Dimensional Stability and Moisture Content of White Teak Wood Treated with Nano-SiO_2 and Furfuryl Alcohol

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ABSTRACT

The objective of this study is to assess the impact of nanoparticle impregnation on the moisture content and dimensional stability of white teak wood derived from Southeast Sulawesi, Indonesia. The impregnation method was employed to process white teak wood samples, with varying concentrations of Furfuryl Alcohol (FA) and nano-SiO_2. The wood samples underwent examinations to quantify the moisture content, dimensional changes, and mechanical properties after treatment, including Weight Percent Gain (WPG), Bulking Effect (BE), Anti-Swelling Efficiency (ASE), and Water Uptake (WU). The results indicated that the dimensional stability of white teak wood was considerably enhanced with the impregnation process, as evidenced by a decrease in swelling, compared to the untreated wood. Additionally, the moisture content of impregnated wood decreased significantly, suggesting improved moisture resistance. These findings demonstrate that the application of nano-SiO_2 and FA as impregnation materials offers a viable solution for enhancing the quality and durability of white teak, potentially expanding its applications in the construction sector.

Keywords-dimensional stability; moisture content; impregnancies; nano-SiO_2; furfuryl alcohol

I. INTRODUCTION

Wood is a critical building material in the construction industry, particularly in tropical regions including Indonesia. An impregnation process is necessary to enhance the physical and mechanical properties of wood, including strength, stability, and durability [1]. This process not only enhances the wood's selling value, but also renders it more viable for use in the construction of structures. The application of nanoparticles, such as nano-SiO_2 and furfuryl alcohol, in the treatment of white teak wood, offers an eco-friendly solution that promotes the utilization of waste materials. This method mitigates the dependence on harmful chemicals and minimizes environmental pollution, while producing more stable and durable building products [2-4]. Nano-SiO_2, a nanostructure material, is recognized for its exceptional mechanical properties and its capacity to enhance the resilience and strength of wood. Similarly, FA exhibits favorable binding properties and can increase the moisture-resistance of wood [5-6].

A. Wood Impregnation Process

The wood impregnation process is a technique that introduces preservatives or compounds into the wood tissue, enhancing its mechanical properties and durability. Figure 1 depicts the equipment used in the wood impregnation process.

Fig. 1. Wood impregnation equipment.

Various methods can be deployed, including vacuum, pressure, and sprinkling methods. Among these, the vacuum method is widely utilized due to its ability to ensure the penetration of impregnation materials into wood fibers. Authors in [6] investigated the potential of vacuum methodologies to enhance the penetration of nano-SiO_2 into wood tissues. The findings indicated that the nano penetration of SiO_2 can enter a depth of 5-10 mm, which is sufficient to enhance the resistance of wood to fungal and rodent attacks. Furthermore, it is crucial to evaluate the concentration and contact duration of the impregnation material with the wood. In [7], authors demonstrated that the mechanical properties of wood can be enriched by increasing the concentration of FA in the impregnation process. Specifically, wood impregnated with a 20% concentration, exhibited a 25% increase in compressive strength compared to unimpregnated wood.

B. Nano-SiO_2

Nano-SiO_2 is a nanomaterial that has been extensively studied in a variety of applications, such as timber processing. It provides unique characteristics including its high stability, compact size, and capacity, enhancing its mechanical properties. Authors in [8] indicated that the utilization of nano-SiO_2 in wood impregnation can substantially improve the compressive and tensile strength of teak wood. The hydrophobic properties of nano-SiO_2 further contribute to the enhanced resistance of wood to moisture [9]. In [10], the absorption of water by white teak wood impregnated with nano-SiO_2 decreased by 30%, extending the lifespan of the wood in humid environments. This is of paramount importance, as white teak wood is frequently employed in tropical regions with elevated humidity levels. Therefore, the utilization of nano-SiO_2 in the impregnation of white teak wood exhibits significant potential for enhancing the mechanical performance and durability of wood, which could have a beneficial effect on the Indonesian timber industry [11].

C. Furfuryl Alcohol

FA, with the chemical formula $C_5H_6O_2$, is an organic compound derived from the hydrogenation of furfural, which is typically obtained from lignocellulose materials, such as rice husks, maize, and wood. In the woodworking industry, FA is used as an additive in wood treatment, enhancing resistance to environmental factors, like moisture, pests, and decay. During the impregnation process, FA acts as a binding agent, penetrating the cellulose structure of wood and interacting with its chemical components, particularly lignin and hemicellulose. This interaction strengthens the wood by forming stable chemical bonds, improving its mechanical properties and durability. The treatment reduces water absorption, increases density, and decreases porosity, making the wood more resistant to decomposition. Impregnation is typically carried out using pressure or vacuum methods, ensuring a deep penetration of FA into the wood fibers. This process significantly enhances the wood's structural integrity, making it ideal for construction applications requiring high resistance to extreme weather and biological threats. FA treated wood is well-suited for outdoor structures, bridges, decking, and cladding exposed to high humidity or water. By improving the mechanical performance and longevity of white teak and other timber, FA treatment offers substantial benefits to the Indonesian timber industry, extending the service life of wood while reducing maintenance needs.

This study aims to evaluate the mechanical performance of white teak wood treated with nano-SiO_2 and furfuryl alcohol, focusing on the effects of impregnation on dimensional stability and compressive strength. The findings are expected to contribute to the advancement of wood impregnation technology and offer industry recommendations for improving the white teak wood products. As a result, this investigation will not only benefit academics, but also hold considerable potential for practical applications in the construction sector, particularly in the development of more durable and high-performance wooden building materials.

II. RESEARCH METHODOLOGY

This research follows a structured methodology consisting of four main stages: material selection, sample preparation, impregnation process, and mechanical performance testing. Each stage is carefully designed to ensure accuracy and reliability in evaluating the mechanical properties of white teak wood treated with nano-SiO_2 and furfuryl alcohol. A flow diagram illustrating the methodology is provided in Figure 2.

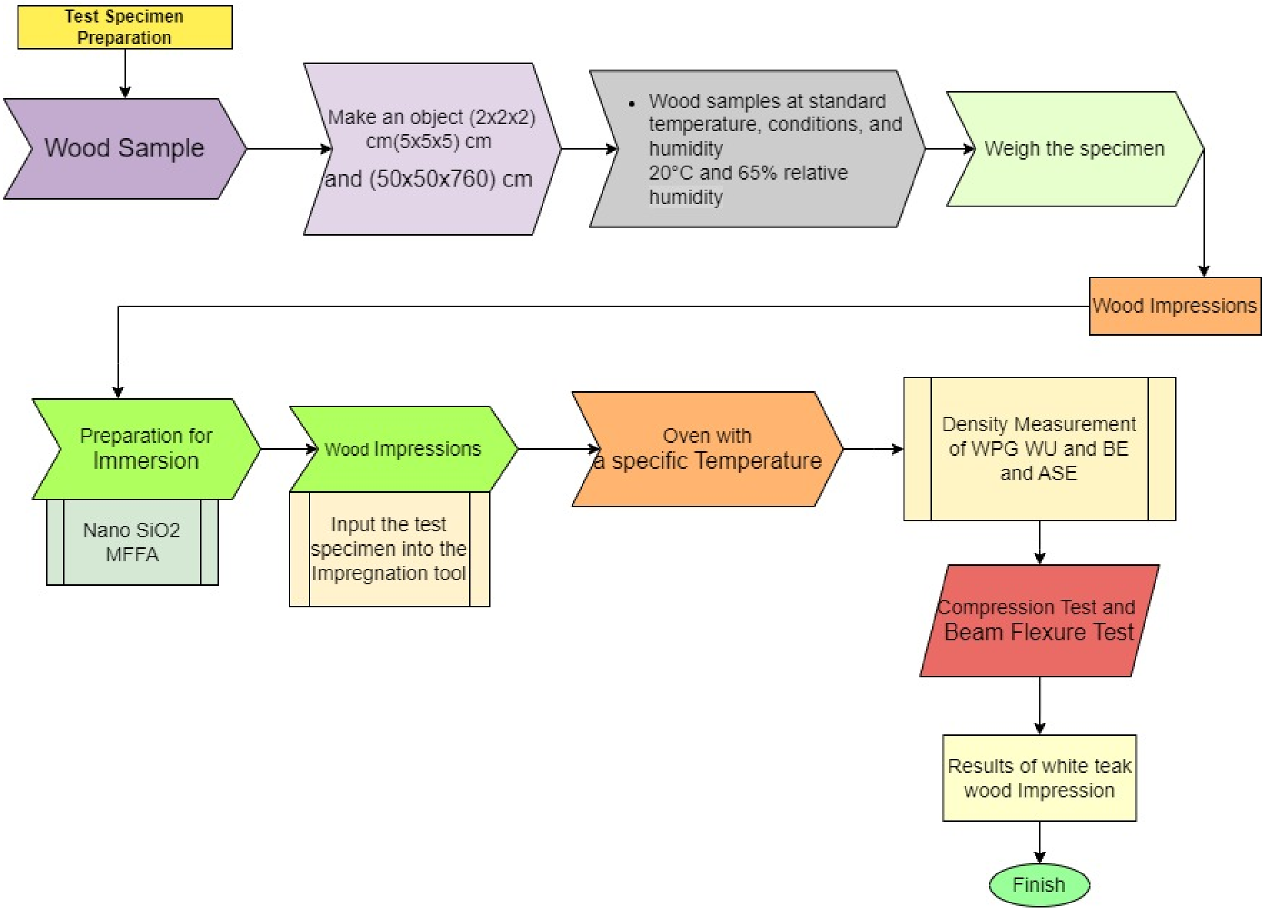


Fig. 2. Wood impregnation methodology.

A. Key Parameters

The study examines key parameters to evaluate wood quality, especially in the context of impregnation and construction applications. These parameters include density, WPG, BE, ASE, and WU, and provide valuable insights into wood quality, mechanical performance, and suitability for various applications. Understanding them allows the wood industry to enhance product quality, improve durability, and promote sustainable wood usage. Table I presents the composition of the wood specimens used in this study.

TABLE I. WOOD IMPREGNATION COMPOSITION

No.	Test specimen	Test	Dimensions (cm)	Quantity
1.	Control wood	Physical properties	2 × 2 × 2	5
3.	Impregnation wood		2 × 2 × 2	

1) Density Test

The density test evaluates the density of wood, which is directly related to its strength and durability. Generally, denser wood exhibits greater strength and characteristics. Additionally, density can also predict other mechanical properties, such as compressive strength, tensile strength, and resistance to decay. The density (ρ) is calculated before and after treatment using:

$$\rho = \frac{sample\ weight}{\text{specimen volume}}$$

2) Weight Percent Gain

The WPG measures the amount of impregnation material absorbed by wood, expressed as a percentage increase in weight. This test is important to understand the effectiveness of impregnation treatment in enhancing wood properties, such as durability, dimensional stability, and resistance to moisture and decay. The WPG is calculated using:

$$WPG = \frac{W_1 - W_0}{W_0} \text{x } 100\%$$

where W_0 is the dry weight before impregnation (g) and W_1 is the dry weight after impregnation (g).

3) Bulking Effect

The BE aims to assess the strength of wood by measuring its ability to return to its original shape after being subjected to load. This is an important indicator of the structural strength of wood. BE is essential for engineers and architects in designing safe and efficient structures, as it provides information on how much wood can be loaded before it undergoes permanent deformation. In addition, BE testing enables comparisons between different types of wood or different treatments, allowing it to determine which is more suitable for a particular application. The BE is calculated by:

$$BE = \frac{V_1 - V_0}{V_0} x\ 100\%$$

where V_0 is the dry volume before impregnation (cm^3) and $V1$ is the dry volume after impregnation (cm^3).

4) Anti-Swelling Efficiency

The ASE evaluates the effectiveness of impregnation treatments in reducing wood swelling due to moisture absorption. This parameter is crucial for assessing dimensional stability, as excessive swelling can lead to warping, cracking, and other forms of deformation in wood products. In addition, by determining the ASE value, researchers can compare different treatments and assess their ability to enhance wood durability, making it more suitable for humid environments and various applications.

5) Water Uptake

The WU measures the amount of water absorbed by wood over a specific period. This is important for understanding the wood's moisture resistance, as excessive water absorption can lead to swelling, degradation, and reduced durability. The WU data evaluate the effectiveness of impregnation treatments in limiting the water absorption, which is essential for applications that require water resistance, such as in building construction in humid areas.

B. Impregnation Process

The impregnation process was carried out using untreated white teak samples and a 5% w/v impregnation solution. Before impregnation, the wood samples were dried in an oven at 105 °C for 48 hours to remove moisture, The impregnation solution was sonicated at an 40% amplitude for 60 minutes. To ensure equal dispersion of nanoparticles. The dried wood samples were then placed in a container filled with impregnation solution, and nylon wire weights (which do not react with the impregnation solution) were added. The container was inserted into an impregnation tube where the process took place. It was carried out with a vacuum of -0.5 bar for 30 minutes and continued with a pressure of 1 bar for 120 minutes. After impregnation, the wood samples were rinsed with demineralized water to remove any remaining solution. Additionally, the wood was wrapped in aluminum foil and heated at 65 °C for 12 hours, then dried in an oven at 105 °C for 48 hours until a constant weight was achieved. Following impregnation, the wood mass and dimensions were measured to calculate density, WPG, BE, ASE, and WU.

To evaluate the effects of impregnation, the mechanical properties of the treated white teak samples were tested, including compressive strength, tensile strength, and modulus of elasticity using standard mechanical test equipment. The results were compared with those of untreated white teak.

III. RESULTS AND DISCUSSION

A. Moisture Content

Table II portrays the moisture content values of both impregnated and natural wood.

TABLE II. MOISTURE CONTENT

Specimen 2 × 2 × 2 cm	Initial weight	Air dry weight	Moisture content (%)
Impregnation	4.35	3.93	0.11
	4.23	3.81	0.11
	4.27	3.85	0.11
	4.05	3.68	0.10
	3.95	3.58	0.10
	4.59	4.13	0.11
	4.09	3.69	0.11
	4.09	3.68	0.11
	3.75	3.36	0.12
	3.82	3.45	0.11
Natural conditions	4.25	3.66	0.16
	4.91	4.22	0.16
	4.05	3.48	0.16
	4.37	3.76	0.16
	4.7	4.04	0.16
	3.98	3.41	0.17
	4.07	3.51	0.16
	4.57	3.91	0.17
	4.54	3.9	0.16
	4.38	3.73	0.17

Impregnated wood exhibited a significant lower moisture content (0.11%) compared to natural wood with a moisture content of 0.16%, representing a 34% decrease in water absorption capacity. This reduction demonstrates the effectiveness of the impregnation process in filling wood pores, inhibiting water penetration into its structure [12]. This is also essential to improve wood resistance to decay, microorganism attacks, and dimensional changes due to moisture fluctuations, as wood becomes more stable and durable, especially in humid environmental conditions [12]. By using natural wood as a control sample, these findings strengthen the evidence of the effectiveness of impregnation treatment [4]. Previous research has confirmed a difference in moisture content between impregnated wood and natural wood [13]. This explains that the impregnation process in wood reduces the moisture content that wood can absorb [14].

B. Specific Gravity

Timber specific gravity, which is a comparison between the mass of dry wood without water and its volume, indicates that if the specific gravity values of natural and impregnated wood are the same, the impregnation process does not significantly increase the mass of solid material or drastically change wood volume. Table III depicts the specific gravity of impregnated and natural wood. The consistency of this wood structure indicates that despite the differences in water absorption properties, the mass and volume distribution between natural and impregnated wood remains similar [15]. This suggests that the impregnation materials do not significantly increase the dry wood mass, implying that the material either fills only a small portion of the wood's pores or is thinly distributed on the surface. Although the specific gravity is the same, the difference in moisture content shows that the impregnation successfully changes wood properties in order for it to be more resistant to water [16]. This indicates that the impregnation process affects the functional properties of the wood, such as reduced water absorption, without altering its basic characteristics, such as specific gravity [17]. In practical applications, wood with the same specific gravity but lower moisture content will be more stable in a variety of environmental conditions, without altering its basic mechanical properties (such as strength or durability). These findings confirm that the impregnation process primarily impacts water absorption rather than altering the fundamental structure of the wood [18].

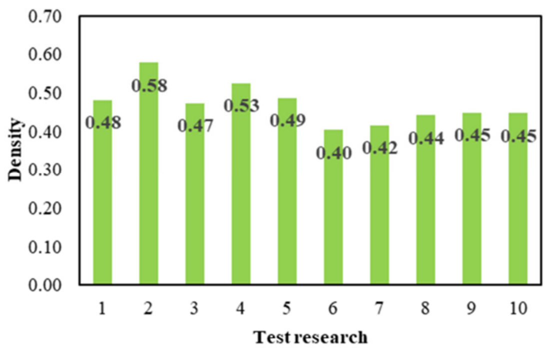
TABLE III. SPECIFIC GRAVITY

Specimen 2 × 2 × 2 cm	Specific gravity	Average
Impregnation	0.57	0.545
	0.59	
	0.57	
	0.53	
	0.53	
	0.60	
	0.54	
	0.54	
	0.48	
	0.50	
Control	0.56	0.547
	0.67	
	0.55	
	0.61	
	0.56	
	0.47	
	0.48	
	0.52	
	0.52	
	0.52	

C. Density Test of White Teak Wood

The dimensional stability of white teak wood is illustrated in Figures 3(a) and 3(b), presenting the variation in dry weight density across different samples.

(a)



(b)

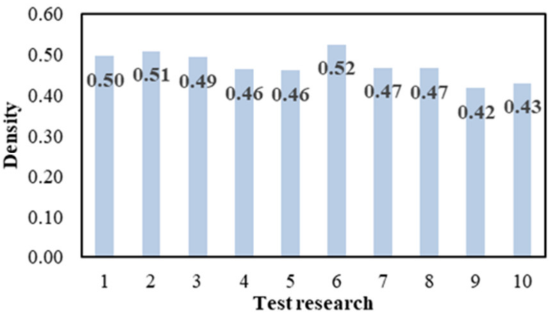


Fig. 3. Dry weight density in (a) natural conditions, (b) impregnated wood.

In the impregnated samples, the highest density recorded was 0.52 (in Sample 6), while the lowest was 0.42 (in Sample 9). The density variations between samples showed significant differences, indicating that the material may have different structures, compositions, or treatments. Sample 6, probably exhibits a higher level of compactness and lower porosity, making it denser and resistant to pressure. In contrast, Sample 9 is lighter and may have more pore space, making it easier to absorb liquids and having lower mechanical strength.

D. Weight Percent Gain Results

The WPG results for natural conditions and impregnated wood are illustrated in Figures 4 and 5, respectively. WPG indicates how much of the impregnating substance (e.g., polymer, chemical compound, or liquid) has been maintained in the wood, rather than just absorption or deposition.

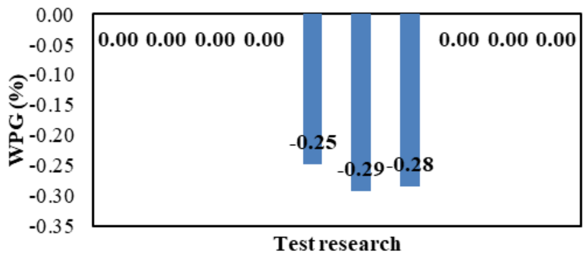


Fig. 4. WPG natural conditions.

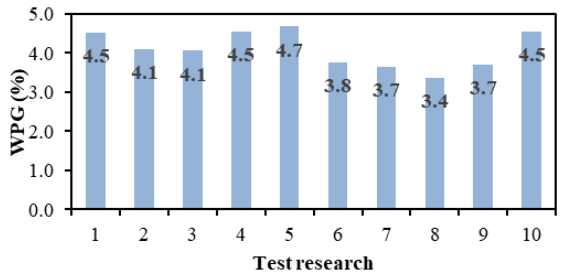


Fig. 5. WPG impregnation.

The WPG values, in the case of impregnated wood, range from 3.4% to 4.7%, indicating variations in the amount of material retained after impregnation across different samples. These results provide insight into the material's ability to retain additional materials, such as coatings, copolymers, or nano-based materials, like SiO_2, and FAs.

- High WPG (Samples 1, 4, 5, 10):

These samples exhibit the highest material absorption or deposition, indicating more effective chemical interactions or better material quality in receiving additional materials.

- Low WPG (Samples 6-9):

These samples exhibit the lowest material absorption or deposition, likely resulting from the material's less compatible surface properties, suboptimal application process, or different material composition.

E. Bulking Effect Results

Figures 6 and 7 illustrate the BE measured in natural conditions and during the impregnation process, respectively. BE is performed to evaluate the increase in wood volume after impregnation. The results demonstrated that BE values range from 2.9% (Sample 2) to 5.1% (Sample 6). This variation suggests differences in the extent of impregnation and treatment efficiency across the samples.

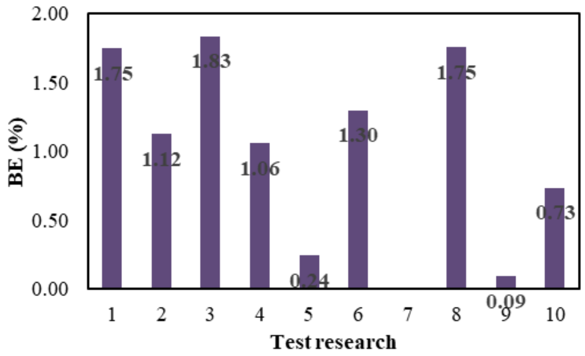


Fig. 6. BE natural conditions.

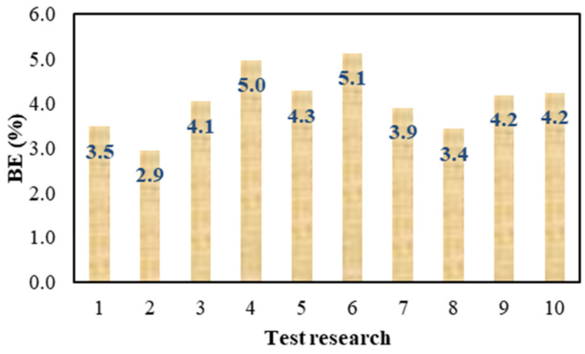


Fig. 7. BE impregnation.

The majority of BE values were in the range of 3.4% - 5%, showing a relatively consistent trend with some samples diverging (Samples 2 and 6). Samples with higher BE values (such as Sample 6) likely experienced greater penetration of the treatment, which may enhance properties, like dimensional stability and resistance to environmental factors, compared to untreated wood.

F. Water Uptake Results

Figures 8 and 9 illustrate the WU percentages in natural conditions and during the impregnation process, respectively. WU indicates the ability of wood to absorb water. A higher value demonstrates better water absorption, which can reduce the wood's resistance to swelling, decay, and mechanical degradation. Category 4 (61.7%) exhibited the highest WU, indicating greater water absorption between samples, which may suggest lower resistance to moisture-related degradation. In comparison, category 5 (53.9%) exhibited the lowest WU, suggesting better moisture resistance. The average overall WU value was about 56.2%.

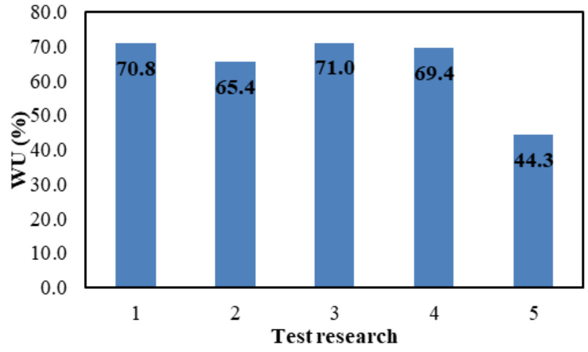


Fig. 8. WU natural conditions.

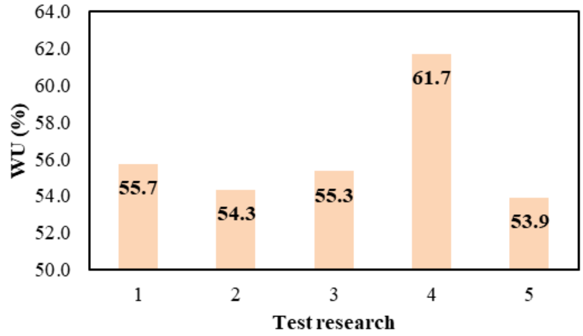


Fig. 9. WU impregnation.

G. Anti-Swelling Efficiency Results

Figures 10 and 11 present the ASE (%) for five categories, illustrating the effectiveness of impregnation in reducing wood swelling due to moisture absorption. Higher ASE values indicate better dimensional stability, while negative ASE values suggest increased susceptibility to shrinkage or expansion. Category 5 exhibited a negative ASE value (-0.6%), indicating a greater shrinkage compared to other categories. This aligns with its low WU value (53.9%), demonstrating that it absorbed less water but still showed poor resistance to dimensional changes. In contrast, Category 4 displayed the highest ASE value (0.3%), exhibiting the best resistance to swelling and shrinkage. However, it also had the highest WU (61.7%), meaning that although it absorbed more water, it maintained its structural stability better than other categories. Categories 1 and 3, with the same ASE value (0.2%), revealed moderate swelling resistance, aligning with their mid-range WU values. Their performance suggests a balance between water absorption and dimensional stability. Meanwhile, Category 2 with an ASE value of zero (0.0%) showed no significant anti-swelling efficiency, meaning its swelling behavior remained unchanged despite impregnation. The relationship between ASE and WU suggests that high WU does not necessarily correlate with poor dimensional stability. Instead, the effectiveness of impregnation in stabilizing the wood structure plays a key role.

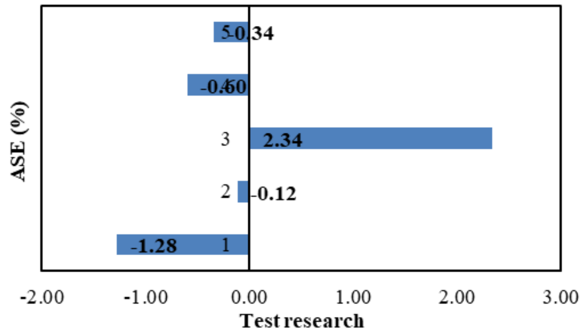


Fig. 10. ASE (%) natural conditions.

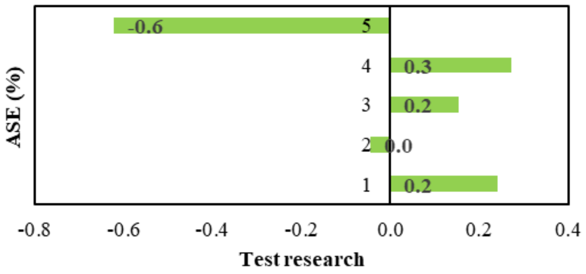


Fig. 11. ASE (%) impregnation.

The impregnation process of white teak wood utilizing nano-SiO_2 and FA was carried out through a vacuum and pressure method, ensuring optimal penetration of the impregnation material into the wood fibers [19]. In [20], it is demonstrated that the use of high-pressure during impregnation enhances the efficiency of material penetration into the wood structure, thereby significantly improving mechanical performance. According to [21], specific temperature and time control is essential during impregnation to ensure that the impregnation material can permeate well without damaging the wooden structure. It has been also highlighted that excessively high concentrations of impregnation material can lead to precipitation within the wood, reducing treatment effectiveness [22].

IV. CONCLUSION

The purpose of this paper is to investigate the effects of impregnating Southeast Sulawesi white teak wood with nano-SiO_2 and Furfuryl Alcohol (FA) copolymers, aiming to enhance its stability, durability, and mechanical properties for improved performance in various structural applications. The impregnation process utilized vacuum and pressure methods to ensure optimal penetration of the materials into the wood fibers. The results demonstrated significant improvements in Weight Percent Gain (WPG), Bulking Effect (BE), and density compared to the untreated wood, indicating enhanced physical properties and the potential for diverse applications. Given the increased need for sustainable and high-quality materials, other impregnations and their uses in the wood sector need further investigation.

Recommendations for further research include exploring various concentrations of nano-SiO_2 and FA to determine the most effective combinations. Additionally, research on the long-term effects of these treatments under various environmental conditions is also very important for understanding the durability of impregnated wood.

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