties evaluation

The physical properties of impregnated sengon and jabon wood include weight percent gain (WPG), specific gravity, and color test. The following equation calculates the specific gravity (Equation. 1 and Equation. 2).

$$WPG\ (\%) = \frac{W_1 - W_0}{W_0}\ x\ 100 \quad (1)$$

$$Specific\ gravity = \frac{W_1}{V_1/\rho_{water}} \quad (2)$$

where W_0 is the oven-dried weight of the wood samples before impregnation (g), W_1 is the oven-dried weight of the wood sample after impregnation (g), V_1 is the oven-dried volume of the wood sample after impregnation (cm^3), and ρ_{water} is the density of water (1 g/cm^3).

The color of impregnated wood was measured using the CIE L*a*b* method by measuring three times at three predetermined points. The impregnated wood was scanned using CanoScan LiDE 300 (Canon Singapore Pte. Ltd.), and then the color analysis was conducted using Adobe Photoshop CS 4 software (Muflihati et al. 2014). The L* value represents the brightness parameter

from black to white color (0–100). Meanwhile, the parameter a* is equivalent to the ratio of red to green color, with values from +a (0 to +80) for the red color and –a (0 to –80) representing the green color. Conversely, the blue-to-yellow color parameter is also represented by the b* value, which implies that the b+ (0 to +70) represents the yellow color and –b (0 to –70) means the blue color (Christie 2015). The equation below describes the color change of modified wood, and the CIEL*a*b* color space is illustrated in **Fig.1**.

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 (\Delta b)^2} \quad (3)$$

where ΔE describes the visible color change of the impregnated wood, ΔL represents the change in wood brightness before and after treatment, and Δa is the red or green color change before and after treatment. At the same time, Δb is the yellow or blue color change before and after treatment.

The wood discoloration can be evaluated using the criteria written in **Table 2.**

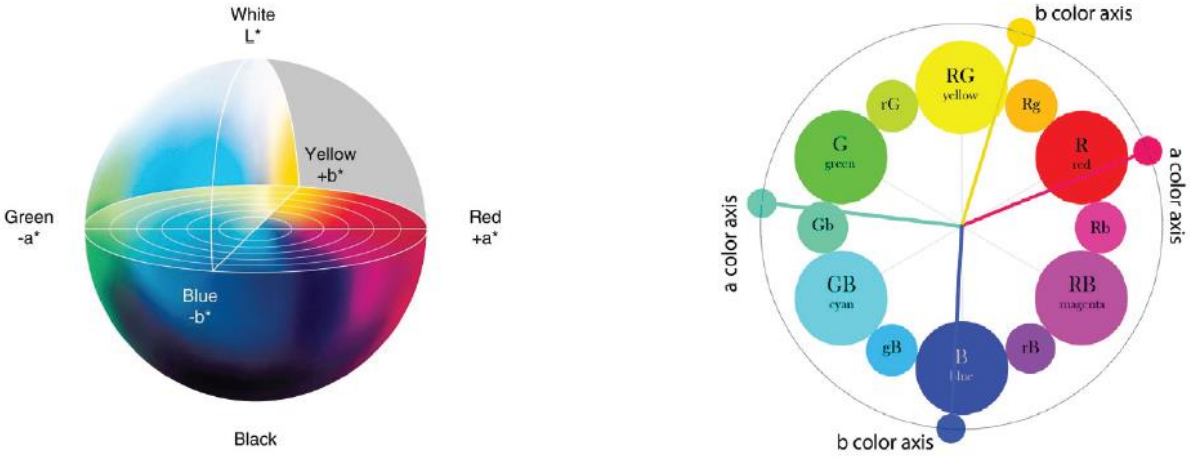


Fig. 1. The representation of CIEL*a*b* color space (Barcík et al. 2015).

Table 2. The classification of color change levels (Barcík et al. 2015)

Color differences	Effects
$0.2 < \Delta E^*$	Invisible discoloration
$0.2 \leq \Delta E^* < 2$	Minor discoloration
$2 \leq \Delta E^* < 3$	Discoloration with high-quality filters
$3 \leq \Delta E^* < 6$	Discoloration with medium-quality filters
$6 \leq \Delta E^* < 12$	Major discoloration
$\Delta E^* \geq 12$	Different colors

2.6.2. *Mechanical properties evaluation*

The evaluation of wood mechanical properties includes modulus of elasticity (MOE), modulus of rupture (MOR), and hardness (H). The wood sample dimension refers to the ASTM D 143-22 (ASTM 2022) with the one-point loading method. The Universal Testing Machine (UTM) brand Instron 3369 from Buckinghamshire, UK, utilized these tests. To read the MOE value on this tool, the wood samples were weighed until they reached the elastic limit, while the MOR value was obtained when the wood samples were broken or damaged. Equations 4 and 5 were used to calculate the MOE and MOR values.

$$MOE\ (kg/cm^2) = \frac{\Delta P L^3}{4 \Delta Y b h^3} \quad (4)$$

$$MOR\ (kg/cm^2) = \frac{3\ Pmax\ L}{2bh^2} \quad (5)$$

where ΔP is defined as the load below the proportion limit, L represents the span distance (cm), ΔY is the deflection at load P (cm), $Pmax$ is the maximum load applied to the wood sample (kg), b is the width of the test sample (cm), and h is described as the thickness of the wood sample (cm).

The hardness (H) of the impregnated wood was tested according to the Janka method, namely by pressing half of a hemispherical steel ball to pass through the sample surfaces. To determine this parameter of the impregnated wood, Equation 6 was used.

$$H\ (kg/cm^2) = \frac{Pmax}{A} \quad (6)$$

where P_{max} represents the wood sample's maximum load (kg), and A is defined as the cross-sectional surface area subject to load.

2.6.3. Durability test

2.6.3.1. Dry wood termite test

This test was carried out in the laboratory by feeding each wood sample to 50 termites of *Cryptotermes cynocephalus* species for 12 weeks. Termite mortality (TM) and weight loss (P) toward the dry wood termite attacks were determined using Equation 7 and Equation 8.

$$TM\ (\%) = \frac{D}{50} \times 100\% \quad (7)$$

$$P\ (\%) = \frac{W_1 - W_2}{W_1} \times 100\% \quad (8)$$

where D represents the number of dead termites after feeding, 50 shows the number of initial termites, W_1 is the air-dried weight of the wood sample before feeding (g), and W_2 is the air-dried weight after feeding (g). In addition, the wood's durability against dry wood termite attacks was classified according to SNI 01-7207 (BSN 2006) (**Table 3**).

Table 3. The grading system of wood resistance to dry wood termite attacks

Class	Resistance Level	Weight Loss (%)
I	High durable	< 3.52
II	Durable	3.52 – 7.40
III	Moderate	7.50 – 10.80
IV	Low durable	10.90 – 18.90
V	Vulnerable	>18.90

2.6.3.2. Graveyard field test

This test lasted 3 months at the arboretum area of the Faculty of Forestry and Environment, IPB University. Geographically, this area was 207 meters above sea level, with a latitude of 06°33'S and a longitude of 106°E. After being oven-dried to a constant weight, the wood samples

were randomly buried with a sample spacing of 40 cm, row spacing of 60 cm, and a depth of around 23 cm (**Fig. 2**).

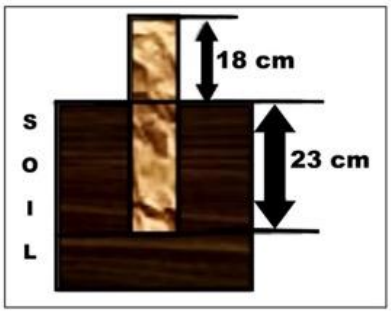


Fig. 2. The wood sample's condition when buried in the ground.

Following 3 months, the wood samples were removed, the adhering soil was cleaned from the samples and then weighed after being oven-dried to a constant weight. The weight loss (WL) was calculated using Equation 9.

$$WL\ (\%) = \frac{W_1 - W_2}{W_1} \times 100\% \quad (9)$$

where W_1 is defined as the oven-dried weight of wood samples before burial, and W_2 explains the oven-dried weight of wood samples after burial.

The wood damage after being buried and attacked by subterranean termites is evaluated using ASTM D 1758-06 (ASTM 2000) (**Table 4**).

Table 4. The grading system of wood resistance to subterranean termite attacks

Grade	Wood Condition
10	No attack, 1–2 small nibbles still permitted
9	Nibbles to 3% in the cross-section
8	Penetration of 3–10% in the cross-section
7	Penetration of 10–30% in the cross-section
6	Penetration of 30–50% in the cross-section
4	Penetration of 50–75% in the cross-section
0	Failure

2.7. Data Analysis

A completely randomized factorial design by IBM SPSS (Statistical Package for Service Solutions) version 25.0 (California, USA) was used in this study. The factors analyzed were the wood species and the concentration levels of the solution. The obtained data were evaluated using analysis of variance (ANOVA) and continued by Duncan's Test at a significance level of 5%. The correlation among parameters was analyzed via Pearson correlation.

3. Results and Discussion

3.1. Particle Size and Zeta Potential Analysis

The particle size analysis plays a crucial role in wood impregnation efficiency. Smaller particles tend to penetrate the wood more effectively. For example, 70 nm particles in pine wood were impregnated efficiently, while 170 nm were not (Nagraik et al. 2023). Nano-sized silica

particles interact differently in terms of surface area functionalization with wood compared to the bulk silica phase and thus have a greater impact on changing the physical properties of wood (Bossert et al. 2020). Furthermore, the use of particle size analyzers in nanotechnology application research is very important because it is related to important things: efficacy, stability, and quality control (Kastner and Perrie 2016). The size of nanoparticles significantly impacts their effectiveness and stability. Accurate measurement ensures optimal performance. Proper particle size measurement is essential for quality control and assurance during development and manufacturing (Chaturvedi et al. 2024).

Zeta potential (ζ-potential) analysis is necessary to determine the nanoparticle behavior through electrical energy content on the nanoparticle's surfaces. This parameter affects the particle stability, interactions, and behavior in various mediums (Sikora et al. 2015). The present work uses nano-silica dissolved in MEG as a wood impregnation solution. Several factors, such as concentration, cation valence, and soluble salts, can affect the zeta potential value of nano-silica, which also affects the colloidal stability and aggregation (Andriyko et al. 2015). It is known that a high positive or negative zeta potential of nano-silica will be mutually rejected by each other. The lower zeta potential value causes weak repulsion, leading to aggregation and flocculation. Therefore, for effective impregnation, nano-silica needs to have a high absolute zeta potential (> +30 mV or < -30 mV) to ensure that aggregation can be prevented (Sun 2016).

Water was used as a solvent for Zeta Potential analysis because when nano-silica is exposed to water or alcohol like MEG molecules, silanol functional groups (Si-OH) are formed on the silica surface. This occurs due to the hydrolytic reaction with siloxane groups (Si-O-Si) is happened, thereby disrupting Si/O bonds. Other molecules provide a medium for these silanol groups to dissociate via solvation. In strongly hydrogen-bonding liquids, a solvation layer forms on the silica surface. This layer results from hydrogen bonding between liquid molecules and surface silanol groups (Si-OH) (Škvarla and Škvarla 2020). Based on these sources of scientific information, we analyzed the particle size and zeta potential of silica nanoparticles used as a material impregnated into wood to produce high-quality research analysis data.

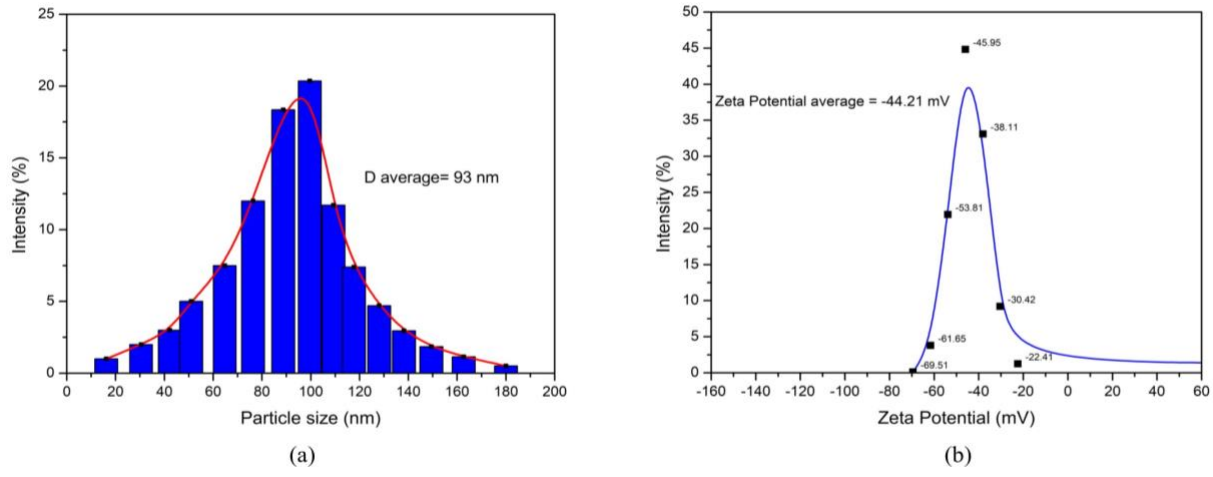


Fig. 3. The PSA results of nano-silica (a) particle size distribution and (b) zeta potential value.

The PSA analysis result provides evidence of the successful synthesis process of nano-silica via the ultrasonication method, which exhibits high stability in water dispersion. Detailed information regarding the nano-silica particle size distribution and zeta potential can be read in

Fig. 3. The particle size distribution of produced nano-silica is 93 nm (16–180 nm). The highest intensity is achieved at 99 nm and the lowest at 180 nm. In addition, zeta potential measurement was performed to determine the stability of nano-silica in demineralized water dispersions, which was conducted using the same PSA instrument. The result of nano-silica zeta potential shows an average of -44.21 mV, with the highest intensity at -45.95 mV and the lowest intensity at -69.51 mV. Due to the particle size of synthesized nano-silica being less than 100 nm, Khan et al. (2019) categorized it as nano-sized particles.

Moreover, the produced nano-silica has a zeta potential that exceeds ± 30 mV, indicating it can dispersed easily in the solution-dispersed form. (Kepekçi et al. 2021). This negative zeta potential result is consistent with the literature ranging from -10 mV to -50 mV (Sikora et al. 2015), meaning its surfaces are negatively charged. The negative zeta potential appears from the dissociation of Si-O or silanol groups on the nano-silica surfaces, resulting in the negative zeta potential of siloxane groups (Si-O-Si) (Alvarez-Berrios et al. 2018).

3.2. Physical-Mechanical Properties of Impregnated Wood

3.2.1. Weight percent gain and specific gravity

The impregnation process using MEG and nano-silica synthesized from betung bamboo stems has positively affected wood's physical and mechanical properties. This statement is associated with the improvement of several points of sengon and jabon wood properties after being impregnated, such as in weight percent gain (WPG), specific gravity, modulus of elasticity (MOE), modulus of rupture (MOR), and hardness. It can be concluded from **Table 5** that there is an obvious improvement in the WPG of sengon and jabon wood after impregnation compared to the untreated wood.

Table 5. The physical properties of impregnated sengon and jabon wood in various concentrations

Wood Species	Treatments	WPG (%)	Specific Gravity
Sengon	Untreated	0.09 ± 0.00^{a}	0.31 ± 0.01^{a}
	50% MEG	22.05 ± 3.65^{b}	0.34 ± 0.02^{b}
	MEG-Silica 0.5%	60.12 ± 8.90^{d}	0.37 ± 0.01^{c}
	MEG-Silica 0.75%	69.21 ± 8.40^{e}	0.39 ± 0.01^{d}
	MEG-Silica 1%	79.19 ± 0.96^{f}	0.45 ± 0.01^{f}
Jabon	Untreated	0.42 ± 0.24^{a}	0.39 ± 0.01^{d}
	50% MEG	19.98 ± 0.75^{b}	0.41 ± 0.01^{e}
	MEG-Silica 0.5%	48.37 ± 5.80^{c}	0.44 ± 0.01^{f}
	MEG-Silica 0.75%	65.05 ± 4.09^{de}	0.47 ± 0.02^{g}
	MEG-Silica 1%	77.76 ± 4.50^{f}	0.50 ± 0.01^{h}

Notes: $^{a-d}$ value = the significance of Duncan's test results. WPG = weight percent gain, MEG = monoethylene glycol.

This condition is affected by the deep penetration of MEG and increasing concentration levels of nano-silica in wood samples. The nano-sized particle is believed to be evenly distributed into the wood interior (Paul et al. 2023). The drying process at the end of the impregnation process also played a crucial role in ensuring the progressive reaction between silica and wood polymers continued to occur, leading to increased solution concentration in certain areas inside the wood due to the water evaporation. This reaction produces chain structures from the condensation

reaction of two silanol groups, also called a polymerization reaction (Yona et al. 2021). This is evidenced by the fact that both impregnated woods experienced a significant improvement, which is linear to the addition of nano-silica concentration. Accordingly, the highest WPG was obtained at the concentration of MEG-Silica 1%, namely 79.19% and 77.76% for sengon and jabon wood, respectively. These numbers are agreeable with the work of Rahayu et al. (2020a), who impregnated sengon wood with the same combination of chemicals. Although sengon wood has higher WPG than jabon wood, this circumstance is considered quite reasonable because the 5-year-old jabon wood has an average vessel area of 14.96 µm^2 with a, meanwhile, an average vessel area of 5-year-old sengon wood is 30.49 µm^2 (Darmawan et al. 2018). Prihatini et al. (2023) also mentioned that nanomaterials measuring below 300 nm can still move into wood pores.

As predicted, the specific gravity of sengon and jabon wood also obviously improved, corresponding to the increase in their WPG value. This increasing parameter is also related to variations in nano-silica concentration. Despite both wood species having the highest specific gravity at the MEG-Silica 1%, i.e. consecutively of 0.45 and 0.50 for sengon and jabon wood, the impregnated jabon wood was superior to the sengon wood because its initial specific gravity is higher than sengon wood, represented by the untreated wood of sengon (0.31) and jabon (0.39). This upgrading parameter gives both kinds of wood a specific gravity equal to teak wood, which has a specific gravity of 0.51 (Bahanawan et al. 2020). However, there is a strong positive correlation between the WPG and the specific gravity of sengon and jabon wood (Pearson correlation coefficient of 0.90), as shown in the following graph (**Fig. 4**).

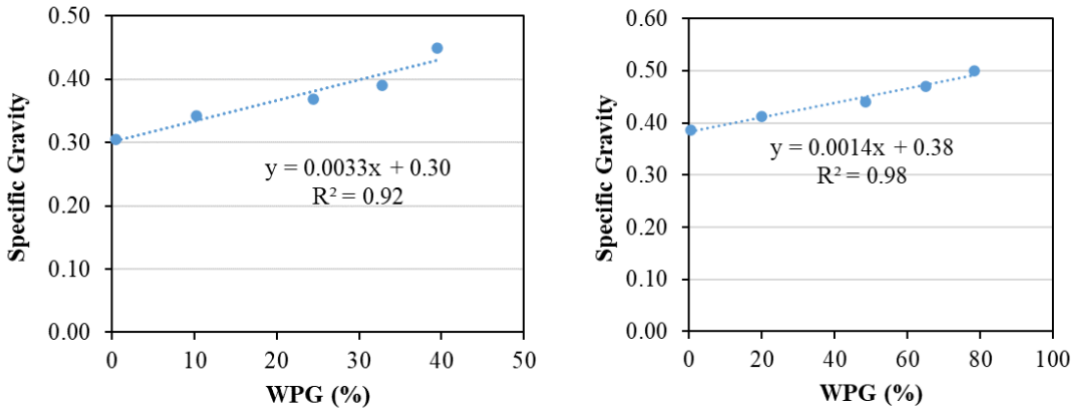


Fig. 4. The correlation between WPG and specific gravity of (a) sengon and (b) jabon wood.

The solution containing MEG and nano-silica was thought to occupy the empty cell lumens that were originally filled by water molecules, as stated by Hill (2006). Samanta et al. (2022) confirmed the presence of nano-silica that was homogeneously distributed within the mesopores of transparent wood using the Scanning Electron Microscope-Energy Dispersive X-ray spectroscopy (SEM-EDX) instrument. The nano-silica that MEG disperses will stabilize the wood structure against aggregation tendencies, while it is known that nano-silica diffusion depends on particle size and charge density. Small particle-size silica can help its accessibility in migrating the solution down to the nanoscale of wood, resulting in bulking and swelling of the wood cell walls (Hazarika and Maji 2014). At the same time, the high concentration of nanoparticles infused into the wood can lead to agglomeration, which blocks the wood pores, so the solution cannot penetrate well into the wood (Fadia et al. 2023). These factors certainly affect the increase of

specific gravity of sengon and jabon wood after impregnation treatment. Based on the WPG and specific gravity of the impregnated wood that has been evaluated, the MEG-Silica 1% is the most suitable treatment for sengon and jabon wood modification.

3.2.2. Impregnated wood discoloration

The wood discoloration is also detected on the treated wood, which can be analyzed by the L^*, a^*, and b^* values after being impregnated with MEG and nano-silica. There was a significant brightness (L) reduction of MEG-treated wood compared to the untreated sengon and jabon wood; therefore, the MEG-treated wood seemed darker. On the other hand, the negligible brightness change occurred in the sengon wood samples of MEG-Silica 0.5%, MEG-Silica 0.75%, and MEG-Silica 1%. It can be seen in **Fig. 5** that their L^*, a^*, and b^* trends on all three MEG-Silica treated sengon wood are not completely clear to explain the color shift. The same results were also experienced by jabon wood after being impregnated. This condition provided a different view from the consequence of Rahayu et al. (2021) that the additional concentration of nano-silica caused an important effect in brightening the color of the wood.

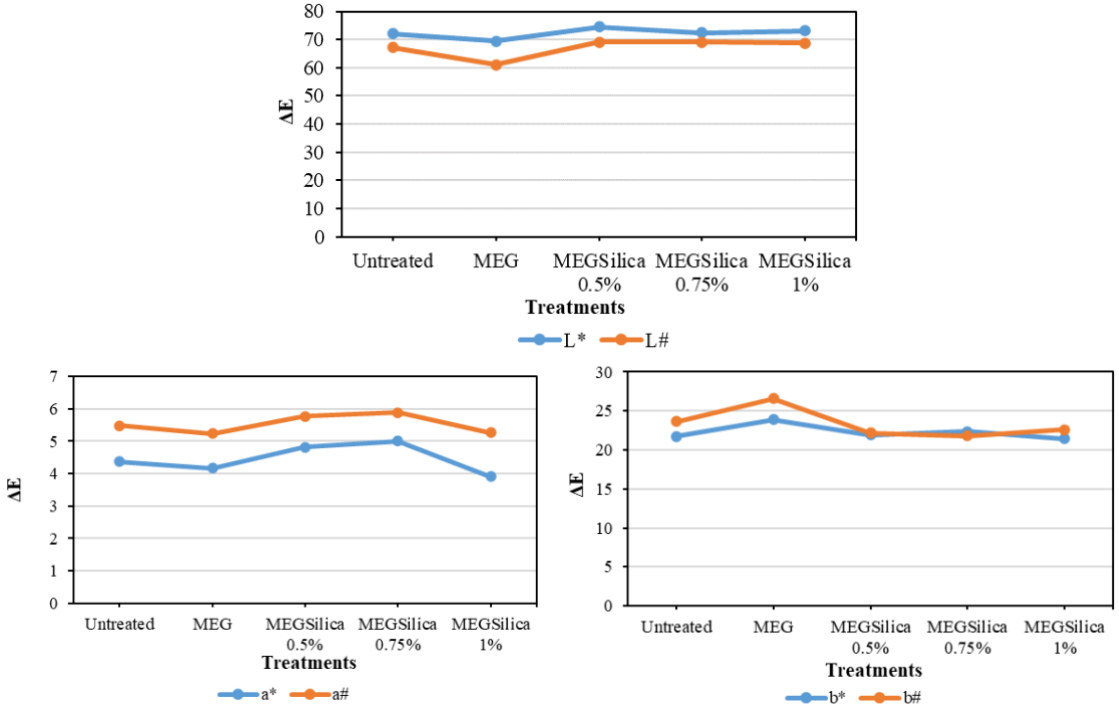


Fig. 5. The L^*, a^*, b^* values before impregnation and L#, a#, b# values after impregnation of sengon wood in various concentrations.

This condition was explained by Mustoe (2023), stating that lignin persistence is the cause of the darkening of silicified cell walls. When nano-silica is deposited in the wood substrate, it forms a mineral film on the wood cell walls, which is the beginning of the hydrogen bonding of Si-O-Si. This darkening effect of wood cellulose is also experienced by Bak et al. (2022), which is likely caused by drying temperature (Klement et al. 2021). However, this darkening color is no more significant than the MEG-treated wood. This wood product can be a choice for consumers who like darker-colored wood. The visual appearance of the discoloration of sengon wood in the tangential section is presented in **Fig. 6**.

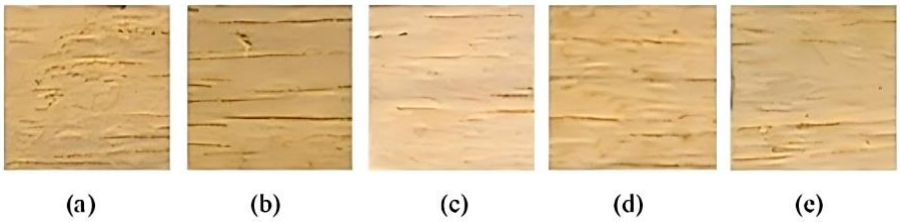


Fig. 6. The tangential section of impregnated sengon wood color as seen visually (a) untreated, (b) MEG-treated, (c) MEG-Silica 0.5%, (d) MEG-Silica 0.75%, and (e) MEG-Silica 1%.

Similar changes also occurred in jabon wood, and MEG caused a darkening of the wood color. The a* and b* values of the MEG-Silica treated wood still show an unclear change, even though their color brightens up more than MEG-treated wood. The increasing nano-silica concentration also allows jabon wood to have a darker color. This proves that polymerization occurred successfully between the wood polymers, MEG, and nano-silica, thus increasing crystallinity and hydrogen bonds (Hill 2006). The L*, a*, and b* trends of jabon wood color change are demonstrated in **Fig. 7,** and its visual appearance in the tangential section is displayed in **Fig. 8**.

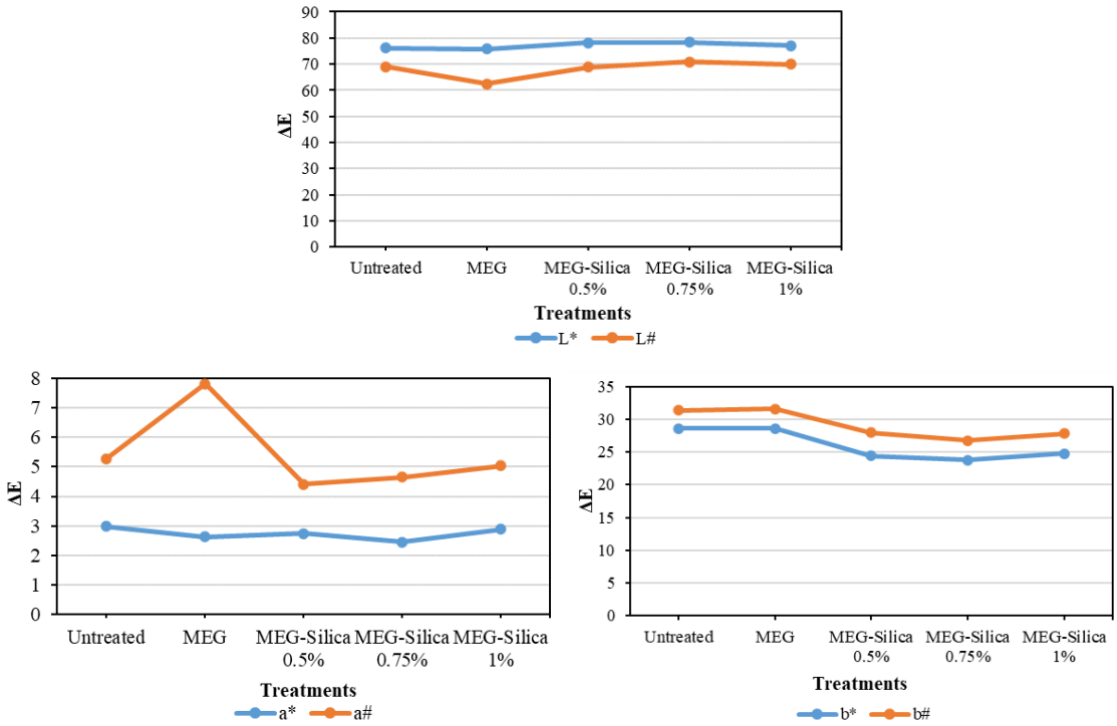


Fig. 7. The L*, a*, b* values before impregnation and L#, a#, b# values after impregnation of jabon wood in various concentrations.

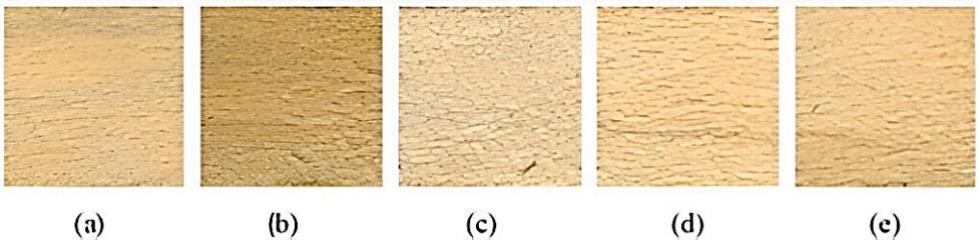


Fig. 8. The tangential section of impregnated jabon wood color as seen visually (a) untreated, (b) MEG-treated, (c) MEG-Silica 0.5%, (d) MEG-Silica 0.75%, and (e) MEG-Silica 1%.

In addition, the ΔE value of sengon and jabon wood is also presented in the following picture (**Fig. 9**). This analysis measures the overall color change that happened in the sengon and jabon wood after being impregnated with MEG and nano-silica using Photoshop CS4 software. The most significant effect in the sengon and jabon wood color change is obtained by the MEG-treated wood, respectively 9.15 and 16.02. According to the color change evaluation criteria promoted by Barcík et al. (2015), all of the jabon wood samples reached point 6, which means there has been a major color change. There are also two treatments in sengon wood, MEG-Silica 0.75% and MEG-Silica 1%, which do not reach point 6. Therefore, these kinds of wood experience moderate discoloration.

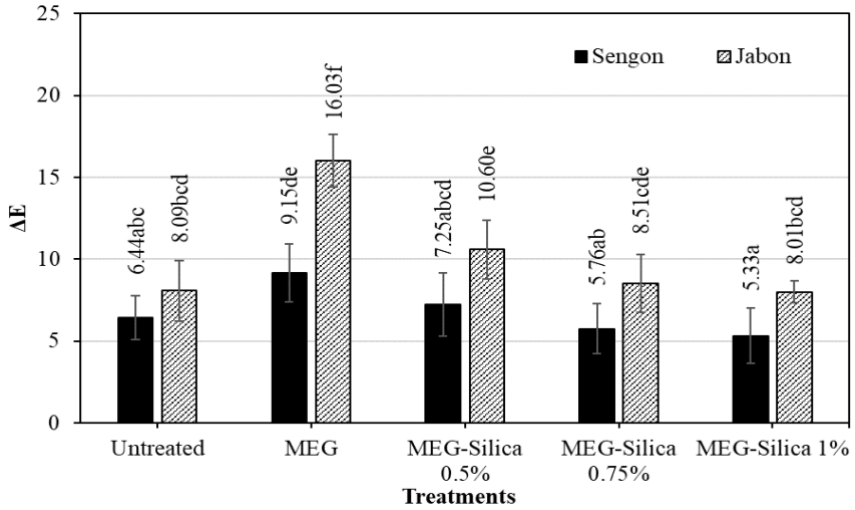


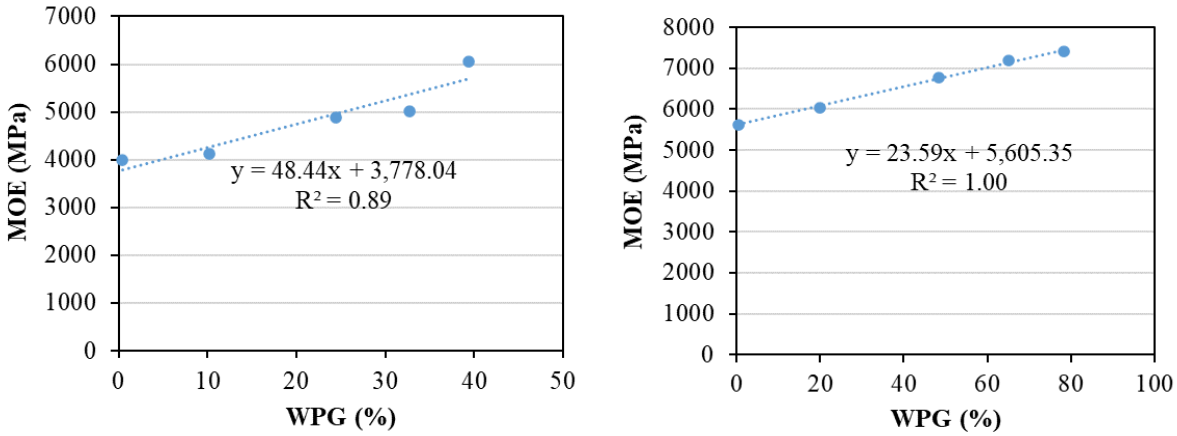
Fig. 9. The average color change value in various treatments of impregnated sengon and jabon wood with the vertical bars expressing the standard error after ANOVA analysis (P<0.05) and Duncan's test. A similar alphabet indicates an insignificant difference in a particular variable.

The discoloration occurred due to the reaction between MEG and wood cell wall components. Rahayu et al. (2021) confirmed the darkening color of MEG-treated wood, which becomes bright again when silica is added. Therefore, there is only a small increment in the overall discoloration of the MEG-Silica of sengon and jabon wood compared to the untreated wood. It can be observed with the image of the wood that has been scanned previously, which is shown in **Fig. 6** and **Fig. 8**. According to the discussion above, the MEG-Silica 1% becomes the most suitable for sengon and jabon wood modification.

3.2.3. Mechanical properties

A similar indication was also found in the mechanical properties of sengon and jabon wood after being impregnated using MEG and nano-silica. The increase in MOE, MOR, and hardness is caused by nano-silica being dispersed into a polymer that was applied to the wood, forming a large number of interfaces compared to the micro-composite materials (Saha et al. 2023). Untreated sengon and jabon woods show the lowest MOE, whereas the MEG-Silica 1% yields the highest MOE. This increment is significant because the MOE continues improving with each additional nano-silica concentration. The polymerization formed the cross-linking bond between MEG, nano-silica, and wood polymers. Therefore, more solution getting into the wood will improve their

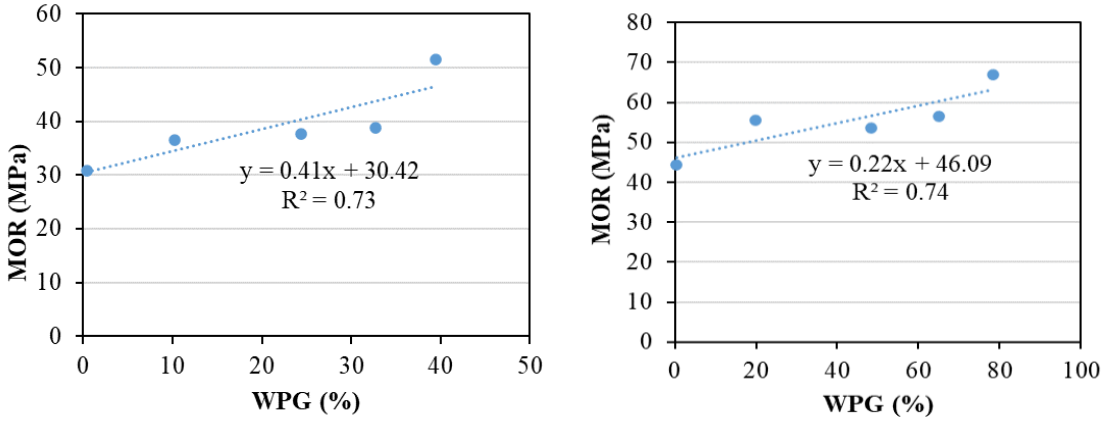
elasticity (Surachman, 2014). It is proved by the highly linear relationship between WPG and MOE (Pearson correlation efficient of 0.84), as displayed in **Fig. 10**.



(a) (b)

Fig. 10. The correlation of the MOE and WPG of impregnated (a) sengon and (b) jabon in various concentrations.

The analysis shown in **Fig. 11** also reveals the strong positive correlation between MOR and WPG of both impregnated wood with the Pearson correlation coefficient of 0.81. The increasing MOR is also consistent with the additional concentrations, although there is an outlier in the concentration of MEG-Silica 0.75% in jabon wood. This might be due to the agglomeration occurring in the wood surfaces and fewer nano-silica distributed within the wood interior (Bak et al. 2018). Nevertheless, the trend of increasing MOE and MOR for jabon wood remains on the rise, surpassing that of sengon wood, which is the initial of these parameters of jabon wood that is already higher. The possibility of tyloses that clogged the wood pores of sengon wood should be investigated further, considering the extractive content of sengon wood is higher than that of jabon wood (Augustina et al. 2023; Hadi et al. 2022). For more details, the MOE and MOR of sengon and jabon wood are compared in **Table 6**.



(a) (b)

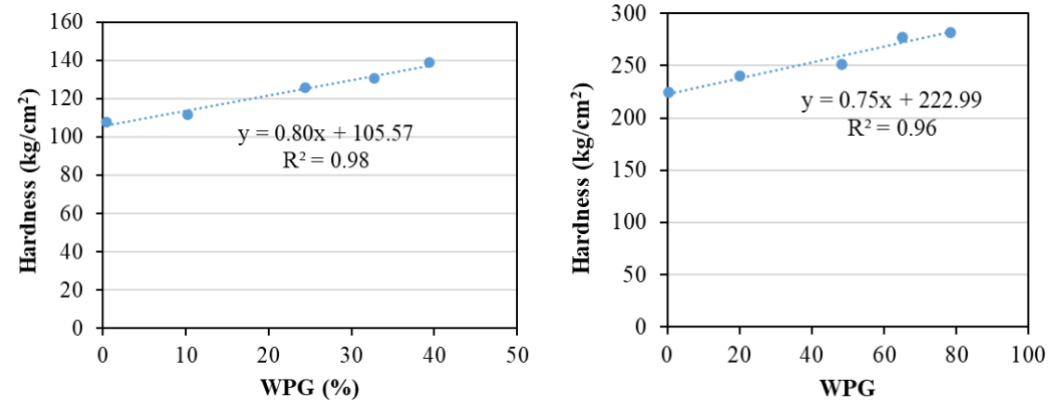
Fig. 11. The correlation of the MOR and WPG of impregnated (a) sengon and (b) jabon in various concentrations.

Table 6. Mechanical properties of impregnated sengon and jabon wood in various treatments

Wood Species	Treatments	MOE (MPa)	MOR (MPa)	Hardness (kg/cm^2)	Strength class
Sengon	Untreated	3989.36 ± 217.85^{a}	30.91 ± 10.60^{a}	107.74 ± 2.26^{a}	IV-V
	50% MEG	4129.29 ± 490.03^{a}	36.57 ± 5.60^{ab}	111.41 ± 19.03^{ab}	IV
	MEG-Silica 0.5%	4892.15 ± 518.21^{b}	37.75 ± 4.11^{ab}	125.46 ± 6.15^{bc}	IV
	MEG-Silica 0.75%	5020.33 ± 838.09^{bc}	38.78 ± 5.23^{ab}	130.58 ± 9.53^{c}	III–IV
	MEG-Silica 1%	6050.49 ± 209.33^{d}	51.56 ± 9.35c	138.62 ± 17.52^{c}	III
Jabon	Untreated	5623.76 ± 805.81^{cd}	44.29 ± 11.67^{bc}	224.00 ± 5.74^{d}	III–IV
	50% MEG	6042.68 ± 173.89^{d}	55.40 ± 9.66^{c}	239.94 ± 8.16^{e}	III–IV
	MEG-Silica 0.5%	6772.53 ± 234.04^{e}	53.61 ± 7.96^{c}	251.61 ± 5.37^{e}	III
	MEG-Silica 0.75%	7181.59 ± 356.90^{e}	56.38 ± 9.34^{c}	276.83 ± 9.22^{f}	III
	MEG-Silica 1%	7411.00 ± 274.29^{e}	67.00 ± 12.56^{d}	282.07 ± 15.84^{f}	III

Notes: $^{a-f}$ value = the significance of Duncan's test results, MOE = modulus of elasticity, MOR = modulus of rupture, and MEG = monoethylene glycol.

Wood hardness also increased linearly with the MOE and MOR, and the MEG-Silica 1% of sengon and jabon wood became the most difficult to destroy. Previous studies conclude that the ascending nano-silica content leads to improved hardness of fir and beech wood (Doubek et al. 2018). As water evaporates during the drying process, cell wall components can easily engage MEG and nano-silica to replace the role previously played by moisture filling in the lumens. The crystallite of nano-silica is claimed to reinforce the wood fiber, producing high wood hardness (Suryana et al. 2018). It is also observed by Kumar et al. (2020) that silicon dioxide, used as a filler for lignocellulose composites, enhances its mechanical properties, such as flexural strength, flexural modulus, and many more. In this study, WPG and the hardness of impregnated sengon and jabon wood are valuably related to each other, supported by the high coefficient of Pearson correlation of 0.64, which is illustrated in **Fig. 12**. From the revealed data above, we can conclude that sengon wood has improved its strength class from IV–V to III. Meanwhile, jabon wood also experienced the same improvement from III–IV to III.



(a) (b)

Fig. 12. The WPG and hardness correlation of impregnated (a) sengon and (b) jabon wood in various concentrations.

3.3. Durability of Impregnated Wood

3.3.1. Dry wood termite resistance

Fig. 13 shows the weight loss percentage of sengon and jabon wood impregnated with MEG and nano-silica. The largest weight loss of both woods is experienced by the untreated wood, namely 23.82% in sengon wood and 24.20% in jabon wood. These results are supported by the termite mortality of 76% and 80%, respectively, for sengon and jabon wood, which is extremely high (**Fig. 14**). This is due to the lack of chemical exposure in the untreated wood, making it easy for termites to consume, especially when the wood is moist. For comparison, Usmani et al. (2020) reported that the termite mortality of untreated Scots pine reached almost 50% and caused a weight loss of up to 15%. Pine wood is considered the favorite food of termites; however, it was immediately dropped after being treated with magnesium fluoride (MgF_2) and calcium fluoride (CaF_2), dissolved by ethylene glycol. This work also proves the effect of MEG in reducing the weight loss of baiting wood, which succeeded in increasing the termite mortality by 80% and 86% for sengon and jabon wood. However, it does not show much difference with the untreated wood. Nandasiri and De Silva (2021) compared the wood-treated borate combined with monoethylene glycol and monopropylene glycol. The result verified that MEG significantly impacted dry wood termites' mortality rate.

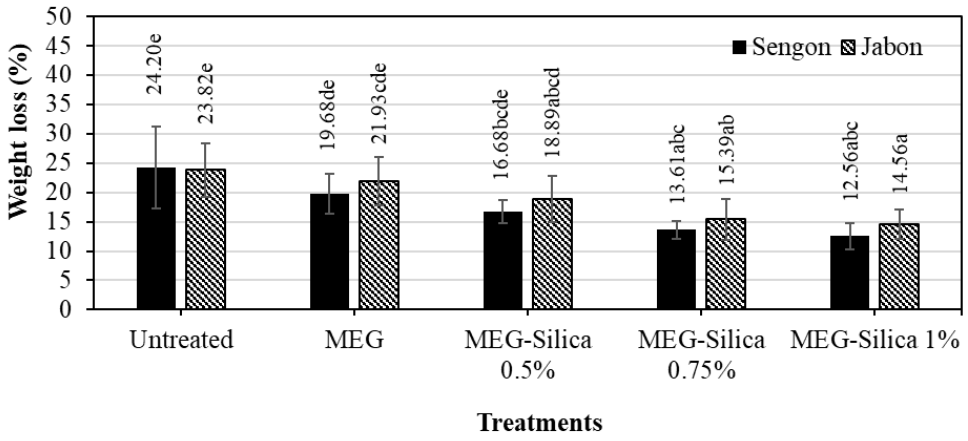


Fig. 13. Weight loss percentage of sengon and jabon wood treated by MEG and nano-silica in several concentrations after being attacked by dry wood termites. The vertical bars express the standard error of the values after ANOVA analysis ($P < 0.05$) and Duncan's test. A similar alphabet indicates an insignificant difference in a particular variable.

Following the three concentrations of MEG-Silica, wood weight loss keeps declining with the addition of nano-silica. In contrast, supporting data about termite mortality also reveals the disproportion. Although it does not cause much difference with lower concentrations, the mortality of dry wood termites continues to rise, which is associated with the addition of nano-silica content in both kinds of wood. The MEG-Silica of 1% treatment showed effectiveness in maximizing dry wood termite mortality up to 96% in sengon wood and 98% in jabon wood. This circumstance is reasonable because the previous researcher stated that nano-silica is a toxic particle that can protect the wood from wood-destroying organisms with a low rate of weight loss so the wood can be used for a longer period (Saw et al. 2023). Therefore, the high level of nano-silica incorporated into the wood significantly affects its weight loss.

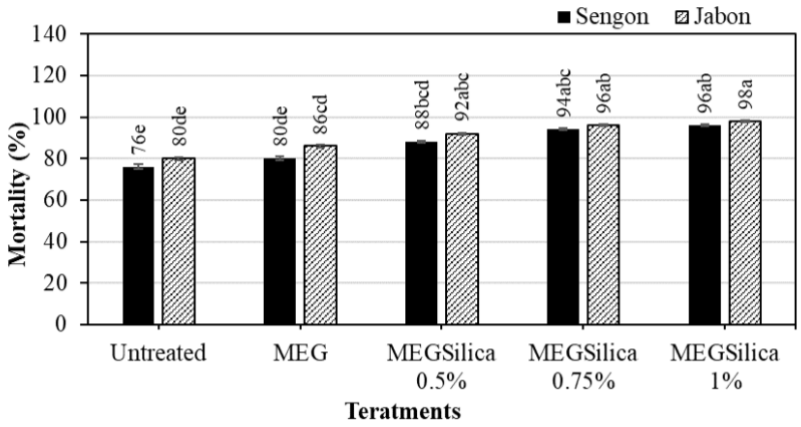
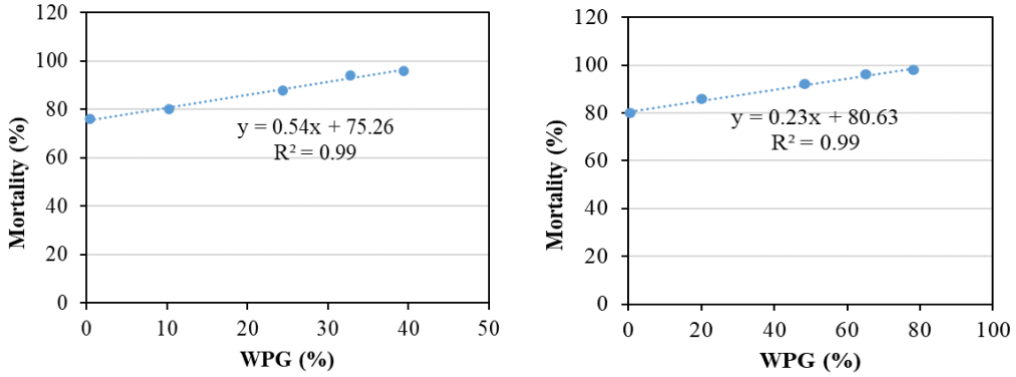


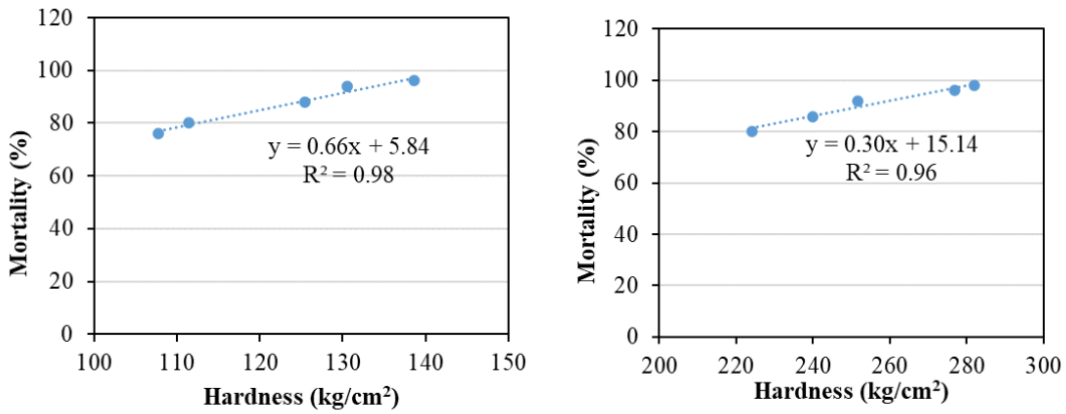
Fig. 14. Termite mortality of sengon and jabon wood treated by MEG and nano-silica in several concentrations with the vertical bars that express the standard error after ANOVA analysis ($P<0.05$) and Duncan's test. A similar alphabet indicates an insignificant difference in a particular variable.

The Pearson correlation coefficient obtained was 0.91, which defined that the WPG has a strong positive correlation with the hardness of wood. This relation can be seen in **Fig. 15**. The same effects also happen in the wood hardness, which is necessary to prevent wood damage by biological attacks (Tampubolon et al. 2015). This relevancy is also illustrated in **Fig. 16**. A Limited supply of termite food, especially poisonous wood, causes termites to be forced to consume it and causes high termite deaths (Lin et al. 2023). Dirna et al. (2020a) strengthen these statements by concluding that nano-silica synthesized from betung bamboo leaves has good characteristics in covered wooden surfaces and blocks the wood cavities thoroughly. Thus, the wood-destroying organisms cannot enter and live inside it (Peters et al. 2019). Therefore, by the lowest weight loss and highest termite mortality obtained in the MEG-Silica 1% treatment, these woods are categorized into durability class IV, and this treatment is recommended for modifying sengon and jabon wood.



(a) (b)

Fig. 15. The positive correlation between WPG and dry wood termite mortality on modified (a) sengon and (b) jabon wood.



(a) (b)

Fig. 16. The relevancy between hardness and the mortality of dry wood termites on modified (a) sengon and (b) jabon wood.

3.3.2. Subterranean Termites Resistance

The level of wood damage due to subterranean termite attacks via the graveyard field test is determined by calculating the weight loss percentage after being fed with modified wood and inspecting its damage based on the wood damage classification (**Table 6**). The wood with the most damage can be considered the worst durable wood. However, good differences are seen in each treated wood. It can be analyzed from the following report (**Fig. 17**) that the most damage happens in untreated wood, which has almost reached 100%, for both sengon and jabon wood. Meanwhile, the wood that had the lowest damage was achieved by the MEG-Silica 1% wood. This section also showed the effect of MEG addition, which reduces the wood and termite interaction to reduce the weight loss in sengon and jabon wood by up to 60–70%. However, this value is relatively much higher than those caused by the subterranean termites. This condition was allegedly due to the leaching that might have occurred during the test period.

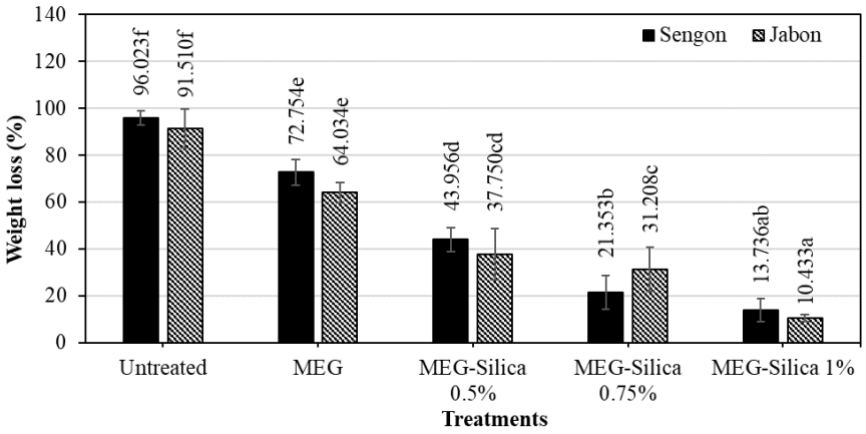
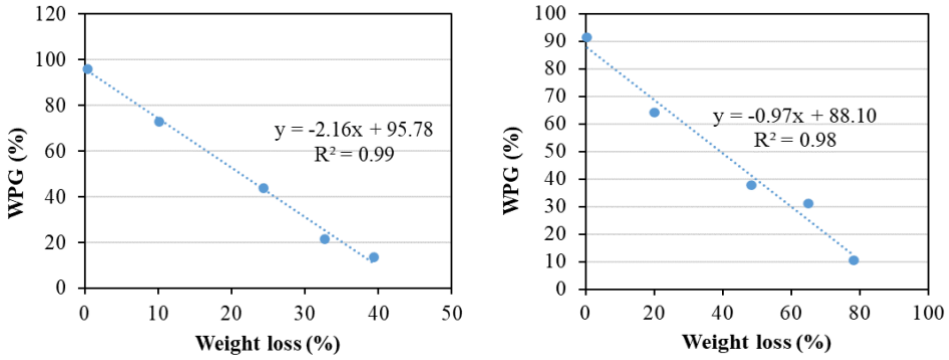


Fig. 17. Weight loss percentage of sengon and jabon wood by subterranean termites with the vertical bars that express the average standard error after ANOVA analysis ($P<0.05$) and Duncan's test. A similar alphabet indicates an insignificant difference in a particular variable.

It was also confirmed by Badi et al. (2021) that wood treated with MEG can easily leach by water, especially in higher temperature conditions. Moreover, the Dramaga, Bogor, is categorized as an area with heavy rainfall. It was reported that the maximum daily rainfall ranges from 63 mm

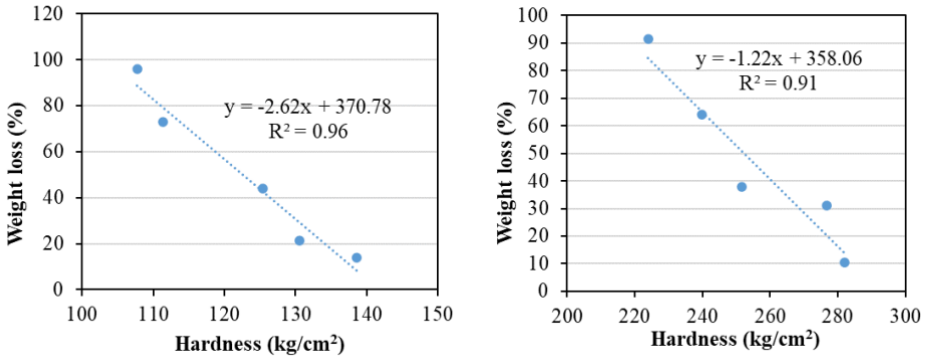
to 188.3 mm, with an average of 105.80 mm (Muna 2023). This leads to a high leaching possibility, considering the water's fast movement into the soil, causing termites to build tunnels and shelters to connect food distribution zones in the ground, then easily nest in wood because subterranean termites prefer humid places (Bakaruddin and Majid 2019). Arif et al. (2019) also added their opinion that termites develop in the temperature range of 15–38°C and the humidity of 95–98%.

In the MEG-Silica treated woods, the weight loss of sengon and jabon wood decreased gradually and appeared to be significantly different, especially at the level of 1%. As Peters et al. (2019) reported, silica is a toxic agent that can eradicate termite colonies in the grounds. However, based on this result, subterranean termites did not completely consume the wood. It is suspected to be caused by several probabilities, such as the different amounts of bait wood consumed by each termite, the occurrence of leaching due to the solution only incorporated in the wood surfaces, and the least number of termite colonies in that place. Nevertheless, we cannot calculate the termite mortality in this section. The success of MEG and nano-silica in reducing weight loss of sengon and jabon wood is also associated with the increase of wood's WPG and hardness, with the Pearson correlation coefficient respectively showing a strong (–0.94) and moderate correlation (–0.43), which the data shown in the following graphs (**Fig. 18** and **Fig. 19**).



(a) (b)

Fig. 18. The strong negative correlation between WPG and weight loss caused by subterranean attacks on the modified (a) sengon and (b) jabon wood.



(a) (b)

Fig. 19. The moderate negative correlation between hardness and weight loss caused by subterranean attacks on the modified (a) sengon and (b) jabon wood.

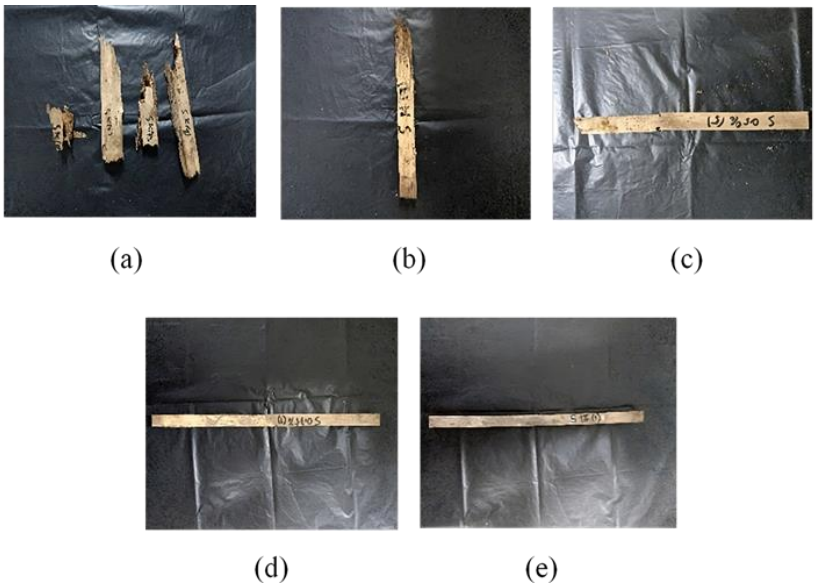
Based on **Fig. 18**, WPG continues to improve and is inversely proportional to the weight loss of both treated woods after being attacked by subterranean termites. Similarly, a strong correlation also happened in the weight loss of sengon and jabon wood with hardness value (**Fig. 19**). This is

due to the successful incorporation of MEG and nano-silica with the wood polymers. Dirna et al. (2020a) confirmed the interaction between MEG, nano-silica, and wood polymers, indicated by Si–O–Si, cross-linked with the wood cell wall components. Accordingly, the addition of these chemicals can improve the durability of sengon and jabon wood. **Table 7** shows the level of wood damaging impact after being attacked by subterranean termites.

Table 7. The level of wood-damaging impact

Wood Species	Repetitions	Treatments				
		Untreated	MEG	MEG-Silica 0.5%	MEG-Silica 0.75%	MEG-Silica 1%
Sengon	1	0	0	0	10	10
	2	0	0	1	8	10
	3	0	0	2	8	9
	4	0	0	1	10	10
	5	0	0	4	9	9
Jabon	1	0	0	3	10	10
	2	0	0	1	5	10
	3	0	0	2	8	10
	4	0	0	1	6	10
	5	0	0	2	7	10

Fig. 20 and **Fig. 21** show that the untreated wood has more serious damage than the MEG-treated wood. This condition aligns with the wood damage number presented in **Table 7**. Adding 0.5% nano-silica to the solution did not turn out to be enough to stop termite activity. From **Fig. 20c** and **Fig. 21c**, there still appears to be moderate damage to the wood, likewise with the damage numbers shown in **Table 5**, which are close to zero. Contrarily, nano-silica content of 0.75% and 1% seem effective in preventing subterranean attacks and only cause minor damage.



(a) (b) (c)

(d) (e)

Fig. 20. The condition of sengon wood after being damaged by subterranean termites (a) untreated, (b) MEG-treated, (c) MEG-Silica 0.5%, (d) MEG-Silica 0.75%, and (e) MEG-Silica 1%.

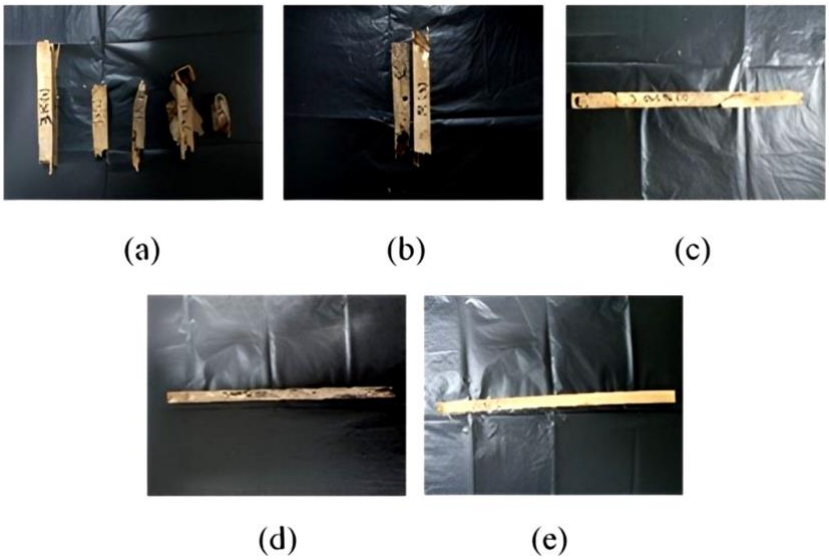


Fig. 21. The condition of jabon wood after being damaged by subterranean termites (a) untreated, (b) MEG-treated, (c) MEG-Silica 0.5%, (d) MEG-Silica 0.75%, and (e) MEG-Silica 1%.

The results show increased wood durability from class V to IV for sengon wood, whereas jabon wood increases from V to IV. More concisely, the durability class of sengon and jabon wood after being impregnated with MEG and nano-silica against dry wood termites and subterranean termites can be seen in **Table 8**. Thus, the treatment recommended for sengon and jabon wood modification is the MEG-Silica 1%.

Table 8. Sengon and jabon wood durability class against subterranean termite attacks

Wood samples	Treatment	Strength class	
		SNI 01-7207	ASTM D 1758-06
Sengon	Untreated	V	0
	50% MEG	V	4
	MEG-Silica 0.5%	IV	6
	MEG-Silica 0.75%	IV	7
	MEG-Silica 1%	IV	7
Jabon	Untreated	V	0
	50% MEG	V	4
	MEG-Silica 0.5%	IV	6
	MEG-Silica 0.75%	IV	6
	MEG-Silica 1%	IV	8

4. Conclusions

Nano-silica was successfully synthesized from betung bamboo stems using the ultrasonication method. The PSA analysis explained that the produced nano-silica had an average particle size of 93 nm. The zeta potential value of nano-silica showed an average of -44.21 mV. This nanoparticle had also been successfully impregnated with sengon and jabon wood. According to the results, the MEG-Silica 1% had the greatest impact on the physical properties, such as WPG, specific gravity, and wood discoloration. The wood's mechanical properties, such as MOE, MOR,

and hardness, also experienced a significant improvement in contrast to the other treatments. It also increased the strength class of sengon wood significantly to III compared to the sengon untreated wood with a strength class of IV–V. Jabon wood also improved strength class from III – IV (untreated wood) to III. Both woods are also highly resistant to dry wood and subterranean termite attacks. The durable class of sengon wood also improved from V (untreated wood) to IV with the addition of MEG-Silica 1%. Similar to sengon wood, jabon wood also experienced an increasing durable class from V (untreated wood) to IV.

References

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