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The Potential of Ramie Fiber as Reinforcement in Calcium Carbonate-Filled Polyester Resin Matrix Composites for Roofing Applications

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ABSTRACT

Polymer matrix composite roofing materials available in the Indonesian market typically consist of 30%wt chopped strand mat glass fiber embedded in unsaturated polyester resin, filled with 30 parts per hundred resin (PHR) calcium carbonate. The aim of this research is to evaluate whether natural ramie fibers can potentially replace glass fibers. In the first stage of the study, we compared three types of natural fibers abundant in Indonesia: banana stem fibers, sugarcane bagasse, and ramie. Showed that ramie fiber performed the best. Its flexural strength, flexural modulus, and impact toughness were the highest, measured at 191.57 MPa, 6691 MPa, and 0.056 J/mm², respectively. In the second stage, we produced composite material specimens with the same composition as commercial roofing materials but replaced the glass fibers with ramie fibers. Compared to the material without ramie fibers, the composite reinforced with ramie fibers shows an increase in tensile strength to 47.53 MPa from 34.62 MPa, an increase in maximum water absorption over 14 days to 3.746% from 1.145%, and an improvement in the sound transmission class to 26 dB from 23 dB. Additionally, the ramie fibers did not significantly affect the density of the composite material. However, the inclusion of ramie fibers resulted in a reduction of the elastic modulus to 1324 MPa from 1630 MPa, and a higher mass loss in the TGA examination, at 86.95% compared to 74.65%. Ramie fiber composites achieve the minimum roofing requirement of 40 MPa tensile strength, thus having the potential to replace glass fibers.

Keywords: *Calcium carbonate, natural fiber, ramie fiber, roofing material, unsaturated polyester*

I. Introduction

Corrugated roofing sheets have long utilized advanced materials such as glass fiber-reinforced polymer composite (GFRP) as their primary raw material. In Indonesia, GFRP materials are widely used for natural lighting roofs and industrial building roofs in corrosive environments [1], [2]. One commercial factory in Indonesia that produces GFRP roofing materials is PT Intec Persada. The matrix used in these products is an unsaturated polyester resin, reinforced with synthetic glass fiber. The roofs produced by this factory have a minimum tensile strength of 40 MPa. The commercial roof products have a material composition of 30 wt% glass fiber and 30 parts per hundred resin (PHR) calcium carbonate filler [3].

Indonesia is home to various abundant natural fibers, including banana stem fiber (*Musa acuminata*), sugarcane bagasse fiber, and ramie fiber (*Boehmeria nivea*). The country's vast agricultural sector generates significant organic waste, such as banana stem fiber, with up to 640,000 stems discarded annually [4]. Sugarcane production in Indonesia reaches 1.16

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million tons per year, while ramie fiber production is about 100,000 tons per year [5], [6]. Currently, these natural fibers are used in the production of furniture such as chairs, tables, and cupboard shelves due to their good mechanical strength [7]. Given their abundance, these natural fibers have the potential to be further utilized as alternative materials to replace synthetic fibers like glass fiber.

Unsaturated polyester resin is an economical standard resin with wide-ranging applications. Calcium carbonate is a highly economical filler that is also compatible with unsaturated polyester resin [8]. Composite materials consisting of a matrix of unsaturated polyester resin mixed with calcium carbonate filler and reinforced with natural fibers have the potential to be used as roofing sheet materials. In addition to being cost-effective and possessing good mechanical properties, these materials incorporate environmentally friendly elements through the use of natural fibers. The desired properties for roofing materials include adequate tensile or flexural strength, as well as sound or noise reduction capabilities.

Previous studies using banana stem fiber composites with epoxy matrix, at a weight fraction of 20% achieved the highest tensile strength, flexural strength, and impact toughness, respectively, of 68 MPa, 90 MPa, and 13 13 kJ/m² [9]. Meanwhile, composites using recycled polypropylene (RPP) matrix achieved a tensile strength of 59.32 MPa and flexural strength of 86.3 MPa at a volume fraction of 42% [10]. Other studies using banana stem fiber reinforced polyester resin matrix achieved the highest tensile strength of 67.2065 MPa at a volume fraction of 28% and the highest impact strength of 0.0101 J/mm² at a volume fraction of 50% [11]–[13].

Several previous studies using bagasse fiber as composite reinforcement in epoxy resin matrix achieved the highest tensile strength of 28.43 MPa at a volume fraction of 12%. Other studies using polypropylene (PP) resin matrix achieved the highest tensile strength and flexural strength of 22.3 MPa and 46 MPa at a volume fraction of 20%. The tensile modulus and flexural modulus were 1442.5 MPa and 1750 MPa, respectively. Meanwhile, those using polyester resin matrix in bagasse fiber-reinforced composites achieved the highest tensile strength of 20.028 MPa at a volume fraction of 65% and the highest Charpy impact toughness of 160 J/m² at a volume fraction of 30% [14]–[19].

Researchers have used ramie fiber to reinforce polymer composites with both thermoset and thermoplastic matrices. The orientation of the reinforcing fibers includes unidirectional and woven fibers. In one study, a ramie fiber-reinforced epoxy matrix with five woven layers achieved a flexural strength of up to 138.84 MPa. Ramie fiber, with a volume fraction of 50%, was able to achieve a tensile strength of 248.677 MPa. These results meet the qualifications for SAE J1717 standard automotive components [20]–[22]. A polypropylene (PP) matrix reinforced with short ramie fibers in a random fiber orientation, with a weight fraction of 30%, produces a tensile strength of 23 MPa, a tensile modulus of 1165 MPa, a flexural strength of 37.1 MPa, and a flexural modulus of 2053 MPa. Based on its tensile strength and elongation properties, this composite is suitable for biomedical applications [23], [24].

In several studies related to soundproofing, Poly L-lactic acid (PLLA) used as a composite matrix reinforced with ramie fiber in a random fiber orientation produces a sound absorption coefficient of 0.079, while the woven fiber orientation achieves a coefficient of 0.067, making it suitable for sound absorption applications [25]. Bamboo fiber, with a volume fraction of 35%, added to rigid polyurethane (RPU) foam enhances sound dampening, with a noise reduction coefficient (NRC) of 0.37 and a transmission loss of 21 dB at the 1600 Hz frequency range [26]. Several other natural fibers, including coconut fiber, kapok, pineapple, banana stem, and straw combined with a polyvinyl chloride (PVC) matrix, have also been applied in acoustic panels. The highest sound absorption coefficient was achieved with straw fiber at 0.44, while the lowest was with banana stem fiber at 0.26, both at a frequency of 1400 Hz. A sound absorption coefficient greater than 0.2 categorizes the material as a sound-absorbing material. Thus, all the natural fibers mentioned have been successful as sound absorption materials [27].

There are several other studies that use ramie fiber as a composite reinforcement with a polyester resin matrix achieving the highest tensile strength and flexural strength of 89 MPa and 212 MPa at a volume fraction of 30%. Still at a volume fraction of 30% also achieved a charpy toughness of 1 kJ/m^2 and an izod toughness of 0.59 kJ/m^2. In addition, ramie fiber given alkali treatment with 5% NaOH can achieve a tensile strength of 190.27 MPa at a volume fraction of 35%. Polyester resin matrix ramie fiber composites have also been applied in a hybrid manner with glass fiber and achieved the highest tensile strength of 60 MPa, an elastic modulus of 3064 MPa, a flexural strength of 177.51 MPa, and an impact toughness of 2.95 J/mm^2 [28]–[34].

Based on previous studies, it is seen that ramie fiber has several advantages, namely higher mechanical properties compared to other natural fibers, can be applied with various types of matrices, has good soundproofing, and has met the standards for automotive components and biomedical applications. Therefore, the initial hypothesis is that ramie fiber has the potential to be used as a roofing application material that can replace glass fiber, as well as other advantages that ramie fiber is a natural fiber so it is harmless and easily decomposed. Thus, research on the physical and mechanical properties of polyester matrix composite materials with calcium carbonate fillers and natural fibers as reinforcement should be conducted using the same composition as commercial roofs, specifically 30% fiber by weight and 30 PHR calcium carbonate. The natural fibers used include banana stem fiber, sugarcane bagasse, and ramie. This material has the potential to be applied as a roof considering its economical price, as long as its physical and mechanical properties meet technical requirements. This study aims to prove whether ramie fiber has the potential to be used as a roofing application material using the same composition as commercial roofs and whether it can replace synthetic fibers, namely glass fiber. This study evaluates the mechanical and physical properties of composite materials, including flexural strength, impact toughness, tensile strength, surface morphology, density, water absorption, thermogravimetric analysis, and sound absorption in order to see a comprehensive picture of the material.

II. Material and Methods

1. Materials

The matrix composite samples consisted of orthophthalate unsaturated polyester resin (Ortho-UP SHCP 2668 W-NC-HLU resin from PT SHCP Indonesia, Surabaya, Indonesia) and calcium carbonate (from Jia Dah Chemical Industrial Co. Ltd., Tainan, Taiwan). The curing process of the composite used 1% volume of resin as an initiator, specifically methyl ethyl ketone peroxide (MEPOXE M, PT Kawaguchi Kimia, Jakarta, Indonesia). The composite reinforcement utilized natural fibers: ramie fiber from Toko Plastik60, Sleman, Yogyakarta, Indonesia; banana stem fiber from an online shop in Bogor, Indonesia; and sugarcane bagasse fiber from a sugarcane beverage shop in Tangerang, Indonesia. Basic sodium hydroxide was sourced from Rofa Laboratium Center, Bandung, Indonesia.

2. Preparation of Natural Fiber

Soak the natural fibers in a 5% NaOH solution for 2 hours. After soaking, dry the fibers in the sun until they are fully dry. Additionally, cutting the fibers to a length of 5 cm will help achieve a randomly distributed fiber orientation [30], [35].

3. Fabrication of Composites

The matrix is composed of resin and filler mixed evenly, with the filler amounting to 30 PHR. Additionally, 1% volume of resin, as an initiator of methyl ethyl ketone peroxide, is added to the matrix and stirred thoroughly [36]. We prepared samples measuring 300 mm × 300 mm × 3 mm using a glass mold equipped with a vacuum bag. Short fibers were randomly distributed on the glass mold, and the matrix was applied to cover all the fibers, which were then pressed with a roller. Air removal was continued by activating the vacuum pump on the vacuum bag for one hour. Afterward, the composite was left to cure for 24 hours.

4. Method

In the first stage, a comparison was made among three natural fibers: banana stem fiber, bagasse fiber, and ramie fiber. The composition of the material is detailed in Table 1. The tests conducted were flexural tests and impact tests. The parameters of flexural strength, flexural modulus, and impact toughness will be analyzed to select one natural fiber for further research on mechanical and physical properties.

Table 1. Composition of natural fiber-reinforced polyester composite with calcium carbonate filler in the first stage

Sample	Fiber	Fiber fraction	Calcium carbonate
A1	Banana Stem	30%wt	30 PHR
A2	Sugarcane Bagasse	30%wt	30 PHR
A3	Ramie	30%wt	30 PHR

In the second stage, one selected natural fiber was further investigated for its mechanical and physical properties. To assess the impact of the natural fiber, it was compared with a solid matrix containing 30 PHR calcium carbonate. Two types of samples were used: Sample S1, which consists of the matrix only without reinforcing fiber, where the matrix is a mixture of resin and 30 PHR filler; and Sample S2, which is a composite with the same matrix as S1 but with the addition of 30% fiber by weight of the matrix. Table 2 shows the details of these samples. The tests conducted include tensile tests, SEM examination, water absorption, specific gravity, thermogravimetric analysis (TGA), and impedance tube measurements.

Table 2. Composition of natural fiber-reinforced polyester composite with calcium carbonate filler in the second stage

Sample	Fiber fraction	Calcium carbonate
S1	0%wt	30 PHR
S2	30%wt	30 PHR

5. Mechanical and Physical Characterization

Flexural Strength: This flexural test uses three test specimens to obtain an average, aiming to determine the ability of the composite material to withstand flexural loads. The specimen size follows the ASTM D790 standard, measuring 133 mm × 12.7 mm × 3 mm. Flexural testing was conducted at the Center for Materials and Processing Failure Analysis (CMPFA), *Faculty* of Engineering, University of Indonesia. Flexural strength is calculated using Eq. (1), while flexural modulus is calculated using Eq. (2) [37]. In these equations, σ represents flexural strength (MPa), P is the load (N), L is the distance between supports (mm), b is the specimen width (mm), d is the specimen thickness (mm), E is the flexural modulus (MPa), and m is the slope.

$$\sigma = \frac{3.P.L}{2.b.d^2} \quad (1)$$

$$E = \frac{L^3 m}{4.b.d^3} \quad (2)$$

Impact Strength: This impact test uses five test specimens to obtain an average, aiming to determine the ability of the composite material to withstand impact loads. The specimen size follows *the* ASTM D6110 standard, measuring 75 mm × 10 mm × 3 mm. Impact testing was conducted using the *Terco* MT220 tool at the Material Characterization and Engineering Laboratory, Faculty of Engineering, Atma Jaya Catholic University of Indonesia.

Tensile Strength: This tensile test uses five specimens to obtain an average, aiming to determine the ability of the *composite* material to withstand tensile loads. The specimen size follows the ASTM D638 Type IV standard and has a thickness of 3 mm.

Scanning Electron Microscope (SEM): Examining the fracture surface morphology of the material from the tensile test was conducted using an SEM with an acceleration voltage of 10 kV and a magnification of 75 times at a working distance of 400 µm.

Water Absorption: Water absorption properties of the material were tested according to ASTM D570 standards. The specimen size was 76.2 mm × 25.4 mm × 3 mm. Initially, the specimen was heated in an oven at 105°C for 1 hour and then weighed. Next, the specimens were soaked in distilled water for 14 days. Every 24 hours, the mass was measured. Water absorption is calculated using Eq. (3) [38], where *WA* represents water absorption (%), W_t is the weight of the specimen during the soaking period (kg), and W_0 is the initial weight (kg).

$$WA = \frac{W_t - W_0}{W_0} \times 100\% \quad (3)$$

Specific Gravity: The specific gravity of the material was obtained using testing based on ASTM D792 standards with Eq. (4) [39]. The specimen size was 30 mm × 30 mm × 3 mm. The dry mass of the specimen was measured, and its apparent mass in distilled water was also recorded. The mass of the composite specimen was measured using a scale with 1 mg precision. *The* results are the average of five specimens. In this case, *SG* represents specific gravity, ρ_s is the specimen density (kg/m³), and ρ_r is the density of the reference used (kg/m³). The reference density used is water, which, according to the ASTM D792 standard, is 997.5 kg/m³.

$$SG = \frac{\rho_s}{\rho_r} \quad (4)$$

Thermo-Gravimetric Analysis (TGA): TGA is a technique used to analyze changes in a material's weight with temperature changes to determine its thermal stability. Tests were conducted *following* the ASTM E1131 standard at the Integrated Laboratory of Diponegoro University, Semarang, Indonesia. Composite samples with dimensions of 1 mm × 1 mm × 1 mm were heated in a nitrogen environment to a maximum temperature of 550°C at a rate of 10°C/min and a flow rate of 50 mL/min.

Impedance Tube: Impedance tube testing is used to determine the nature of sound transmission loss in composite materials. This test follows the ASTM E2611 standard for sound *transmission* loss, with measurements taken using four microphones at the Vibration and Acoustics Laboratory, Department of Engineering Physics, Sepuluh November Institute of Technology, Surabaya, Indonesia. The composite sample had a diameter of 10 cm and a thickness of 3 mm, with testing frequencies ranging from 125 to 4000 Hz. Data collection was performed three times for each sample. The sound transmission loss test results were evaluated using the ASTM E413 standard. The parameter obtained is the Sound Transmission Class (STC), which measures the material's ability to reduce sound transmission. The overall method in this research can be seen in Figure 1.

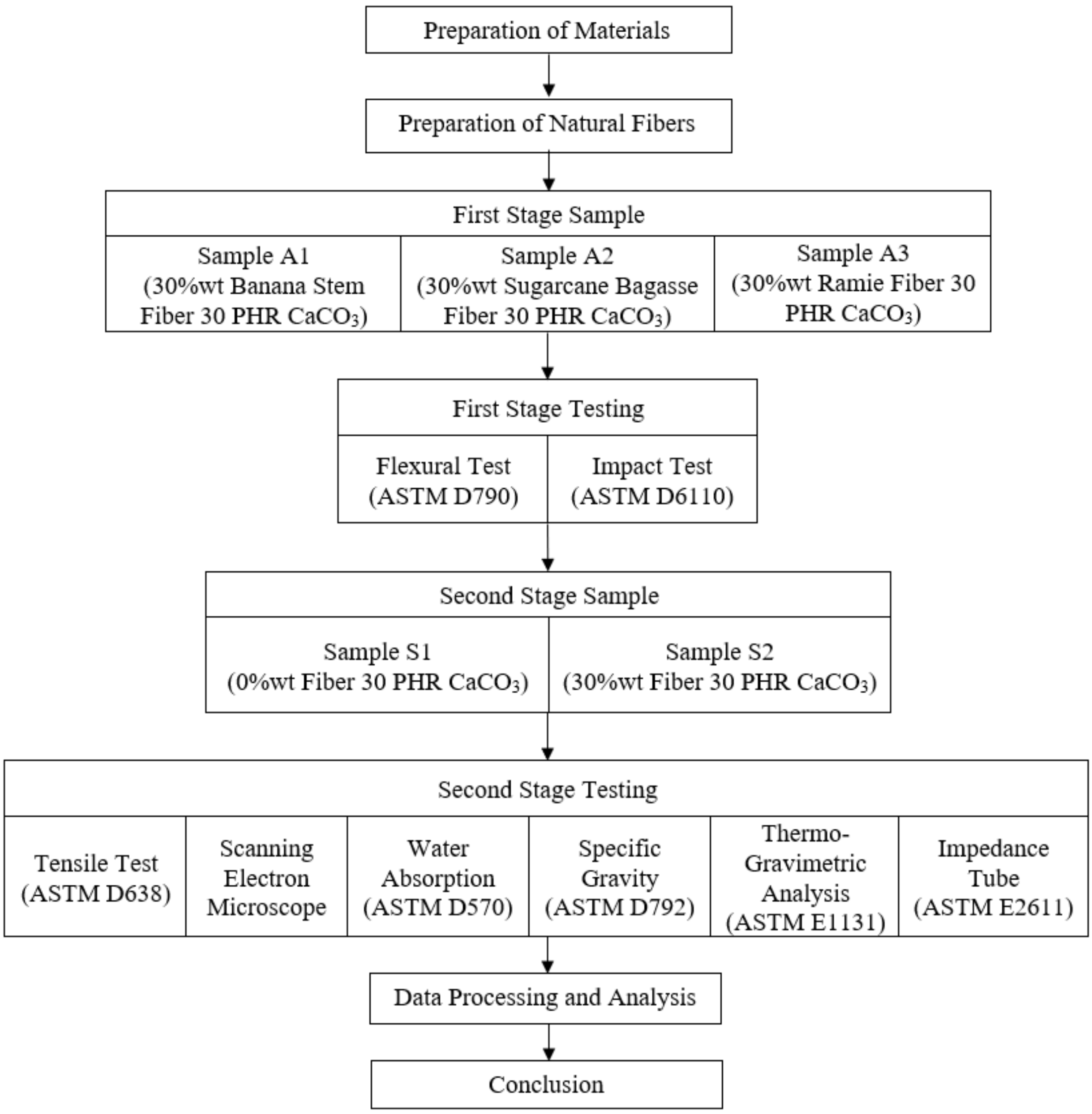

Fig. 1. Research methods

III. Results and Discussions

1. Mechanical Properties

Flexural Test: Flexural testing on three samples, namely A1, A2, and A3, produced the flexural strength and flexural modulus values shown in Figures 2 and 3. The respective values are 53.07 MPa, 56.86 MPa, and 191.57 MPa for flexural strength, and 3207 MPa, 2015 MPa, and 6691 MPa for flexural modulus.

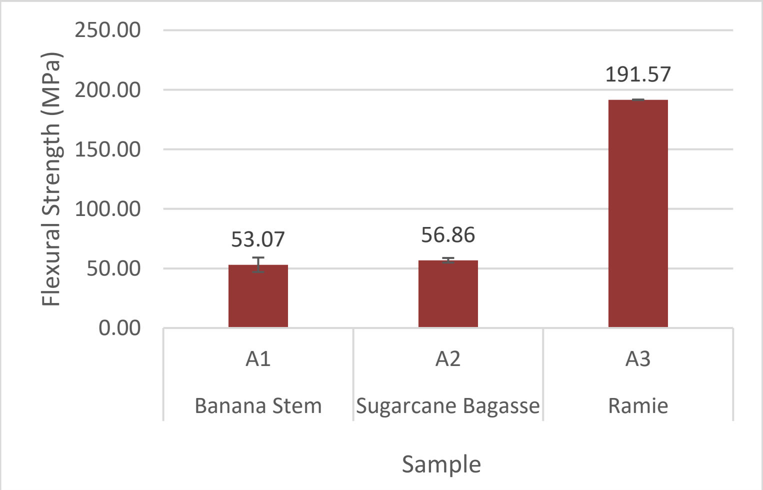

Fig. 2. Flexural strength of the tested composite samples

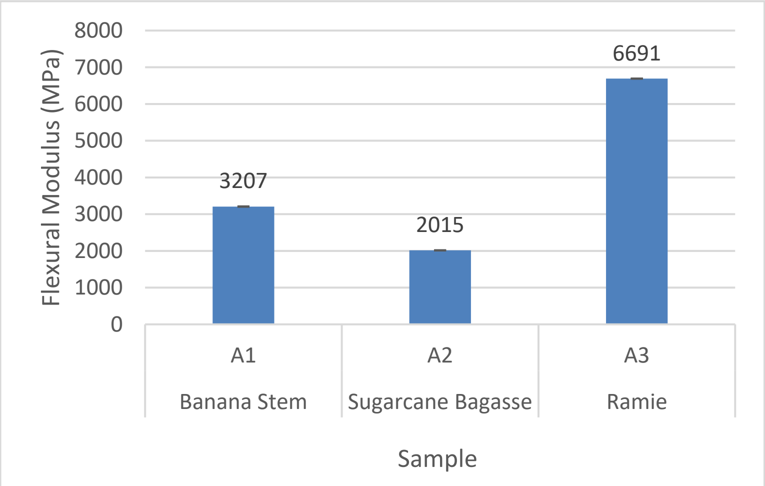

Fig. 3. Flexural modulus of the tested composite samples

Figures 2 and 3 show that the highest composite flexural strength is found in ramie fiber, at 191.57 MPa, while the lowest is found in banana stem fiber, at 53.07 MPa. Similarly, the highest composite flexural modulus is observed in ramie fiber, at 6691 MPa, and the lowest *in* bagasse fiber, at 2015 MPa. This is likely due to the high tensile strength of ramie fiber, which ranges from 400 to 1050 MPa, and its elastic modulus of 61.5 GPa [40]. In comparison, banana stem fiber has a tensile strength of 95 MPa and an elastic modulus of 3.48 GPa, while bagasse fiber has a tensile strength of 96 MPa and an elastic modulus of 6.42 GPa [17], [41], [42]. The significant difference between ramie fiber and the other fibers indicates that fiber strength and modulus play crucial roles in the stiffness of the composite. Higher elastic modulus contributes to greater stiffness, and stronger fibers can better withstand bending loads, enhancing the composite's stiffness. This phenomenon has also been observed by previous researchers [9], [17], [28], [43], [44]. Therefore, composites incorporating ramie fibers exhibit superior flexural strength and modulus compared to those with other natural fibers.

On the other hand, calcium carbonate filler also contributes to increasing both flexural strength and flexural modulus. The elastic modulus of calcium carbonate ranges from 65 to 76 GPa [45]. The rigid calcium carbonate particles help inhibit composite deformation by resisting external forces applied to the resin. In addition, the effect of calcium carbonate filler on natural fiber composites can also increase the interfacial bond between the fiber and the matrix. This can happen because calcium carbonate can fill the empty cavities between the fiber and the matrix. Thus the material will be stiffer and increase flexural strength. This finding is supported by other researchers [8], [43], [44], [46]–[48].

Impact Test: Impact testing on three samples, namely A1, A2, and A3, produced impact toughness values as shown in Figure 4. The respective values are 0.017 J/mm², 0.023 J/mm², and 0.056 J/mm².

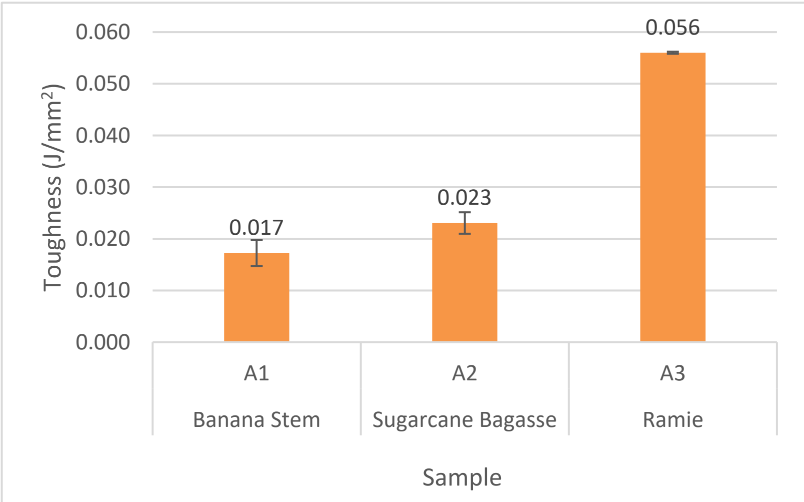

Fig. 4. Toughness of the tested composite samples

It can be seen in Figure 4 that the highest impact toughness is found in the ramie fiber composite, with a value of 0.056 J/mm², while the lowest is found in the banana stem fiber composite, with a value of 0.017 J/mm². The role of fiber in the composite is to withstand shock loads until the *fiber* breaks. After the initial fiber breaks, the force is transmitted through the matrix to the remaining intact fibers. Therefore, the higher the tensile strength of the fiber, the higher the toughness, as the fiber is less likely to break easily. This observation is consistent with findings from other researchers [9], [12], [15], [34], [43], [44], [49]. Therefore, composites using ramie fiber exhibit the highest toughness.

Calcium carbonate plays a role in reducing the toughness of the material. This is due to the higher elastic modulus of calcium carbonate compared to ramie fiber and polyester resin, which ranges from 65-76 GPa [45]. A higher elastic modulus results in lower deformability and toughness of the material. Consequently, this can lead to stress concentration at specific points when a load is applied. This observation is supported by other researchers [46], [48], [50], [51].

Based on the results of the flexural and impact tests, the use of ramie fiber in unsaturated polyester resin matrix composites filled with 30 PHR calcium carbonate achieved the highest values in the three mechanical properties: flexural strength, flexural modulus, and impact toughness. Therefore, ramie fiber was chosen for further research in the next stage to explore the mechanical and physical properties of composite materials, evaluating the potential of ramie fiber as an alternative to glass fiber for roofing applications.

The next stage will use two types of samples. The first sample, S1, consists of a matrix only, without reinforcing fibers, where the matrix is a mixture of resin and 30 PHR calcium carbonate filler. The second sample, S2, is a composite with the same matrix as S1 but with the addition of ramie fiber at 30% by weight of the matrix.

Tensile Test: Tensile testing on two samples, S1 and S2, produced the following results for tensile strength and modulus of elasticity, as shown in Figures 5 and 6: 34.62 MPa and 47.53 MPa for tensile strength, and 1630 MPa and 1324 MPa for modulus of elasticity.

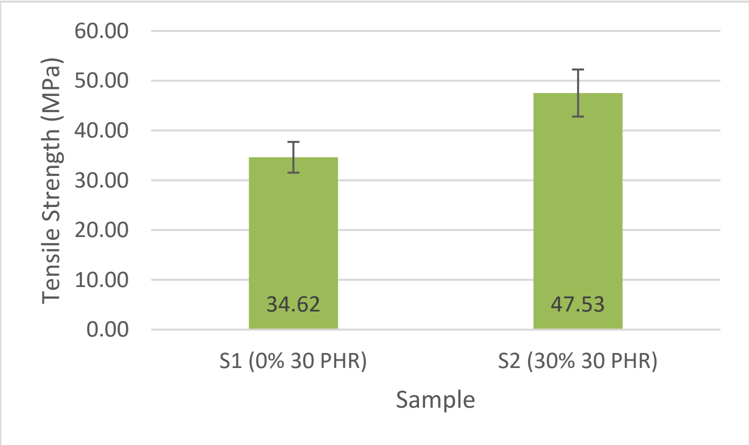

Fig. 5. Tensile strength of the tested composite samples

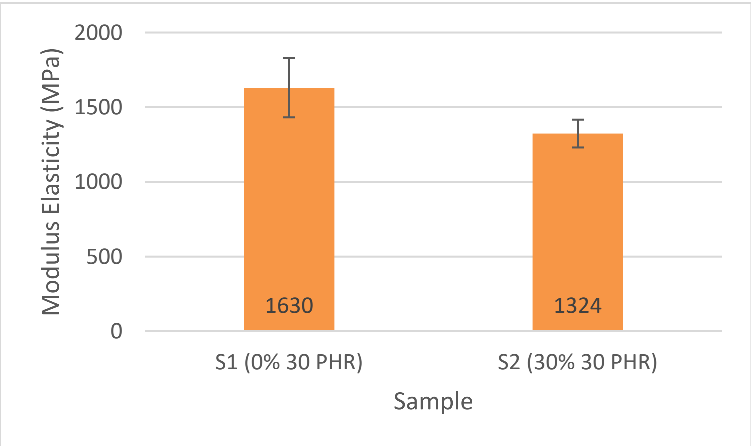

Fig. 6. Modulus elasticity of the tested composite samples

The test data show that ramie fiber increases tensile strength but decreases the elastic modulus. Ramie fiber effectively functions as reinforcement when integrated with a matrix consisting of unsaturated polyester resin and 30 PHR calcium carbonate filler. Ramie fiber with high tensile *strength* properties contributes to resisting tensile loads in composites. This finding aligns with previous research results [20], [28]. The elastic modulus of ramie fiber is 61.5 GPa, which is lower than that of calcium carbonate, which ranges from 65 to 76 GPa [40], [45]. Consequently, the elastic modulus of sample S2 is lower than that of sample S1.

Sample S1, which consists of a solid matrix made from a mixture of unsaturated polyester resin and 30 PHR calcium carbonate filler, exhibits a tensile strength of 34.62 MPa, which is higher than that of pure resin. The tensile strength of pure resin without filler is 29.4 MPa [52]. This indicates that 30 PHR calcium carbonate filler still contributes to an increase in tensile strength. Calcium carbonate, being rigid, acts as an obstacle to deformation when the resin is subjected to external forces. Therefore, calcium carbonate filler, in amounts up to 25% wt, enhances the strength and stiffness of matrices like that of sample S1. In addition, calcium carbonate and ramie fiber can synergistically affect the tensile strength properties, where calcium carbonate filler can fill the empty cavities between the fiber and the matrix, thereby increasing the interfacial bond between the fiber and the matrix. Thus, it can increase the tensile strength of the composite because the fiber can withstand the maximum load. This observation is consistent with previous research [29], [46], [47], [53]. However, exceeding a certain amount of calcium carbonate filler, usually more than 25% wt, tends to cause agglomeration, where the filler grains do not mix homogeneously with the resin, leading to a decrease in both tensile strength and elastic modulus [48].

Reviewing the tensile test results, the ramie fiber composite with 30 PHR calcium carbonate filler achieves a tensile strength of 47.53 MPa, meeting the minimum specification of 40 MPa for roof tensile strength [3]. Therefore, ramie fiber has the potential to serve as an alternative material to replace glass fiber in commercial roof applications in Indonesia.

2. Physical Properties

Scanning Electron Microscope (SEM) Examination: Figures 7 and 8 present the results of the scanning electron microscope (SEM) examination, displaying the morphology of the tensile test fracture sections for samples S1 and S2.

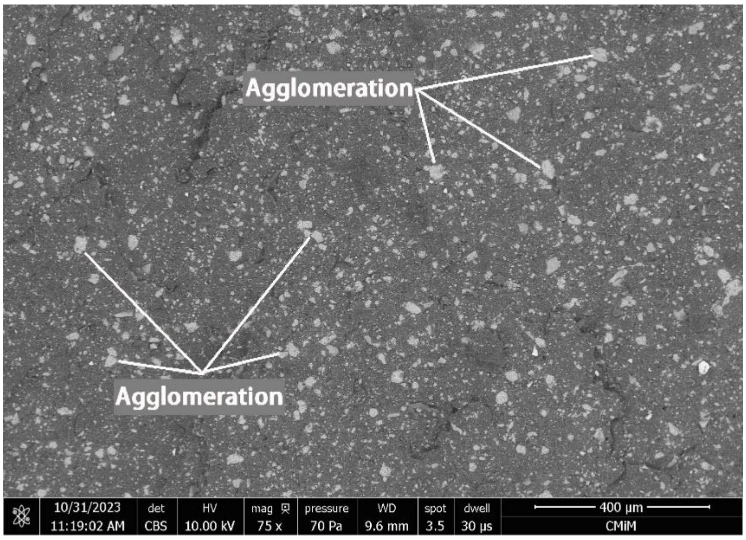

Fig. 7. SEM micrograph of sample S1

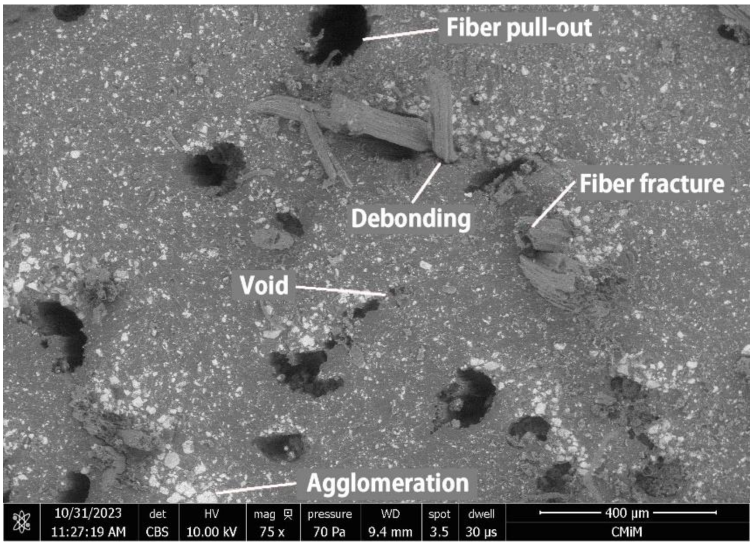

Fig. 8 SEM micrograph of sample S2

Sample S1 exhibits a relatively brittle fracture, and both sample S1 and sample S2 show signs of agglomeration. The small size of the calcium carbonate particles, when used in large quantities, prevents them from mixing homogeneously with the resin, leading to agglomeration. This observation is consistent with previous research [38]. Despite the agglomeration in sample S1, the calcium carbonate filler still contributes to increased strength, as evidenced by the higher tensile strength of sample S1 compared to pure resin. The size and quantity of the agglomerations do not significantly impact the tensile strength [46]–[48].

Sample S2 also displays a brittle fracture, with relatively short fiber breaks observed in Figure 8. This suggests a good bond between the fiber and the matrix. The fiber pull-out phenomenon, which appears as large dark holes, indicates imperfections in the bond between the fiber and the matrix. There is also evidence of fiber debonding within the matrix. Nevertheless, ramie fiber continues to reinforce the composite material, as reflected in the higher tensile strength of sample S2 compared to sample S1. This finding aligns with other studies that show how different fiber shapes and calcium carbonate fillers can interact to fill voids, thereby enhancing the bond between the fiber and matrix and increasing tensile strength [38], [51]. Additionally, the presence of voids or pores, which are smaller than the diameter of the ramie fiber, can affect sound transmission loss. These voids may allow sound waves to travel along their paths, causing heat transfer and sound dissipation due to friction with the pore walls [26].

Water Absorption Test: Figure 9 shows the maximum water absorption over 14 days for sample S1 and sample S2, with values of 1.145% and 3.746%, respectively. The water absorption of sample S2, which contains ramie fibers, is higher than that of sample S1, which does not contain ramie fibers. The natural fiber ramie is hydrophilic, significantly increasing the water absorption of the composite. The test results show a difference in water absorption of 2.601% between samples S1 and S2. This phenomenon occurs because ramie fiber, being a hydrophilic natural fiber, absorbs water due to its high cellulose content, which binds more water molecules [38], [54], [55]. Additionally, the composite matrix with 30 PHR calcium carbonate, which has tiny particle sizes and is present in large amounts, has the potential to agglomerate and form water clusters. These clusters can retain water, contributing to increased water absorption. However, the impact of calcium carbonate on water absorption is not as significant as the effect of the cellulose content in ramie fiber [38], [56]. Therefore, adding ramie fiber to the calcium carbonate-filled composite leads to increased water absorption.

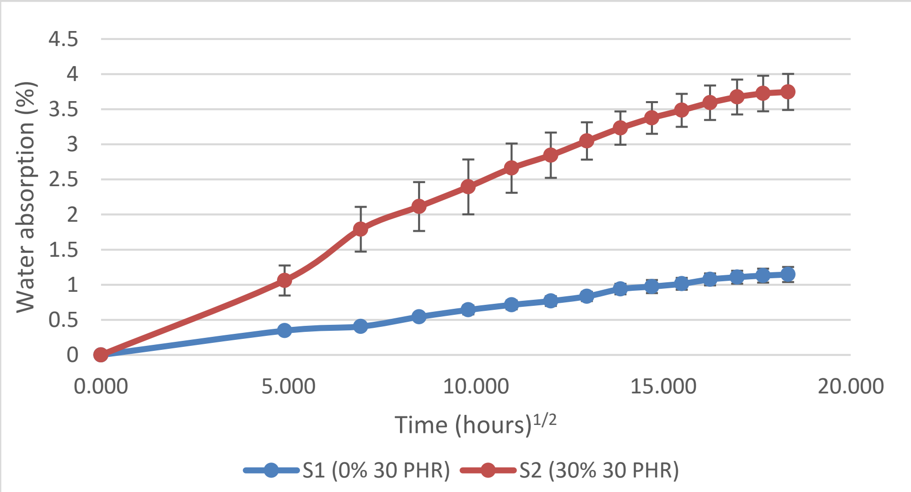

Fig. 9. Water absorption of the tested composite samples

Specific Gravity Test: Specific gravity testing on samples S1 and S2 provided actual and theoretical *densities*, as shown in Figure 10. The respective values are 1.414 g/cm³ and 1.432 g/cm³ for actual density, and 1.470 g/cm³ and 1.480 g/cm³ for theoretical density.

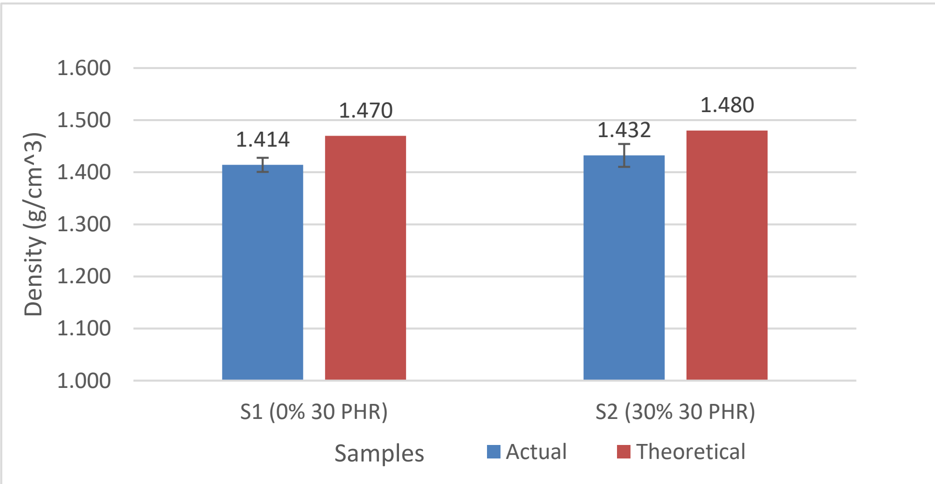

Fig. 10. Density results of the tested composite samples

It can be seen in Figure 10 that sample S2 has a density that is 1.273% greater than sample S1. Adding ramie fiber to the polyester resin matrix composite filled with 30 PHR calcium carbonate increases the density. This increase is attributed to the density of ramie fiber, which is 1.5 g/cm³, higher than that of the 30 PHR calcium carbonate matrix mixture [40]. The respective densities of polyester resin and calcium carbonate are 1.1 g/cm³ and 2.7 g/cm³ [57]–[59]. The 30 PHR mixture produces a theoretical density of 1.47 g/cm³ for a solid matrix, which aligns with findings from other researchers [8], [52], [59]. Thus, adding ramie fiber increases the density of the composite containing 30 PHR calcium carbonate.

The theoretical density is higher than the actual density because theoretical density is calculated under ideal conditions where voids are assumed to be non-existent. In reality, voids occur due to air trapped by the ramie fibers and the agglomeration of the calcium carbonate filler [8], [38], [60].

This ramie fiber composite has a lighter density of 1,432 g/cm³ compared to commercial roof specifications of 1.5–1.9 g/cm³ [3]. This is an advantage for ramie fiber as an alternative material for roofing applications because it has a lighter weight compared to glass fiber.

Thermogravimetric Analysis (TGA): TGA of samples S1 and S2 shows the degradation of mass loss as the temperature increases to a maximum of 550 °C, as depicted in Figure 11. The mass loss in samples S1 and S2 is 74.65% and 86.95%, respectively. The significant difference of 12.30% is attributed to the influence of ramie fiber.

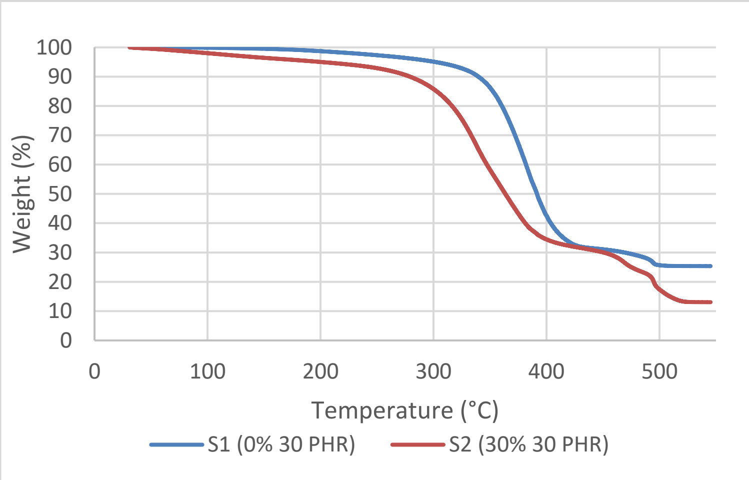

Fig. 11. TGA results of the tested composite samples

Materials undergo degradation in several stages. In the first stage, both samples lose mass in the temperature range of 90-150 °C due to the evaporation of water from the composite [61], [62]. In the second stage, significant mass loss is observed. Sample S1 shows a notable decrease in mass at temperatures around 350-400 °C, attributed to the degradation of polyester resin, which decomposes at 360-400 °C [63]. Sample S2 experiences substantial mass loss in the temperature range of approximately 300-400 °C, caused by the degradation of cellulose, hemicellulose, and polyester resin. Research indicates that hemicellulose decomposes at 220-315 °C and cellulose at 315-400 °C [64]. In the third stage, Sample S2 shows additional mass loss between 400-500 °C, due to the degradation of lignin content in the ramie fibers [26], [65].

Sample S2 exhibits lower thermal stability compared to Sample S1. The ramie fibers in Sample S2 are flammable due to their cellulose, hemicellulose, and lignin content [55], [65]. Consequently, the presence of ramie fiber reduces the composite's thermal stability. The test results also indicate that the calcium carbonate in both samples has not decomposed within the tested temperature range. This is because the maximum test temperature of 550 °C is below the decomposition temperature of calcium carbonate, which is reported to be between 680-875 °C [66].

Sound Transmission Loss: Figure 12 shows the results of the sound transmission loss test. The highest transmission loss value is found in sample S2 at a frequency of 630 Hz, measuring 77.7 dB, while the lowest value is found in sample S1 at a frequency of 2000 Hz, measuring 19.1 dB. Both samples exhibit a decrease in transmission loss at a frequency of 315 Hz, followed by an increase at 630 Hz, and then a subsequent decrease to the lowest point at 2000 Hz. Both samples demonstrate good soundproofing at 630 Hz but poor soundproofing at 2000 Hz. Across the entire frequency range, sample S2 consistently shows higher transmission loss values compared to sample S1.

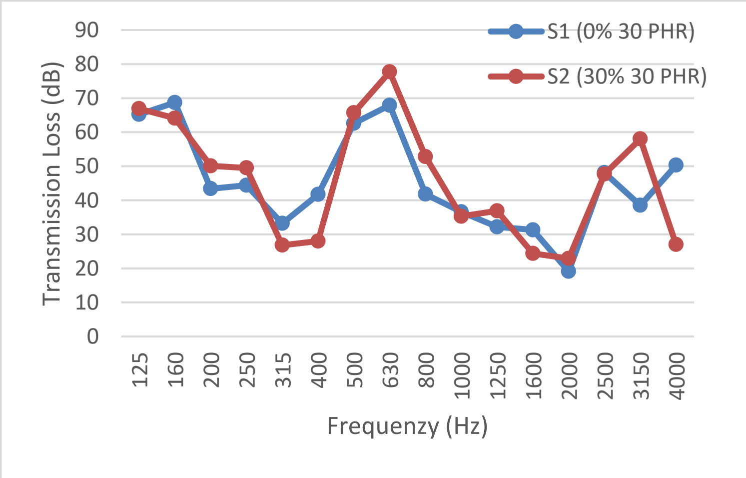

Fig. 12. Sound transmission loss of the tested composite samples

The material's ability to reduce sound transmission is measured by the Sound Transmission Class (STC) value, which is calculated according to the ASTM E413 standard. A higher STC value indicates better sound isolation. The STC values for samples S1 and S2 are 23 dB and 26 dB, respectively, as shown in Figure 13.

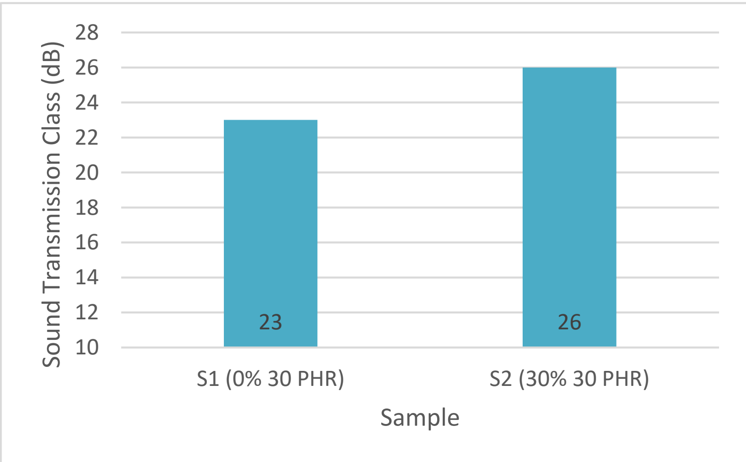

Fig. 13. Sound transmission class of the tested composite samples

Figure 12 shows the peaks and valleys in the transmission loss values for samples S1 and S2. Such variations are typically caused by the material structure's resonant frequencies. At specific frequencies experiencing resonance, the material may perform better at dampening sound, while the peaks indicate anti-resonance, suggesting that the material can dampen sound effectively [67]. This phenomenon of sound transmission loss peaks and valleys has also been observed by other researchers [68]–[70].

Sample S2 has an STC value that is 13.043% higher than that of sample S1, indicating that the ramie fiber content in sample S2 enhances sound isolation. Several factors contribute to this. Sample S2 can be classified as a fibrous material with a structure containing channels and cavities [26]. The distribution of fibers in a composite affects sound dampening; short fibers arranged randomly can create a porous structure that absorbs sound waves. Additionally, the single ramie fiber structure contains numerous micropores, as noted in previous research [25]. This composite structure allows sound waves to pass through various channels and pores, impacting sound dampening. As sound waves traverse the composite structure, they experience air viscous effects and heat transfer. Viscous effects occur as sound waves moving through air encounter friction between the pore walls, causing sound dissipation. This friction results in heat transfer to the material through the pore walls, converting sound energy into heat and thus enhancing sound dampening. This phenomenon aligns with other studies on natural fibers as sound-dampening materials [25], [26], [71], [72]. Consequently, the presence of ramie fibers improves the sound insulation ability of composite materials, as evidenced by increased sound transmission losses.

An STC value of 20-25 is considered very poor, where soft sounds like whispers, footsteps, and gentle breezes are audible. An STC value of 25-30 is deemed poor, where normal sounds such as conversations, electronic devices, and household activities can be heard [70], [73]. Based on this classification, sample S1 is considered very poor, while sample S2 is categorized as poor. Given that the sample thickness in this study is only 3 mm, its ability to isolate louder sounds is limited. However, this research primarily assesses the impact of ramie fiber on increasing mechanical strength and sound-dampening properties. It is evident that ramie fiber enhances the mechanical properties of composite materials by increasing tensile strength and sound dampening. Nonetheless, the addition of ramie fiber also increases specific gravity and water absorption while reducing the elastic modulus. Further study is required to determine whether this polyester matrix composite with 30 PHR calcium carbonate filler reinforced with 30% wt ramie fiber meets the criteria for roofing material.

IV. Conclusions

Research on various natural fibers in Indonesia as reinforcements for unsaturated polyester resin matrix composites filled with calcium carbonate for roofing applications has been conducted. A comparison of three types of unsaturated polyester resin matrix composites with 30 PHR calcium carbonate fillers, reinforced with natural fibers from banana stem fiber, bagasse fiber, and ramie fiber, showed that ramie fiber performed the best. Its flexural strength, flexural modulus, and impact toughness were the highest, measured at 191.57 MPa, 6691 MPa, and 0.056 J/mm^2, respectively. Further examination of the composite material, consisting of an unsaturated polyester resin matrix with 30 PHR calcium carbonate fillers and reinforced with 30%wt ramie chopped strand mat fibers, provides more detailed information on its properties. Compared to the material without ramie fibers, the composite reinforced with ramie fibers shows an increase in tensile strength to 47.53 MPa from 34.62 MPa, an increase in maximum water absorption over 14 days to 3.746% from 1.145%, and an improvement in the sound transmission class to 26 dB from 23 dB. Additionally, the ramie fibers did not significantly affect the density of the composite material. However, the inclusion of ramie fibers resulted in a reduction of the elastic modulus to 1324 MPa from 1630 MPa, and a higher mass loss in the TGA examination, at 86.95% compared to 74.65%. The ramie fiber composite meets the requirements for roofing in terms of tensile strength. The tensile strength of 47.53 MPa exceeds the minimum roof requirement of 40 MPa. Ramie fiber composite also has the advantage that its density is lighter than using glass fiber. Therefore, ramie fiber has the potential as an alternative to glass fiber in roofing applications and is worthy of further research for the manufacture of industrial roofs.

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