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Effect of Natural Pahae Zeolite Addition on the Mechanical and Physical Properties of Areca Nut Fiber Reinforced Polyester Composite Boards

Susilawati[1,2]*, Rosi Adelia Simanjuntak[1], Yuan Alfinsyah Sihombing[1,2], and Manovri Yeni[3]

[1]*Departement of Physics, Faculty of Mathematics and Natural Science, Universitas Sumatera Utara, Medan, 20155, Indonesia*
[2]*Center of Excellence for Functional Materials and Instrumentation, Universitas Sumatera Utara, Medan 20155, Indonesia*
[3]*Department of Civil Engineering, Faculty of Engineering, Universitas Muhammadiyah Aceh, Indonesia*
*Corresponding Author: susilawati@usu.ac.id

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ABSTRACT

This study investigates the effect of natural Pahae zeolite as a locally sourced mineral filler on the mechanical and physical properties of areca nut fiber–polyester composite boards. The novelty lies in combining natural Pahae zeolite with areca nut fiber to integrate organic fiber reinforcement and inorganic mineral filling. Composite boards were fabricated using polyester resin, areca nut fiber, and natural Pahae zeolite ratios of 60:40:0, 60:30:10, 60:20:20, 60:10:30, and 60:0:40 by hot pressing. The optimum composition was 60:10:30, yielding the highest Modulus of Rupture (MoR) of 177.3 MPa, Modulus of Elasticity (MoE) of 875.08 MPa, and compressive strength of 212.66 MPa. Increasing zeolite content also affected density and moisture content, while excessive zeolite addition (40 wt%) reduced mechanical performance, potentially due to particle agglomeration and increased brittleness. SEM–EDX analysis revealed morphological changes and increased Si and Al contributions with increasing zeolite content. All MoR values exceeded the minimum requirements of SNI 03-2105-2006 and JIS A 5908:2003, whereas the MoE values did not meet the applicable requirements. These findings demonstrate the potential of natural Pahae zeolite as a locally sourced mineral filler for natural fiber–polyester composites and its role in improving flexural performance at an appropriate composition.

Keywords: Areca nut fiber, Composite board, Mechanical properties, Natural Pahae Zeolite, Polyester resin

ABSTRAK

Penelitian ini mengkaji pengaruh zeolit alam Pahae sebagai pengisi mineral yang bersumber dari lokal, terhadap sifat mekanik dan fisik papan komposit berbasis serat buah pinang–poliester. Kebaruan penelitian ini terletak pada kombinasi zeolit alam Pahae dengan serat buah pinang untuk mengintegrasikan penguatan serat organik dan pengisian mineral anorganik. Papan komposit dibuat menggunakan rasio resin poliester, serat buah pinang, dan zeolit alam Pahae sebesar 60:40:0, 60:30:10, 60:20:20, 60:10:30, dan 60:0:40 dengan metode *hot press*. Komposisi optimum diperoleh pada rasio 60:10:30, yang menghasilkan nilai tertinggi *Modulus of Rupture* (MoR) sebesar 177,3 MPa, *Modulus of Elasticity* (MoE) sebesar 875,08 MPa, dan kuat tekan sebesar 212,66 MPa. Peningkatan kandungan zeolit juga memengaruhi densitas dan kadar air, sedangkan penambahan zeolit secara berlebihan (40% berat) menurunkan kinerja mekanik, yang kemungkinan disebabkan oleh aglomerasi partikel dan peningkatan kerapuhan. Analisis SEM–EDX menunjukkan perubahan morfologi dan peningkatan kontribusi unsur Si dan Al seiring dengan peningkatan kandungan zeolit. Seluruh nilai MoR melebihi persyaratan minimum SNI 03-2105-2006 dan JIS A 5908:2003, sedangkan nilai

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MoE belum memenuhi persyaratan yang berlaku. Hasil penelitian ini menunjukkan potensi zeolit alam Pahae sebagai pengisi mineral lokal pada komposit serat alam–poliester serta perannya dalam meningkatkan kinerja lentur pada komposisi yang tepat.

Kata kunci: Papan Komposit, Resin Poliester, Serat buah Pinang, Sifat Mekanik, Zeolit Alam Pahae

1. Introduction

Composite boards are engineered materials composed of two or more constituents with distinct characteristics, in which each constituent contributes specific properties to the final material [1]. Composite materials offer several advantages, including high mechanical strength, low weight, ease of fabrication, corrosion resistance, electrical insulation, and compatibility with other materials [2]. In recent years, the utilization of natural fibers as reinforcement in composite materials has been widely explored as an approach to reduce dependence on synthetic fibers and promote more sustainable material development [3].

Fibers play a crucial role as the primary reinforcing elements in composite fabrication and can be derived from either natural or synthetic sources [4]. Compared with synthetic fibers, natural fibers have attracted considerable attention because of their abundance, low cost, renewability, biodegradability, and environmental advantages. In composite structures, fibers can improve strength and stiffness while also reducing the density of the resulting material [5]. The performance of fiber-reinforced composites is strongly influenced by the characteristics of the reinforcement and matrix, including fiber type, length, orientation, morphology, matrix composition, catalyst, and fiber–matrix interfacial bonding [6]. Therefore, optimization of the reinforcement characteristics and composite composition is essential for achieving the desired mechanical and physical properties.

Among various natural fibers, areca nut husk fiber (*Areca catechu*) has received considerable attention as a potential reinforcement material because of its high cellulose content, low density, renewability, and favorable mechanical characteristics [7]–[9]. Other lignocellulosic fibers, including coconut husk fiber (*Cocos nucifera*), bamboo fiber, oil palm empty fruit bunch fiber, and bagasse fiber, have also been investigated as sustainable reinforcement materials. Coconut husk fiber, for example, has been reported to improve the density and durability of composite boards [10], whereas bamboo fibers exhibit high strength and elasticity [11]. Similarly, oil palm empty fruit bunch fibers show potential as reinforcement materials [12], while bagasse fibers provide an environmentally friendly alternative for composite production [13].

Several studies have demonstrated that areca nut fiber-reinforced polyester composites can exhibit enhanced tensile and flexural properties, with their performance strongly influenced by fiber treatment, fiber content, and composite composition [14]. These findings indicate that the incorporation and optimization of natural fibers, particularly areca fiber, can play an important role in improving the mechanical performance and sustainability of polymer-based composites.

In addition to natural fibers, mineral fillers such as zeolite have been widely incorporated into polymer composites to improve stiffness, thermal stability, moisture resistance, and interfacial bonding owing to their porous crystalline structure and high surface area [15]–[17]. Natural zeolite is an aluminosilicate mineral characterized by a crystalline framework containing interconnected microscopic pores, which provide high porosity and excellent adsorption capacity [18]–[20]. Its low cost, natural abundance, and environmental advantages further enhance its potential as a multifunctional inorganic filler for polymer composite applications.

Among locally available mineral resources, natural Pahae zeolite is a potentially valuable filler because of its silica- and alumina-rich composition, with SiO_2 and Al_2O_3 contents of 64.44 and 13.16 wt%, respectively [18]. Its particulate mineral structure may provide an inorganic phase capable of modifying the packing, stiffness, and stress-transfer behavior of polyester-based composites. The incorporation of Pahae zeolite into natural-fiber-reinforced composites therefore provides an opportunity to combine the reinforcing characteristics of natural fibers with the mechanical and functional contributions of an inorganic mineral filler.

Previous studies have also demonstrated the potential of areca nut fiber for board production. Nurdin et al. (2020) investigated particleboards fabricated from areca nut fibers bonded with tapioca adhesive using fiber-to-adhesive weight ratios of 90:10, 80:20, 70:30, and 60:40. Based on the JIS A 5908-2003 and SNI 03-2105-2006 standards, the resulting boards exhibited densities of 0.38–0.71 g/cm^3, moisture contents of 8.05–9.58%, water absorption of 51.19–168.02%, thickness swelling of 5.78–13.97%, modulus of rupture (MoR) of 3.92–73.31 kg/cm^2, and modulus of elasticity (MoE) of 552.29–4761.68 kg/cm^2, with the reported properties meeting the applicable quality standards [21].

Despite the extensive investigation of natural-fiber-based composites and mineral fillers in polymer systems, the interaction among natural fiber, mineral filler, and polyester matrix remains insufficiently understood. In particular, the effect of systematically varying the fiber-to-zeolite ratio within a constant polyester matrix has received limited attention. The progressive replacement of areca nut fiber with natural Pahae zeolite represents an important formulation strategy because increasing mineral content may improve rigidity and particle packing, whereas excessive mineral loading may promote particle agglomeration, reduce the reinforcing contribution of the fibers, and modify stress transfer within the polymer matrix.

Therefore, the novelty of this study lies in systematically investigating the transition from a fiber-dominated to a zeolite-dominated reinforcement system through the progressive replacement of areca nut fiber with natural Pahae zeolite while maintaining a constant polyester matrix content. This approach enables the effects of fiber–mineral–polymer interactions on the mechanical, physical, and microstructural properties of the composite boards to be evaluated. In particular, the study examines how changes in the fiber–zeolite balance affects mechanical performance, physical properties, and microstructural characteristics and identifies the composition that provides the most favorable balance among the polyester matrix, natural fiber reinforcement, and mineral filler.

Accordingly, this study aims to investigate the effect of natural Pahae zeolite incorporation on the mechanical, physical, and microstructural properties of areca nut fiber–polyester composite boards and to determine the composition that provides the most favorable overall performance.

2. Methods

2.1. Preparation of Areca Nut Fibers

The areca nut husks used in this study were obtained from waste areca trees in the Percut Sei Tuan area, Medan. The preparation process began with the collection of areca nut husks as the primary raw material. The fibers were then separated from the husks and immersed in a 5% NaOH solution for 2 hours to remove impurities and improve fiber surface adhesion. After the immersion stage, the fibers were thoroughly washed with clean water to remove any residual chemicals and impurities. The fibers were then dried in an oven under controlled temperature conditions for 2 hours. Once dried, the fibers were cut into lengths of 1 cm according to the specified size. Thus, the areca nut fibers were ready to be used as reinforcement material.

2.2. Preparation of Natural Pahae Zeolite

In this study, natural Pahae zeolite obtained from Pahae Village was used in its initial form as chunks. The first step involved crushing the zeolite using a hammer, followed by grinding with a mortar until a finer powder was obtained. The ground material was then sieved through a 100-mesh screen to obtain a particle size of approximately 149 μm. The resulting zeolite powder was then physically activated using a muffle furnace at 400 °C for 4 h. After the activation process, the zeolite was characterized by using X-Ray Fluorescence (XRF) to determine its chemical composition and compare it with relevant standards. Following these processes, the activated zeolite was ready to be used as a filler material in the composite boards.

2.3. Fabrication of Composite Boards Based on Areca Nut Fibers

The composite boards were produced using three main components: areca nut fibers, natural Pahae zeolite, and polyester resin. The unsaturated polyester resin used in this study was Yukalac® 157 BQTN-EX Series, with methyl ethyl ketone peroxide (MEKP) as the catalyst at a concentration of 1 wt% of the resin weight. The composition ratios of polyester resin, areca nut fibers, and natural Pahae Zeolite were determined based on weight fraction (wt%). Five different formulations were prepared as follows: A (60% : 40% : 0%), B (60% : 30% : 10%), C (60% : 20% : 20%), D (60% : 10% : 30%), and E (60% : 0% : 40%). The mixing process was carried out manually by blending the areca nut fibers, zeolite powder, polyester resin, and catalyst until a homogeneous mixture was achieved. The mixture was then poured into a mold with dimensions of 7 cm × 7 cm × 1 cm. The hot-pressing process was conducted at a temperature of 100 °C under a pressure of 1 MPa for 30 minutes to form the composite boards. After pressing, the samples were cooled at room temperature and removed from the mold.

The fabricated boards were then characterized to evaluate their performance. Mechanical properties assessed included Modulus of Rupture (MoR), Modulus of Elasticity (MoE), and compressive strength, while physical properties such as density, moisture content, and water absorption were also measured. Morphological and elemental analyses were performed using Scanning Electron Microscopy with Energy-Dispersive X-Ray (SEM-EDX) to examine surface structure and chemical composition. All findings were evaluated in accordance with the Indonesian National Standard (SNI).

2.4. Mechanical Testing

The mechanical properties of the composite boards were evaluated using a Universal Testing Machine (UTM). Five composite formulations were investigated, namely A (60:40:0), B (60:30:10), C (60:20:20), D (60:10:30), and E (60:0:40) wt% polyester resin:areca nut fiber:natural Pahae zeolite. The specimens were prepared from the fabricated composite boards with dimensions of approximately 7 cm × 7 cm × 1 cm. One specimen was tested for each composition.

The Modulus of Rupture (MoR) and Modulus of Elasticity (MoE) were determined from the same three-point bending (flexural) test using the UTM. Each specimen was placed on two supports with a span length (L), and the load was applied at the midpoint until failure. The applied load and corresponding deflection were recorded to obtain the load–deflection curve. The specimen width (b) and thickness (d) were measured before testing respectively.

The MoR was calculated from the maximum load obtained during the three-point bending test using:

$$MoR = \frac{3P_{\max}L}{2bd^2} \tag{1}$$

where $P_{\max}$ is the maximum load at failure (N), L is the span length between the supports (mm), b is the specimen width (mm), and d is the specimen thickness (mm).

The MoE was determined from the slope of the linear portion of the load–deflection curve using:

$$MoE = \frac{L^3 m}{4bd^3} \tag{2}$$

where m is the slope of the linear portion of the load–deflection curve (N/mm), calculated as:

$$m = \frac{\Delta P}{\Delta \delta} \tag{3}$$

where ΔP is the change in applied load (N) and $\Delta\delta$ is the corresponding change in deflection (mm).

The load values obtained from the UTM were converted to force in Newtons using a conversion factor of 9.81. The calculated MoR and MoE values were then used to evaluate the flexural mechanical performance of the composite boards. Following the flexural test, compressive testing was performed using the same UTM to evaluate the compressive behavior of the composite boards. The specimens were placed between the compression plates and loaded until failure or crushing. The maximum compressive load and corresponding displacement were recorded. The compressive strength was calculated as:

$$\sigma_c = \frac{P_{\max}}{A} \tag{4}$$

where σ_c is the compressive strength (MPa), $P_{\max}$ is the maximum compressive load (N), and A is the initial cross-sectional area subjected to compression (mm^2). The load–displacement response and fracture or crushing behavior were also recorded.

3. Results and Discussion

3.1. XRF Characterization of Natural Pahae Zeolite

The XRF spectrum of activated natural Pahae zeolite is presented in Figure 1, while its oxide composition is summarized in Table 1. The XRF results show that the material is predominantly composed of SiO_2 (68.73 wt%) and Al_2O_3 (14.52 wt%), confirming its aluminosilicate nature. These oxides are the major structural components of zeolite frameworks and are closely associated with the structural characteristics and adsorption behavior of zeolitic materials. In addition, K_2O (6.42 wt%), Fe_2O_3 (5.40 wt%), CaO (3.51 wt%), and P_2O_5 (0.19 wt%) were detected, indicating the presence of other mineral components in the activated natural Pahae zeolite.

The relatively high SiO_2 content is particularly relevant to its application as a filler in polyester-based composite boards, as silica-rich mineral fillers can contribute to stiffness and dimensional stability of polymer composites. Therefore, the oxide composition of the activated natural Pahae zeolite indicates its potential as a mineral filler for polyester-based composite materials.

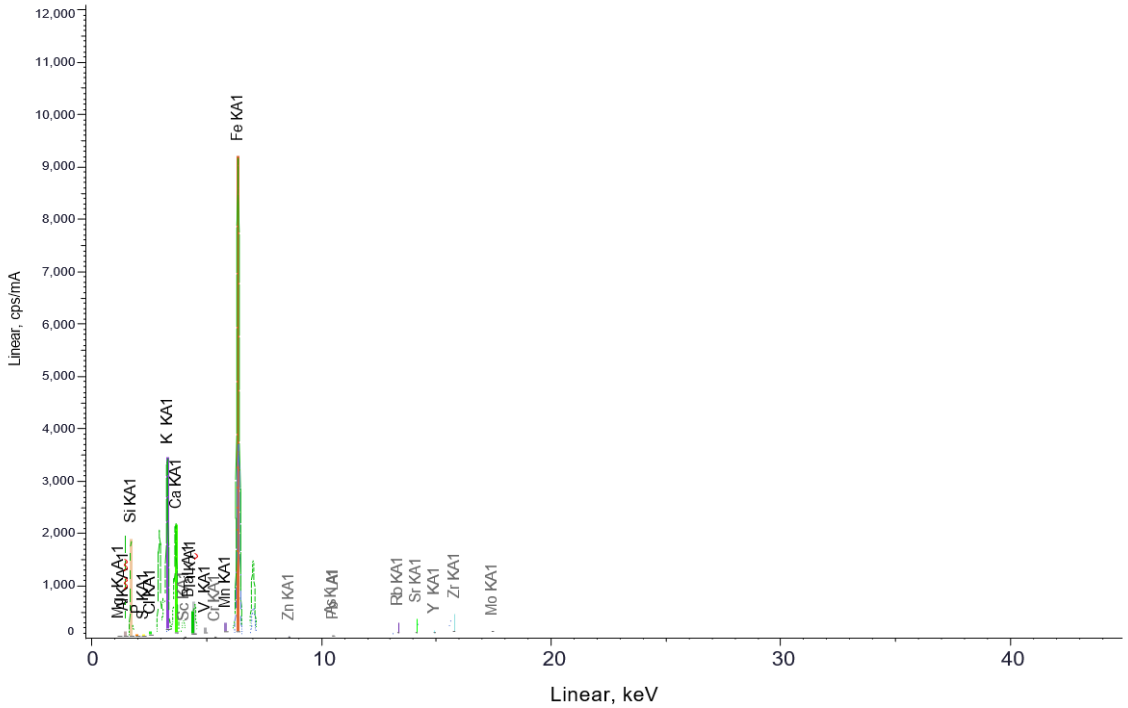

Figure 1. XRF spectrum of activated natural Pahae zeolite.

Table 1. Oxide composition of activated natural Pahae zeolite determined by XRF analysis.

Oxide	Conc. (wt%)
SiO_2	68.73
Al_2O_3	14.52
K_2O	6.42
Fe_2O_3	5.40
CaO	3.51
P_2O_5	0.19

3.2. Modulus of Rupture (MoR)

The Modulus of Rupture (MoR) represents the maximum bending stress that the composite board can withstand before fracture. The results are shown in Figure 2. As presented in Figure 2, the Modulus of Rupture (MoR) values ranged from 159.7 to 177.3 MPa. The MoR increased from 167.1 MPa for sample A to 175.3 MPa for sample B, decreased slightly to 166.2 MPa for sample C, and subsequently increased to the highest value of 177.3 MPa for sample D, which contained 30 wt% zeolite. This result indicates that the incorporation of zeolite up to 30 wt% contributed to an improvement in the flexural strength of the composite board. The improvement may be attributed to the rigid nature of zeolite particles, which can enhance stress transfer within the composite and improve the packing of the constituent materials.

The highest MoR obtained for sample D suggests that the combination of 60 wt% polyester resin, 10 wt% areca nut fiber, and 30 wt% zeolite provided a favorable balance between the polymer matrix, fiber reinforcement, and mineral filler. However, increasing the zeolite content to 40 wt% resulted in a decrease in MoR to 159.7 MPa. This reduction may be associated with excessive filler content, which can promote particle agglomeration, reduce effective wetting by the polyester resin, and decrease the contribution of areca nut fiber to load transfer. Consequently, the interaction between the matrix and reinforcement phases may become less effective at higher zeolite loading.

The MoR values obtained in this study were subsequently compared with the minimum requirements specified in the referenced particleboard standards. According to SNI 03-2105-2006, the minimum MoR requirement is 133 kgf/cm², equivalent to approximately 13.04 MPa, for Type 13 particleboard. In addition, JIS A 5908-2003 specifies a minimum MoR requirement of 8 MPa for Type 8 particleboard. The MoR values obtained in this study, ranging from 159.7 to 177.3 MPa, were higher than both minimum requirements. Therefore, all composite board compositions investigated in this study met the minimum MoR requirements specified by SNI 03-2105-2006 and JIS A 5908-2003.

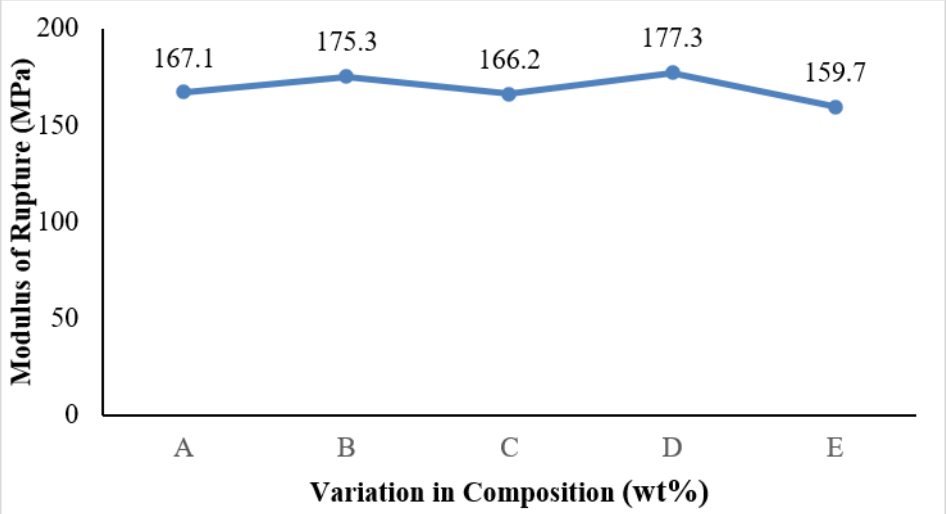

Figure 2. Effect of zeolite content on the Modulus of Rupture (MoR) of the composite boards.

3.3. Modulus of Elasticity (MoE)

The Modulus of Elasticity (MoE) represents the stiffness of the composite board under an applied bending load. The MoE values obtained for the different zeolite contents are presented in Figure 3.

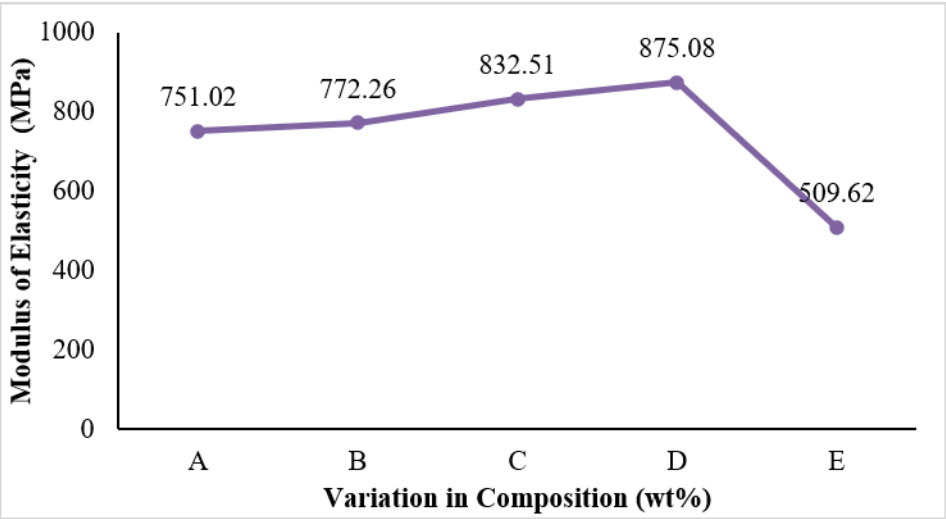

Figure 3. Effect of zeolite content on the Modulus of Elasticity (MoE) of the composite boards.

As presented in Figure 3, the Modulus of Elasticity (MoE) value ranged from 509.62 to 875.08 MPa. The MoE increased progressively from 751.02 MPa for sample A to 772.26 MPa for sample B, 832.51 MPa for sample C, and reached the highest value of 875.08 MPa for sample D, containing 30 wt% zeolite. This increase indicates that the incorporation of zeolite up to 30 wt% improved the stiffness of the composite board. The improvement may be attributed to the rigid mineral characteristics of zeolite particles, which can restrict polymer chain mobility and enhance the rigidity of the composite structure. In addition, zeolite particles may act as micro-fillers that improve particle packing and contribute to more effective stress distribution within the polyester matrix.

The highest MoE obtained for sample D suggests that the combination of 60 wt% polyester resin, 10 wt% areca nut fiber, and 30 wt% zeolite provided a favorable balance between the matrix, fiber reinforcement, and mineral filler. However, increasing the zeolite content to 40 wt% resulted in a substantial decrease in MoE to 509.62 MPa. This reduction may be associated with excessive zeolite loading, which can promote particle agglomeration, reduce effective wetting of the filler by the polyester resin, and decrease the relative contribution of the areca nut fiber to load transfer. Consequently, the stress-transfer efficiency within the

composite may decrease, resulting in lower stiffness. These results indicate that 30 wt% zeolite provided the most favorable composition among the investigated formulations in terms of elastic stiffness.

The MoE values were further compared with the requirements specified in SNI 03-2105-2006 and JIS A 5908-2003. SNI 03-2105-2006 specifies a minimum MoE of 20,400 kgf/cm^2, equivalent to approximately 2,000.6 MPa, while JIS A 5908-2003 specifies a minimum MoE of 2,000 MPa for Type 8 particleboard. The MoE values obtained in this study, ranging from 509.62 to 875.08 MPa, were below both requirements. Therefore, although the incorporation of zeolite up to 30 wt% improved the stiffness of the composite boards, none of the investigated compositions met the minimum MoE requirements specified by SNI 03-2105-2006 and JIS A 5908-2003.

3.4. Compressive Strength

The compressive strength represents the ability of the composite board to resist crushing under an applied compressive load. The compressive strength values obtained for the different zeolite contents are presented in Figure 4.

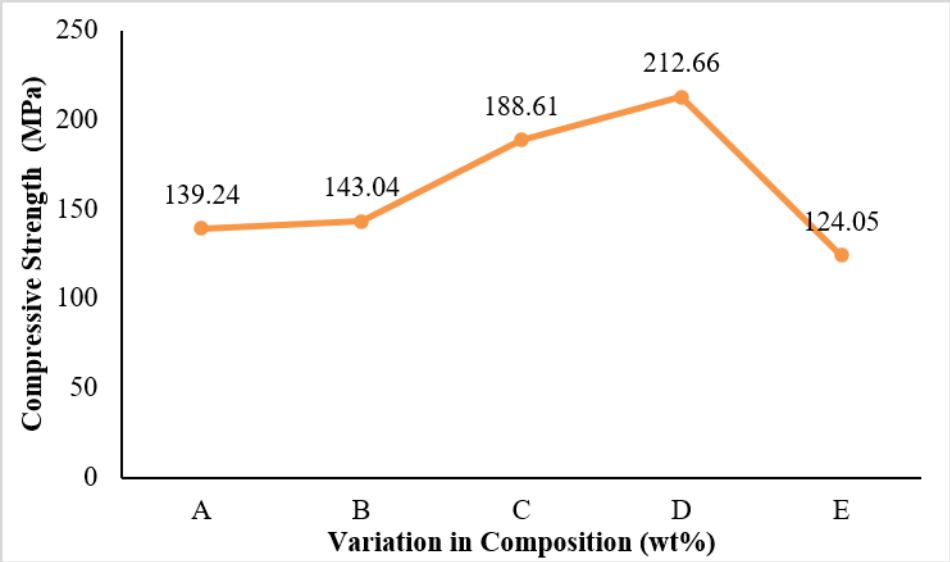

Figure 4. Effect of zeolite content on the compressive strength of the composite boards.

As presented in Figure 4, the compressive strength increased from 139.24 MPa for sample A to 143.04 MPa for sample B and further increased to 188.61 MPa for sample C. The highest value of 212.66 MPa was obtained for sample D, containing 30 wt% zeolite. This increase indicates that the incorporation of zeolite up to 30 wt% enhanced the compressive resistance of the composite board. The improvement may be attributed to the rigid mineral characteristics of zeolite particles, which can increase the stiffness of the composite structure, improve particle packing, and facilitate stress distribution within the polyester matrix. The zeolite particles may also occupy micro voids within the composite, resulting in a more compact structure that can withstand compressive loading more effectively.

However, increasing the zeolite content to 40 wt% resulted in a substantial decrease in compressive strength to 124.05 MPa. This reduction may be associated with excessive filler loading, which can promote particle agglomeration, reduce effective wetting and bonding between the zeolite particles and polyester matrix, and decrease the contribution of the areca nut fiber to reinforcement. These conditions may introduce weak regions within the composite and reduce the efficiency of stress transfer during compression. Therefore, the results suggest that 30 wt% zeolite provided the most favorable balance among the polyester matrix, areca nut fiber, and zeolite filler for improving compressive strength.

Unlike MoR and MoE, compressive strength is not specified as a mandatory performance parameter in SNI 03-2105-2006 or JIS A 5908-2003 for conventional particleboard classification. Therefore, the compressive strength results were not directly compared with these standards. Instead, this test was conducted as an additional mechanical characterization to evaluate the load-bearing behavior of the developed composite boards under compressive loading. The highest compressive strength of 212.66 MPa was obtained for sample D containing 30 wt% zeolite, indicating that this composition exhibited the highest resistance to compressive loading among the investigated formulations.

Taken together, the mechanical results provide insight beyond formulation screening into the balance between organic fiber reinforcement and inorganic mineral filling in the polyester matrix. The progressive replacement of areca nut fiber with natural Pahae zeolite improved the overall mechanical performance up to 30 wt% zeolite, suggesting that the rigid zeolite particles contributed to stiffness and stress distribution while maintaining a sufficient contribution from the areca nut fibers. In contrast, the decline in mechanical performance at 40 wt% zeolite indicates that excessive mineral loading disrupted this balance, likely due to particle agglomeration, reduced fiber reinforcement, and less effective stress transfer. These results demonstrate that the mechanical performance of the hybrid composite is governed by the interaction and balance among the fiber, zeolite, and polyester phases rather than by zeolite content alone.

3.5. Density

The density represents the compactness and internal packing of the composite board. The density values obtained for the different zeolite contents are presented in Figure 5.

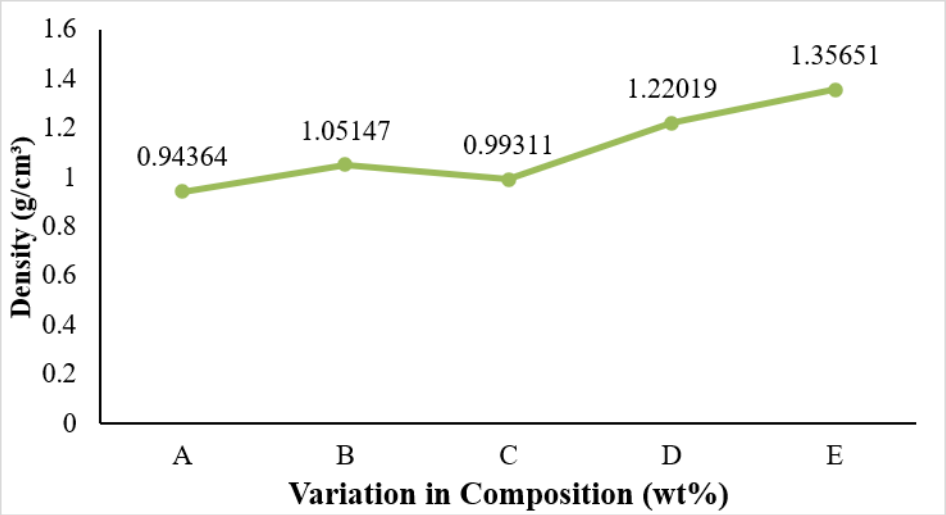

Figure 5. Effect of zeolite composition on the density of composite boards.

As presented in Figure 5, the density values ranged from 0.94364 to 1.35651 g/cm^3. The density increased from 0.94364 g/cm^3 for sample A to 1.05147 g/cm^3 for sample B, followed by a slight decrease to 0.99311 g/cm^3 for sample C. The density then increased substantially to 1.22019 g/cm^3 for sample D and reached the highest value of 1.35651 g/cm^3 for sample E. The overall increase in density with increasing zeolite content can be attributed to the replacement of lower-density areca nut fiber with denser zeolite particles. The higher density indicates a more compact composite structure and greater contribution of the mineral filler to the overall mass per unit volume.

The highest density was obtained for sample E containing 40 wt% zeolite, indicating that the high zeolite content resulted in the greatest mass concentration within the composite board. However, higher density does not necessarily indicate better mechanical performance, as the distribution and interfacial bonding of the constituent materials also influence the mechanical properties. Therefore, density variation should be considered together with the mechanical and microstructural characteristics of the composite boards.

The density values were compared with the requirements specified in SNI 03-2105-2006 and JIS A 5908-2003, both of which specify a density range of approximately 0.40–0.90 g/cm^3 for particleboard. The density values obtained in this study, ranging from 0.94364 to 1.35651 g/cm^3, were higher than the specified upper limit. Therefore, none of the investigated composite boards met the density range specified in these particleboard standards. The relatively high density of the developed boards may be attributed to the high proportion of polyester resin and the increasing incorporation of dense zeolite particles.

3.6. Moisture Content

Moisture content represents the amount of water retained in the composite board after conditioning. The results are shown in Figure 6. The moisture content decreased progressively from 14.88% for sample A to 10.16%, 8.89%, 5.26%, and 0.66% for samples B, C, D, and E, respectively, with increasing zeolite content and corresponding reduction in areca nut fiber content.

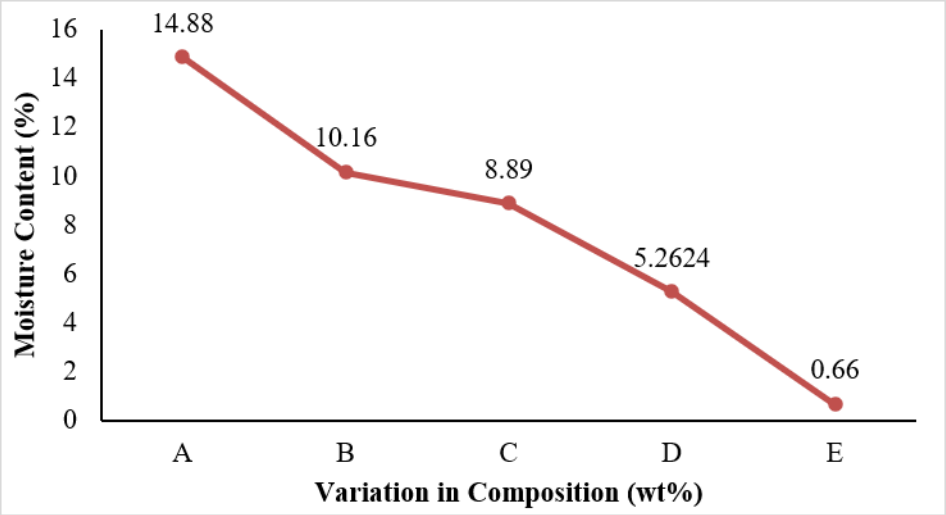

Figure 6. Effect of zeolite composition on the moisture content of composite boards.

The continuous decrease in moisture content can be attributed primarily to the reduction in the proportion of natural fiber. Areca nut fibers contain cellulose and hemicellulose with hydrophilic functional groups that can interact with and retain water. Therefore, reducing the fiber fraction progressively decreases the amount of hydrophilic material available to retain moisture. In contrast, the polyester matrix is relatively hydrophobic, while the replacement of fiber by zeolite changes the overall composition and reduces the proportion of moisture-retaining natural fiber. Consequently, sample E, which contained no areca nut fiber, exhibited the lowest moisture content of 0.66%.

It should be noted that the moisture-content trend does not necessarily imply that water absorption during immersion will follow the same trend. Moisture content represents water retained under conditioning conditions, whereas water absorption is also strongly influenced by the internal morphology of the composite, including porosity, voids, particle distribution, and interfacial regions. Therefore, the continuous decrease in moisture content with increasing zeolite content should be distinguished from the non-monotonic water absorption behavior discussed below.

The moisture content (MC) of the composite boards was compared with the requirements specified in SNI 03-2105-2006 and JIS A 5908-2003. According to SNI 03-2105-2006, the moisture content of particleboard should not exceed 14%. Based on the results obtained, most composite board compositions satisfied this requirement, with the exception of composition A, which exhibited a moisture content of 14.88%. This value is slightly higher than the maximum limit specified by SNI, indicating that composition A did not meet the moisture content requirement of SNI 03-2105-2006. In contrast, the other compositions had moisture content values below 14% and therefore complied with the SNI requirement.

Furthermore, JIS A 5908-2003 specifies a moisture content range of 5–13%. Comparison with this requirement shows that compositions B, C, and D satisfied the JIS requirement because their moisture content values were within the specified range. However, composition A, with an MC of 14.88%, exceeded the upper limit of 13%, while composition E, with an MC of 0.66%, was below the lower limit of 5%. Therefore, compositions A and E did not satisfy the moisture content requirement of JIS A 5908-2003.

3.7. Water Absorption

Water absorption describes the amount of water absorbed by the composite board during immersion. The results are shown in Figure 7. Unlike the moisture content, which decreased continuously with increasing zeolite content, the water absorption exhibited a non-monotonic trend. The water absorption values were 10.57%, 2.08%, 5.27%, 10.21%, and 20.17% for samples A, B, C, D, and E, respectively. Sample B exhibited the lowest water absorption (2.08%), whereas sample E exhibited the highest value (20.17%).

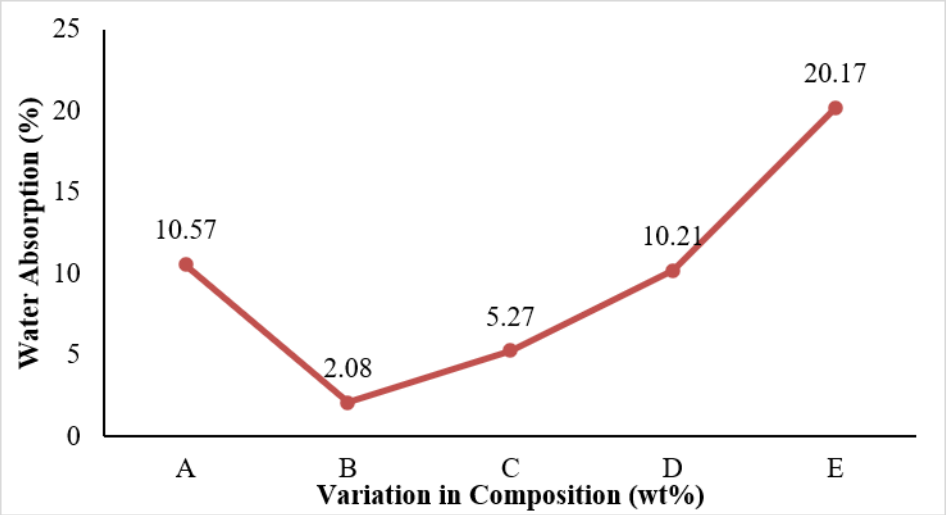

Figure 7. Effect of zeolite composition on water absorption of composite boards.

The different trends observed for moisture content and water absorption can be attributed to the different mechanisms represented by the two measurements. The decrease in moisture content is mainly associated with the progressive reduction of hydrophilic areca nut fiber. In contrast, water absorption during immersion depends not only on the chemical affinity of the constituents for water but also on the physical structure of the composite, including porosity, voids, particle dispersion, and interfacial regions between the fiber, polyester matrix, and zeolite particles.

The relatively low water absorption of sample B suggests that the addition of 10% zeolite produced a relatively compact composite structure with effective interaction among the polyester matrix, areca nut fibers, and zeolite particles. At this composition, zeolite may partially occupy spaces between the reinforcing components and reduce accessible pathways for water penetration. This interpretation is consistent with the substantially lower water absorption of sample B compared with sample A.

However, further increases in zeolite content resulted in progressively higher water absorption, reaching 5.27% in sample C, 10.21% in sample D, and 20.17% in sample E. At higher zeolite concentrations, particle agglomeration, incomplete wetting or impregnation by the polyester matrix, and the formation of micro voids or interfacial gaps may provide additional pathways for water penetration. Thus, although the reduction in fiber content continuously decreased the moisture content, increasing zeolite content beyond the optimum level did not continuously improve water resistance during immersion.

The particularly high-water absorption of sample E, despite its very low moisture content of 0.66%, further demonstrates that moisture content and water absorption should not be interpreted as equivalent properties. The low moisture content indicates limited water retention under conditioning, whereas the high-water absorption indicates that the zeolite-rich structure was capable of taking up substantial water when directly immersed. Therefore, the water absorption behavior is governed by both material composition and the resulting composite microstructure.

Overall, the results indicate that the lowest water absorption was obtained at an intermediate zeolite content of 10% (sample B). This suggests that an optimum filler concentration is required to obtain a balance between reduced hydrophilic fiber content and a sufficiently compact composite structure. Excessive zeolite addition may adversely affect the internal structure and increase water-accessible voids or interfacial pathways.

We have also clarified that low moisture content does not necessarily correspond to low water absorption because the two tests represent different conditions: moisture content reflects water retained after conditioning, whereas water absorption measures water uptake during immersion. This distinction explains why sample E exhibited the lowest moisture content (0.66%) but the highest water absorption (20.17%).

The WA values were not directly compared with SNI 03-2105-2006 and JIS A 5908-2003 because both standards specify requirements for thickness swelling after water immersion rather than water absorption. Therefore, the WA results in this study were used to indicate the trend in the water absorption capacity of the composite boards.

3.8. SEM Analysis

The surface morphologies of the composite boards at 2000 × magnification are presented in Figure 8. The SEM observations were qualitatively used to evaluate the fiber–matrix interface, zeolite particle distribution, visible voids, and particle agglomeration.

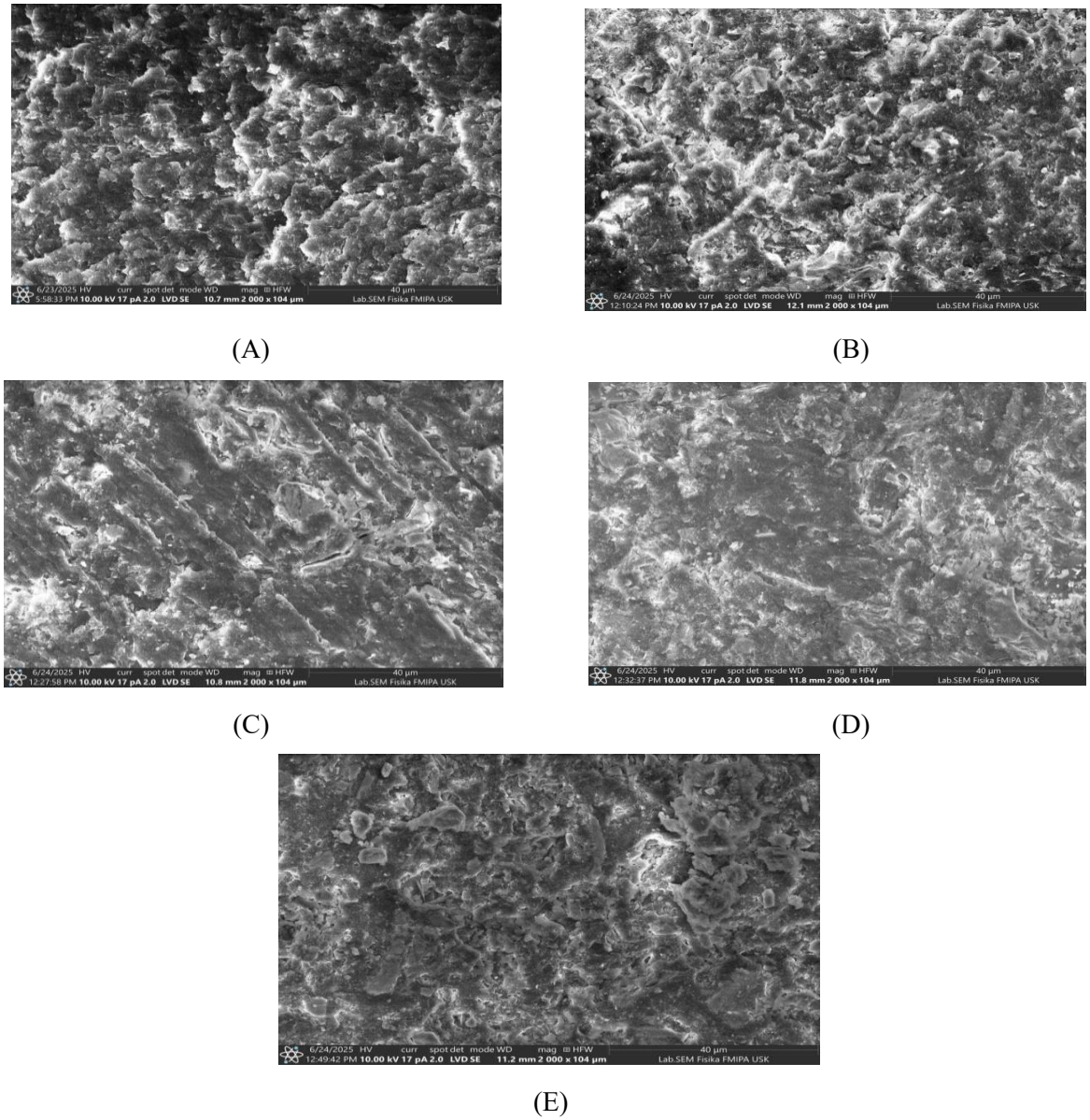

Figure 8. SEM micrographs of composite boards containing polyester resin, areca nut fiber, and natural Pahae zeolite: (A) sample A (60:40:0), (B) sample B (60:30:10), (C) sample C (60:20:20), (D) sample D (60:10:30), and (E) sample E (60:0:40). The micrographs show the distribution of areca nut fibers, zeolite particles, fiber–matrix interfaces, and visible voids under consistent SEM imaging conditions.

Sample A exhibited a relatively rough and heterogeneous surface, with visible fiber pull-out, interfacial gaps, and voids. These features suggest relatively weak adhesion between the areca nut fibers and polyester matrix, which may reduce the efficiency of stress transfer within the composite. Sample B showed a more integrated morphology following the incorporation of 10 wt% zeolite, although some micro voids and non-uniformly distributed particles were still visible. Samples C and D exhibited a relatively more integrated structure, with better embedding of the fibers within the polyester matrix and a more uniform appearance of zeolite particles. Sample D, containing 30 wt% zeolite, showed fewer prominent voids and a relatively more integrated morphology. These features qualitatively correspond to the improved mechanical performance observed for this composition, particularly its highest compressive strength.

In contrast, sample E, containing 40 wt% zeolite without fiber reinforcement, showed a morphology dominated by mineral particles. Several regions exhibited particle agglomeration and poor wetting by the

polyester matrix. These features may act as stress concentration sites and contribute to the reduction in mechanical strength observed at the highest zeolite content.

Overall, the SEM observations qualitatively indicate that the incorporation of zeolite up to 30 wt% improved the apparent integration and distribution of the composite constituents, whereas excessive zeolite loading promoted particle agglomeration and a more heterogeneous morphology. However, the observed changes in void distribution are qualitative, as quantitative image analysis of porosity was not performed.

3.9. EDX Analysis

The elemental compositions of the composite boards obtained from EDX analysis are presented in Figure 9.

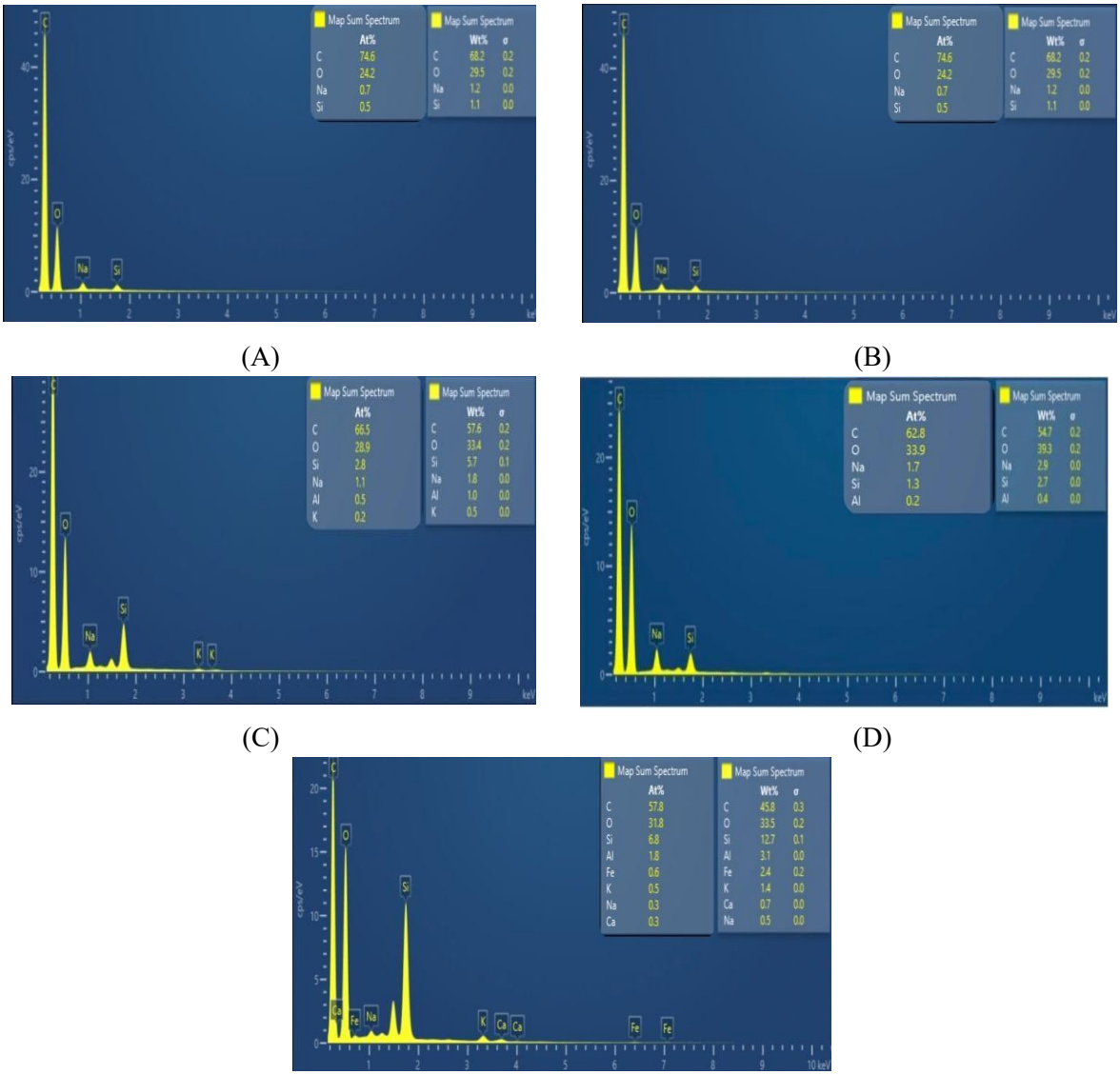

Figure 9. EDX spectra of the composite samples containing polyester resin, areca nut fiber, and natural Pahae zeolite: (A) sample A (60:40:0), (B) sample B (60:30:10), (C) sample C (60:20:20), (D) sample D (60:10:30), and (E) sample E (60:0:40).

The EDX spectra confirmed the presence of C and O as the dominant elements associated with the polyester matrix and areca nut fibers, while Si and Al were primarily associated with the aluminosilicate component of natural Pahae zeolite. Sample A, which contained no zeolite, was dominated by C and O, consistent with its organic fiber–polyester composition. With increasing zeolite content from samples B to E, the relative contributions of Si and Al increased, confirming the incorporation of zeolite into the composite. Sample D showed the presence of C, O, Si, and Al, reflecting the coexistence of organic and inorganic phases at 30 wt%

zeolite. Sample E exhibited the highest Si and Al contributions and a lower relative contribution of C, consistent with its highest zeolite content and absence of areca nut fiber.

The EDX results showed Si/Al ratios of 5.6 and 6.5 for compositions C and D, respectively. These relatively high Si/Al ratios indicate a silica-rich aluminosilicate characteristic, consistent with the Si/Al range commonly reported for mordenite. However, the zeolite framework cannot be definitively identified from EDX alone; therefore, XRD analysis is planned in future work to confirm the mineralogical phase.

The EDX results provide elemental evidence of the composition-dependent incorporation of the zeolite phase. However, EDX provides elemental composition only at the analyzed region and should not be interpreted as direct quantitative evidence of filler dispersion, interfacial bonding, or mechanical reinforcement throughout the composite.

Taken together, the SEM–EDX results show composition-dependent changes in the morphology and elemental composition of the composite boards. The SEM micrographs provide qualitative observations of fiber–matrix contact, visible voids, and zeolite particle agglomeration, while the EDX results confirm the presence and increasing contribution of Si and Al associated with the zeolite phase.

4. Conclusion

This study demonstrated that the incorporation of natural Pahae zeolite influenced the mechanical and physical properties of polyester-based composite boards reinforced with areca nut fiber. Among the investigated compositions, sample D with 30 wt% zeolite showed the most favorable overall mechanical performance of the composite, with sample D (polyester resin/areca nut fiber/zeolite = 60:10:30) showing the most favorable overall mechanical performance among the investigated compositions.

The SEM observations qualitatively indicated relatively more integrated morphology and fewer prominent voids in sample D, while the EDX analysis confirmed the incorporation of zeolite through the presence of Si and Al. However, the SEM observations provide qualitative morphological evidence and do not establish quantitative changes in porosity.

The physical-property results showed that zeolite incorporation affected the density and moisture content of the composite boards. The moisture content of most compositions satisfied the requirements of SNI 03-2105-2006 and JIS A 5908-2003, although not all compositions met both requirements. Water absorption was evaluated as an additional physical property and was not directly compared with these standards because they specify thickness swelling rather than water absorption. Similarly, compressive strength was evaluated as an additional mechanical property because it is not a mandatory classification parameter in the referenced particleboard standards.

The main contribution of this study is the demonstration that progressive replacement of areca nut fiber with natural Pahae zeolite can establish a favorable balance between organic fiber reinforcement and inorganic mineral filling in polyester-based composite boards. The optimum composition of 60:10:30 indicates that mechanical performance depends on the balance among the polyester matrix, areca nut fiber, and zeolite rather than on increasing zeolite content alone. This finding provides insight into the role of a locally sourced aluminosilicate mineral in hybrid natural-fiber–mineral–polymer composites and highlights the potential of natural Pahae zeolite as a functional filler for composite board applications.

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