Mechanics of Advanced Composite Structures

Journal homepage: https://macs.semnan.ac.ir/

Semnan University

ISSN: 2423-7043

Research Article

The Impact of Fiber Architecture on the Mechanical Properties of Hand Lay-up Reinforced Polyester Resin

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ARTICLE INFO

Article history:

Received: 2023-03-22
Revised: 2023-05-12
Accepted: 2023-10-19

Keywords:

Composite materials;
Polyester resin;
Glass fiber;

ABSTRACT

This work aimed to improve the mechanical properties of a glass fiber-reinforced polyester resin composite material. The research evaluated the effect of glass fiber architecture on these properties by using fibrous-like and sheet-like glass fibers to reinforce polyester resins via a hand lay-up method. The prepared specimens were analyzed for various mechanical properties, including tensile, hardness, and flexural, according to ASTM standards. The results showed that glass fiber reinforcement in both fibrous-like and sheet-like forms enhanced the mechanical properties of polyester resin. Specifically, polyester resin composites reinforced with fibrous-like glass fibers exhibited superior mechanical properties. The hardness was 28.03±3.5 HV, the tensile strength was 76.31±11.4 MPa, the tensile modulus was 2293.92±116.7 MPa, and the percent elongation at break was 5.92%, with a flexural resistance of 114.49±22.2 MPa and a flexural modulus of 5377.37±596.6 MPa. Additionally, a simulation model using SIMCENTER 3D software was utilized to assess the stress application on a large water tank fabricated by the as-prepared composites. The simulation confirmed the performance of these composites.

1. Introduction

Composite materials are designed to possess unique qualities that distinguish them from conventional materials, whether they have remarkable features or are markedly different from the original material. These composite materials consist of two main components: the matrix or base materials, which form continuous phases of the substance, and the reinforcement materials, which are dispersed within the substance. The widespread adoption of composite materials can be attributed to their superior properties, such as low density and cost-effectiveness, excellent strength and corrosion resistance, low weight, and improved mechanical properties [1, 2]. They are widely applied in the automotive, construction, electrical components, and aerospace industries [3-5]. Polymer matrix composites have been developed for various applications to enhance the robustness of polymers [6]. These composites, consisting of

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Cite this article as:
Mohammadi, A., Mahdi-Nia, M., 2024. Title of article. *Mechanics of Advanced Composite Structures*, 11(2), pp. 1402-1425
https://doi.org/10.22075/MACS.2023.39315.2050

various resins and reinforcements, are widely used. Among the various resins, polyester resin is the most popular and potentially useful. Thermoset polyester resin has been developed and applied in various fields, including coatings, and adhesives, and as a component in composite materials for shaping tools and machinery parts in engineering, automotive parts, and aircraft parts [7, 8]. This is because polyester resin has the ability to withstand chemicals, heat, and humidity well. Although it is brittle, it possesses high strength [9, 10].

One category of fiber-reinforced polymer composites, known as glass fiber-reinforced polymer composites (GFRPs), has undergone extensive development due to their advantageous composition, consisting of a polymer matrix and glass fiber. This composition is comparatively more economical than other synthetic fibers [11]. Fiberglass, which has glass as its main component, is widely used as reinforcement in various industries. It is chosen for its high melting point, lightweight nature, good bendability, and high strength [12–14]. These characteristics make it suitable for use as reinforcement to enhance the mechanical properties of composite materials. Based on the study conducted by K. Sonsakul and W. Boongsood [15], it was found that glass fiber-reinforced polyester produced through the Vacuum Infusion Process (VIP) exhibited favorable mechanical properties, with flexural strength increasing to 121.52 MPa and tensile strength to 74.56 MPa. Similarly, M.S. EL-Wazery et al. [16] reported that using E-glass fiber with randomly oriented reinforcement in a polyester composite resulted in significant improvement in mechanical properties. Specifically, the tensile strength increased from 28.25 MPa to 78.83 MPa, the flexural strength increased from 44.65 MPa to 119.23 MPa, and the hardness increased from 31.5 BHN to 47 BHN when 60 wt% glass fiber was used. Additionally, the study by O. Sam-Daliri et al. [17] and S. Lou et al. [18] found that using glass fibers as a reinforcing agent could significantly increase the strength of polypropylene. More recently, the research by J. Rongyu et al. [19] demonstrated that glass fiber-reinforced epoxy resin composites exhibited excellent mechanical properties. They found that increasing the glass fiber content significantly enhanced the mechanical performance of the composites. Furthermore, P. Morampudi et al. [20] found that glass fiber could improve the mechanical, thermal, and water absorption properties of both thermoplastic and thermosetting polymers. The properties of glass fiber-reinforced composite depend on many factors, such as the type of glass fiber, the amount of glass fiber, the matrix material, and the production technologies. These studies, along with others, highlight the significant improvements in mechanical properties achieved through the incorporation of glass fibers in various polymer matrices. However, the characteristics of glass fibers, whether they are short fibers, long fibers, or woven glass fibers in various forms, affect the efficiency of enhancing the mechanical properties of composite materials.

Because the efficiency of reinforcing composite materials depends on the size and shape of the reinforcing agent, this work focuses on studying the influence of fiber architecture on the mechanical properties of polyester resin composite materials. Specifically, this research compares fibrous-like and sheet-like glass fibers to determine the most suitable fiber architecture for different applications. This approach aims to optimize the performance and cost-effectiveness of composite materials in various industrial uses, a topic that, to our knowledge, has not been extensively explored in previous research. Additionally, this research examines the material's ability to withstand forces through simulations using SIMCENTER 3D software to ensure that the prepared composite material can be used in real-life applications without damage when subjected to maximum force.

2. Experimental Procedure

2.1. Preparation of Composites

Glass fiber-reinforced polymer composites were prepared using a hand lay-up (HLU) technique with different shapes of glass fibers in polyester, including fibrous-like and sheet-like glass fibers, as shown in Fig. 1.

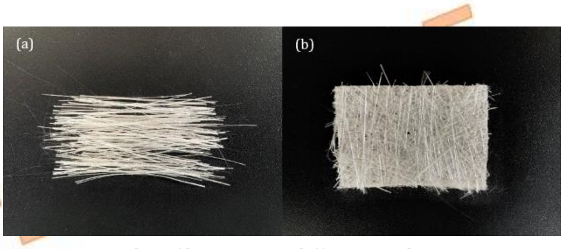

Fig. 1. Glass fibers in two different architectures: (a) fibrous-like and (b) sheet-like.

Polyester resin (RESINX, Infinite Craft Co., Ltd.) and hardener (MEKP, Methyl Ethyl Ketone Peroxide) were combined at a 1% weight ratio. The mixture was stirred slowly in a clean plastic beaker for 1 minute to prevent foaming. The hardener-mixed polyester resin was then applied to an open silicone mold pre-treated with Vaseline to prevent sticking. Glass fiber reinforcement (E-glass No. 450, Infinite Craft Co., Ltd.), with a tensile strength of approximately 1625–3400 MPa [21], was cut to match the dimensions of the mold. Sheet-like glass fibers were cut to fit both the length and width, while fibrous-like fibers were cut to match only the length of the mold. The glass fibers were placed over the first layer of resin, aligning them with the length of the mold. This layering process was repeated for a total of three layers, alternating between resin and glass fibers, using a ratio of 0.5 grams of glass fiber to 1 gram of polyester resin, resulting in a glass fiber content of 50 wt%. The composite was left to set for 1 minute between layers. After the final layer was applied, the composite was allowed to cure into a hard matrix for eight hours at room temperature. Subsequently, the composite was removed from the mold. The fabrication process for a glass fiber-reinforced polyester resin composite is shown in Fig. 2

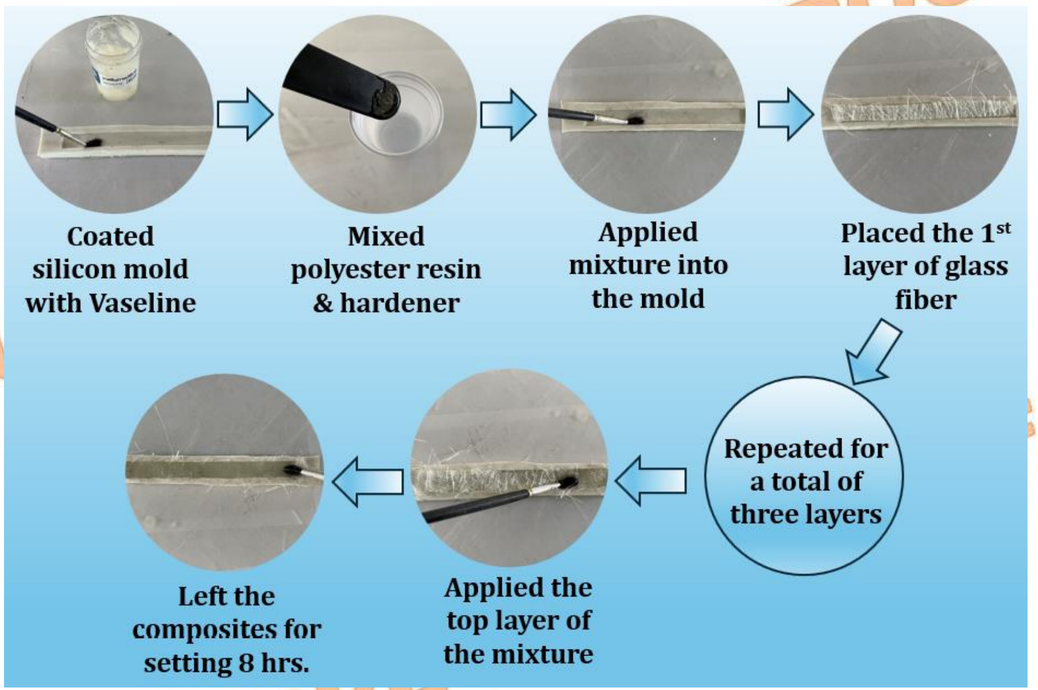

Fig. 2. Illustration of the fabrication process for a glass fiber-reinforced polyester resin composite.

2.2. Mechanical Testing

The tensile strength, Young's modulus, and elongation at break of the prepared glass fiber-reinforced polyester resin composite materials were evaluated using a Universal Testing Machine (LS Plus Series, Lloyd) with a load cell of 10 kN and a test speed of 10 mm/min according to ASTM D638-10. Bending strength and bending modulus were determined using a 10 kN load cell, a test speed of 1.7 mm/min, and a span of 64 mm following ASTM D790-03. Hardness was measured using a Micro Vickers Hardness Machine (Nova240, Innovatest) with a 0.1 kgf load applied for 12 seconds. A minimum of five samples were analyzed to determine the mean and standard deviation values.

2.3. Stress Simulation

To assess the tank's ability to withstand force in practical applications, SiMCENTER 3D software (SIEMENS) was used to examine the stress distribution on a large water tank. A vertical cylindrical vessel with a capacity of 500 liters had a diameter of 700 mm, a height of 1400 mm, and a thickness of 20 mm. In the simulation, the maximum force condition, which occurs when the tank is fully filled with water, was considered. Under these conditions, the simulated maximum water pressure reached 13,300 N/m^2. The model accurately simulated real-world constraints and interactions, with the tank fixed at its base and the applied pressure distributed uniformly across its inner surface.

3. Results and Discussion

3.1. Hardness Properties

The micro-Vickers hardness (HV) values for glass fiber-reinforced polyester resin composites are shown in Fig. 3. The figure illustrates an increase in hardness from 11.5 HV to 28 HV when glass fibers were used as reinforcement. Furthermore, the fibrous-like form of glass fiber reinforcement resulted in a higher hardness when compared to sheet-like form reinforcement. This is attributed to the more dispersed nature of glass fibers in fibrous-like form compared to those in sheet-like form. This observation is consistent with microhardness analyses conducted by B. Taye Wondmagegnehu et al. [22] and M.S. EL-Wazery et al. [16], which indicated that increasing the amount of glass fiber in polyester resin composites increases the hardness value. This is because the test load is distributed across the glass fibers, reducing the penetration of the diamond indenter into the surface of the composite material, thus increasing its hardness.

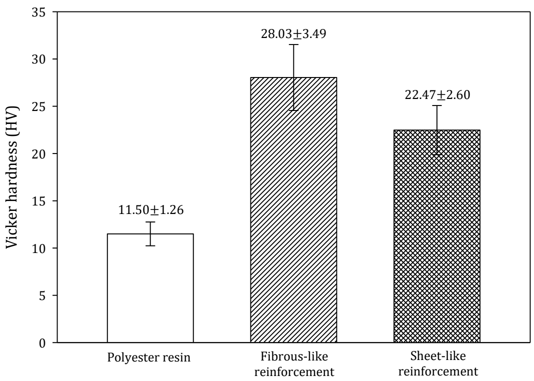

Fig. 3. Hardness of glass fiber-reinforced polyester resin composite.

3.2. Tensile Properties

The results for tensile strength, Young's modulus, and elongation at break of glass fiber-reinforced polyester resin are presented in Table 1. Prior to reinforcement, the tensile strength of the polyester resin was 27.06 MPa. However, reinforcing the polyester resin with glass fibers, whether in fibrous-like or sheet-like form, enhanced its mechanical properties. This enhancement occurs because the polyester resin effectively transfers and disperses the applied stress to the high-strength glass fibers, resulting in increased strength [23, 24]. This finding is consistent with the study by A.F. Zakki and A. Windyandari [25], which suggests that glass fibers could improve the tensile strength of polyester composites, as shown in Table 1. They also found that increasing the number of layers significantly increased tensile strength due to improved laminate strength. Furthermore, when the orientation angle of the reinforcing fibers was 0°, the laminate exhibited a higher tensile strength. Consistent with previous research, this study found that reinforcing with glass fibers in fibrous-like form led to a significant increase in tensile strength (76.31 MPa) compared to using sheet-like fibers. This enhancement is attributed to the alignment of fibers in the same direction as the applied force [26]. When fibers are aligned consistently, they provide optimal support for loads, particularly uniaxial loads that move parallel to the fibers. This alignment maximizes the load-bearing capacity of the laminate, resulting in superior mechanical properties.

Table 1. Tensile properties of glass fiber-reinforced polyester denote statistically significant differences at $p < 0.05$.

Sample	Tensile Strength (MPa)	Young's Modulus (MPa)	Elongation at Break (%)	References
Polyester resin	27.06±0.56	1059.32±43.19	2.92±0.62	This study
Fibrous glass fiber reinforcement	76.31±11.38	2293.92±166.68	5.92±2.48	This study
Sheet glass fiber reinforcement	61.53±4.22	1927.23±65.37	4.23±1.53	This study
chopped strand mat 300 Glass fiber (4 layers)	62.53	1853	3.4	[25]
E-glass fibers (18 wt%)	28.87	2406	N/A	[27]

The experimental data of fibrous-like and sheet-like forms showed p-values of approximately 0.0027 and 0.033, respectively.

The tensile modulus and elongation at break follow a trend similar to the ultimate strength results. This is attributed to the higher stiffness and ductility of the glass fibers compared to the polyester resin [11]. Consistent with the findings of A. Gopinath et al. [27], the higher Young's modulus observed in composites reinforced with E-glass fibers, compared to those reinforced with jute and coconut fibers, is due to both the superior stiffness of E-glass fibers and their better compatibility with the polymer matrix. The superior Young's modulus of fibrous-like reinforcement is primarily due to the effective alignment and dispersion of the fibers, which enhances the load-bearing capacity and stiffness. In contrast, the use of sheet-like fibers led to a reduction in tensile modulus and elongation at break, although these values remained higher than those of the unreinforced polyester resin. This decrease is attributed to the less effective dispersion and the less optimal directional arrangement of sheet-like fibers within the

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polyester resin, which limits their ability to enhance mechanical properties [16].

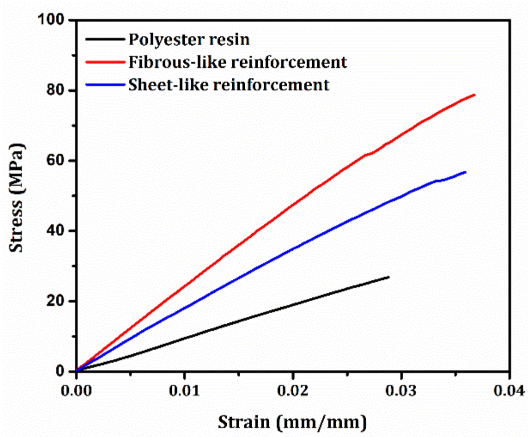

Fig. 4. Stress-strain curve of glass fiber-reinforced polyester resin composite.

Figure 4 illustrates the typical tensile stress-strain curve for the glass fiber-reinforced polyester resin composites studied. The curve reveals that these composites exhibited brittle behavior, characteristic of polyester resin. The addition of glass fiber reinforcement modified both the tensile strength and elongation at break. This improvement can be attributed to the ability of glass fibers to distribute applied stresses more evenly throughout the composite. The high tensile strength and stiffness of the glass fibers reinforce the polymer matrix, which enhances the overall structural integrity and resistance to deformation [12]. According to the study by Y.S. Mohamed and A. Abdelbary [28], tensile loading is primarily dependent on fiber orientation during the layup manufacturing process. Specifically, test specimens with a 0° fiber orientation exhibit the highest resistance to failure compared to specimens with other fiber orientations. Consequently, using glass fiber reinforcement in fibrous-like form resulted in greater improvements in tensile strength compared to the sheet-like form.

3.3. Flexural Properties

The flexural strength of polyester resin increased from 68.98 MPa to 101.15 MPa and 114.48 MPa when reinforced with glass fibers in sheet-like and fibrous-like forms, respectively (Fig. 5). This result aligns with the findings of K. Sonsakul and W. Boongsood [15], who reported that three layers of glass fiber chopped strand mat No. 450 enhanced the flexural strength of polyester resin to 121.52 MPa, as shown in Table 2. The increase in flexural strength can be attributed to the strong interfacial interaction between the polyester resin and glass fibers. Additionally, the gradient interphase layer between the glass fibers and polyester resin likely played a role in retarding interlaminar and intralaminar microcracks, thereby enhancing the material's overall flexural strength [29]. The comparison with previous studies underscores the effectiveness of glass fiber reinforcement in significantly improving the flexural strength of polyester resin, with both fibrous-like and sheet-like forms providing comparable enhancements as shown in Table 2, and other mechanical properties, including tensile strength and hardness, are also exhibited in this table.

Figure 6 shows the flexural modulus of polyester resin and polyester resin reinforced with glass fiber in both sheet-like and fibrous-like forms. It is evident that using glass fiber in fibrous-like form as reinforcement resulted in the highest flexural modulus (5377.37 MPa), which is twice as high as the flexural modulus of polyester resin. This increase is attributed to the high stiffness of glass fiber [27]. According to M.S. El-Wazery et al. [16], the inherent brittleness of the resin results in a low flexural modulus before reinforcement. However, the addition of glass fibers significantly raises the flexural modulus, as the high modulus of elasticity of these fibers allows them to carry larger loads and enhance the material's strength.

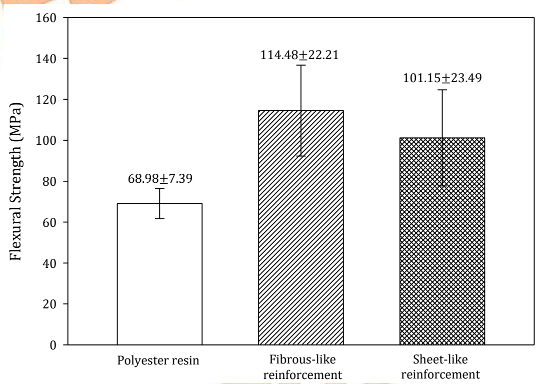

Fig. 5. Flexural strength of glass fiber-reinforced polyester resin composite.

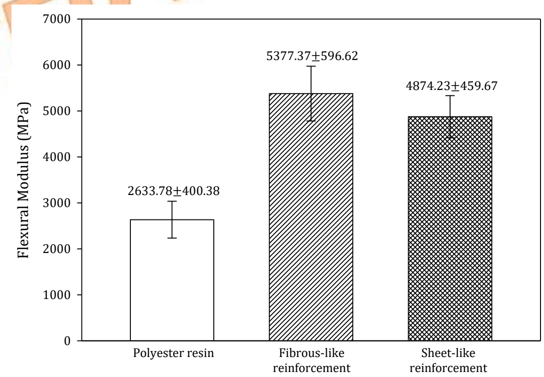

Fig. 6. Flexural modulus of glass fiber-reinforced polyester resin composite.

Table 2. Mechanical properties of glass fiber-reinforced polyester composites, including results from this study and other research.

Sample	Tensile Strength (MPa)	Flexural Strength (MPa)	Hardness	References
Polyester resin	27.06 ± 0.56	68.98 ±7.39	11.50 ± 1.26 HV	This study
Fibrous-like reinforcement	76.31 ± 11.38	114.48 ± 22.21	28.03 ± 3.49 HV	This study
Sheet-like reinforcement	61.53 ± 4.22	101.15 ± 23.49	22.47 ± 2.60 HV	This study
chopped strand mat 450 Glass fiber (3 layers)	74.56	121.52	74.6 (Shore D)	[15]
Fabric E-glass (60 wt%)	78.83	119.23	47 BHN	[16]
E-glass fibers (18 wt%)	28.87	102.27	51.4 HRm	[27]

3.4. Simulation

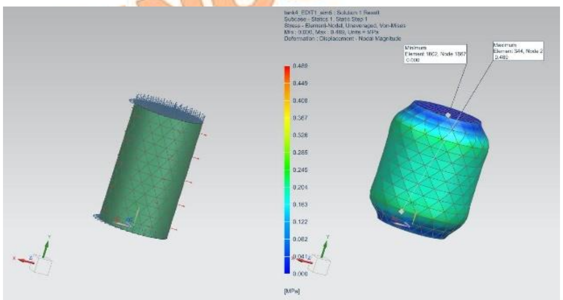

Fig. 7. The stress distribution results for a tank designed to withstand a maximum pressure of 13,300 N/m^2.

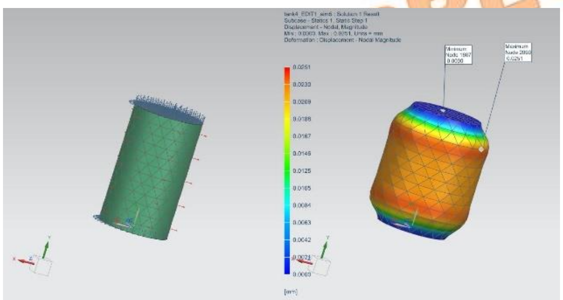

Fig. 8. The deformation results for a tank designed to withstand a maximum pressure of 13,300 N/m^2.

In the simulation, the water pressure resistance of a 500-liter water storage tank was assessed by applying a maximum pressure of 13,300 N/m^2, which represents the maximum water pressure when the tank is full. This resulted in a maximum stress value of 0.489 MPa. This stress value is depicted in the area below and inside the tank, as indicated by the arrow in Fig. 7. The maximum stress value was within the range of the tensile strength of the prepared composite materials. Specifically, polyester resin reinforced with glass fibers in fibrous-like form had a tensile strength of 76.31 MPa, while that of the sheet-like form was 61.53 MPa. These values were 156 times and 125 times greater than the actual stress experienced, respectively. This indicates that the prepared composite is strong, durable, and suitable for use in water tanks larger than 500 liters.

The deformation results of the tank subjected to a maximum pressure of 13,300 N/m^2 revealed a maximum deformation of 0.0251 mm, as indicated in red in Fig. 8. Slight changes in shape occurred under the maximum pressure, however, these changes did not affect the tank's usability.

4. Conclusions

Polyester resin reinforced with glass fiber was prepared using the hand lay-up method. The architecture of the glass fibers in the composites affected their mechanical properties. The polyester resin composites reinforced with fibrous-like glass fiber exhibited superior mechanical properties, including an ultimate tensile strength of 76.31 MPa, a Young's modulus of 2293.92 MPa, a flexural strength of 114.48 MPa, and a flexural modulus of 5377.37 MPa. These properties are attributed to the effective alignment and dispersion of the glass fiber within the polyester resin. Simulations showed that these composites could withstand a stress force 156 times greater than the actual stress force when compared to their tensile strength, indicating that the maximum stress values experienced during actual use fall within the range of the prepared composite materials. Therefore, polyester resin composites reinforced with fibrous-like glass fiber show promise for various applications, including large water tanks.

Acknowledgments

The authors would like to thank the Department of Metallurgical Engineering and Department of Mechanical Engineering, Faculty of Engineering, Rajamangala University of Technology Isan, Khon Kaen Campus, and the Department of Materials Engineering, Faculty of

Engineering and Technology, Rajamangala University of Technology Isan, for providing the necessary research facilities.

Funding Statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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