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Selection of a biocomposite material as an alternative for the manufacture of the rotor of a gravitational vortex turbine

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Summary. In this research study, a polymeric matrix biocomposite reinforced with natural fibers was evaluated as an alternative for the manufacture of impeller blades for a gravitational vortex turbine. Laminates were manufactured using the manual impregnation method, combining unsaturated polyester resin with three layers of fique fiber. Density tests were conducted along with the mechanical properties of the biocomposite, and they were compared with conventional materials such as aluminum, stainless steel, and fiberglass, commonly used in the construction of impellers. As a result of the tests, it was determined that bio composites present advantages such as: low cost, environmental sustainability and lower density compared to traditional materials. Finally, a prototype rotor for a gravitational vortex turbine was manufactured with the material proposed in the present study. In conclusion, the findings suggest that the developed biocomposite has the potential as an alternative to replace conventional materials in the manufacture of hydraulic rotors.

Keywords. Biocomposite, fique, rotor, gravitational vortex turbine, density.

1. Introduction

An innovative machine in the field of micro hydropower is the gravitational vortex turbine, designed to capture the natural flow of water and generate energy. This turbine works through the creation of a free surface vortex, from which its kinetic energy is used. It consists of an inlet channel that leads water to a circular basin, which has an opening at its base, allowing the formation of the vortex that drives a rotor equipped with multiple blades. This rotor is connected to an electric generator that produces energy, and finally, the water is evacuated through an outlet channel.

The rotor, which has multiple blades, is essential for capturing the rotational energy produced by the water flow of the vortex. This process transforms said energy into mechanical and electrical energy, a critical aspect for the efficiency of the system. The efficiency in converting the kinetic energy of water into usable energy increases proportionally with the rotation speed of the rotor [1].

On the other hand, the metallic materials used in the manufacture of the turbine impeller are subject to phenomena such as corrosion, cavitation, and erosion. Likewise, they have a high density, and their cost is significant [2]. In the manufacture of hydraulic turbines, dissimilar materials are selected depending on the specific tasks of the components; For example, stainless steel is used to make blades, guides, and impellers, while the use of carbon steel is preferred for fixed blades [3].

According to Rahman et al., the aim is to accelerate the development of GWVHT in research [4]. To achieve greater efficiency in the operation of the plant, it is suggested to reduce the weight of the impellers and use lighter and more resistant materials [5]. In this sense, in another study it has been proven that the efficiency of the impeller made of aluminum is greater than that made of steel due to its lower density [6].

In accordance with the above, Timilsina et al. recommend investigating lighter materials, such as aluminum, plastic, or composite materials, for their application in structural components for the manufacture of the turbine rotor. In the same study, it was found that physical modeling is the only accurate way to evaluate new materials, using a model size large enough to minimize scale effects, especially when hydroelectric power generation is considered in the model. [7].

Composite materials are made up of two or more materials in which they combine their properties in a single material. These materials have been used since the Egyptians in 1500 BC. C. to make mud bricks [8]. In the 20th century, the aerospace industry began to implement composite materials, standing out for their resistance and lightness superior to conventional materials, which was ideal for said industry; Later, together with the automotive industry, they adopted these materials, first in racing and later in the mass production of vehicles, due to their specific resistance, weight reduction and efficiency in fuel consumption [9].

In the field of composite materials, the manufacturer meticulously selects and combines the reinforcing material and matrix to meet specific goals. When designing a composite with multiple layers, each layer contributes different properties, allowing for detailed customization of the final product. This engineering strategy results in materials that are best for applications requiring a specialized combination of strength, flexibility, and durability. [10]. In contrast to conventional materials, composite material offers exceptional versatility. It can be tailored to the specific demands of any application, taking advantage of its unique features to achieve optimized performance and superior functionality [11].

Natural fiber bio composites, which are heterogeneous materials that combine fibers of plant, animal, or mineral origin with a traditional or biologically based polymer matrix[12] [13], present multiple environmental advantages. They are renewable, biodegradable, emit low amounts of CO_2 and allow the partial replacement of polymers derived from petroleum.[14] [15]. In addition, they have a lower production cost, are more environmentally friendly and can replace synthetic fibers, due to their good mechanical performance. This allows us to manufacture parts for the automotive, packaging, construction, and other sectors.[16] [17].

An example of the reinforcements used in bio composites is fique, a natural fiber extracted from the Andean furcraea plant, abundant in Latin America and native to Colombia. This fiber is biologically based and has good mechanical properties [12]. In addition, the manufacture of ecological composites from fique is low cost compared to synthetic fibers and easy to process. Therefore, fique is ideal for low-budget and environmentally conscious applications [18].

Therefore, in the current research, the selection of a biocomposite reinforced with natural fique fiber in a polymer matrix is contemplated. This material is presented as an alternative for the manufacture of blades in a runner for the GWVHT. To this end, laminates of this material were manufactured to later measure their mechanical efficiency in tensile tests. Other considerations were looked at, such as density and cost, compared to traditional materials such as aluminum and stainless steel. Finally, a first prototype of the impeller was built from the biocomposite.

2. Methodology

A. Materials

The materials used to manufacture the laminates are unsaturated polyester resin P-2002; which was supplied by Poliescol. Fique fiber in unbalanced braided weave configuration was provided by Coohilados. On the other hand, for the manufacture of the blade model and the rotor shaft mold, a PLA filament with a diameter of 1.75mm was used.

B. Methods

1) Selection of biocomposite material.

Initially, conventional materials used in hydraulic turbine rotors were analyzed, such as stainless steel and aluminum, whose mechanical properties were consulted in Askeland's book, Materials Science and Engineering [20], to compare them with that of the manufactured fique biocomposite.

However, some significant disadvantages were found, such as its excessive cost and weight. For this reason, lighter alternatives are being investigated, such as composite materials with a polymer matrix.

But the synthetic fiber production process was found to have a significant carbon footprint and a long degradation time. In response to this, the use of natural fibers instead of synthetic ones is suggested.

In Colombia, the Andean frucacea plant grows naturally without human intervention and some regions have begun to cultivate it for industrial use in the production of textiles, bags, and ropes. These textiles are used to reinforce composite materials, giving rise to a new material known as a biocomposite.

Despite the availability of resins derived from renewable sources, these are not best for the required application due to their rapid degradation upon contact with water. However, the use of unsaturated polyester resin has overcome this limitation.

2) Laminate manufacturing.

For the manufacture of the laminates, fique fiber was used as reinforcement for the biocomposite; where, the warp of the fabric is at 90° to the weft and they are oriented in the same direction. Initially, 4 layers of fabric were cut to 27 x 18 cm; The polyester resin was mixed with a MEK catalyst (methyl ethyl ketone peroxide) in a 100:1 ratio to guarantee its curing.

Subsequently, the resin was impregnated manually with a brush, distributing it evenly throughout the reinforcement, then contact pressure was used to eliminate air bubbles. Finally, the laminates were placed in a controlled environment and allowed to cure at room temperature for approximately 24 hours.

4 laminates were obtained, as illustrated in Fig. 1; The thickness was measured and showed an average value of 4 mm, a homogeneous cross section, and a good surface finish. An estimate of the weight fraction of the components was made using equations 1 and 2, for which values of 60% polyester resin and 40% fique fiber reinforcement were obtained.

Fig. 1. Fique fiber laminate with unsaturated polyester resin

3) Density estimation

With the rule of mixtures for composite laminated materials, the density of the composite can be estimated according to equations 1, 2 and 3 [19],

$$f_f = \frac{M_f}{M_c} \cdot 100 \quad (1)$$

$$1 = f_m + f_f \quad (2)$$

$$\rho_c = f_m \rho_m + f_f \rho_f \quad (3)$$

where:

- $\boldsymbol{M_c\ y\ M_f}$ are the masses of the compound and the fiber.

- f_m y f_f are the volume fractions of the matrix and the fiber, respectively.
- ρ_c , ρ_m y ρ_f are the densities of the composite, matrix, and fiber.

4) Tensile and bending test.

The tensile test was conducted following the ASTM D3039 standard. Separately, a Shimadzu universal machine with a capacity of 600 kN was used. According to the standard, the force application speed is 2mm/min; to 5 biocomposite samples with measurements of 250x25x4 mm as shown in Fig 2.

Fig. 2. Specimens used in tension tests.

The bending test was conducted following the ASTM D790 standard. To conduct the tests, a Shimadzu universal machine with a capacity of 600 kN was used. According to the standard, the force application speed is 2 ± 0.2 mm/min; 5 biocomposite samples measuring 140x14x4 mm; considering the geometry criteria given by the standard such as: Width <1/4 span or 21.2 mm; Length >span+10%span; and light ratio: edge of 16.

To physically and mechanically evaluate and compare the new material with the previously mentioned materials, a material selection method was used based on equations proposed by the authors (equations 4 and 5). This method assigns a score from 0 to 10 to each material property (aluminum, stainless steel, fiberglass composite, and biocomposite), where 10 is the best value and 0 is the worst.

For properties such as density and cost, minimum values are preferable and are scored 10; while for other properties (strength, elastic modulus, etc.), maximum values are best. Each property is assigned a "weight" based on its importance; For example, density had a weight of 30%.

A weighted score is calculated for each material by multiplying its score on each property by the corresponding weight, and all weighted scores for each material are added. The material with the highest total score is selected as the most suitable for the application in question.

$$P_{min} = \left(10 - \left(\frac{\text{Prop} - \text{min}_{\text{prop}}}{\text{máx}_{\text{prop}} - \text{min}_{\text{prop}}}\right)\right) \cdot 10 \cdot \text{Weight} \quad (4)$$

$$\mathbf{P_{máx}} = \left(\frac{\mathbf{Prop - min_{prop}}}{\mathbf{máx_{prop} - min_{prop}}}\right) \cdot \mathbf{10 \cdot Weight} \quad (5)$$

Where:

- $\mathbf{P_{min}}$ and $\mathbf{P_{máx}}$ are the scores obtained for the minimum and maximum properties of the group of materials.
- $\mathbf{min_{prop}}$ and $\mathbf{min_{prop}}$ are the minimum and maximum properties of the group of materials to be selected.
- **Prop** is the property to be evaluated.
- **Weight** is the importance given to the property to be evaluated.

5) Rotor manufacturing

To manufacture the rotor, a full-scale model of the blade was first 3D printed in PLA, as seen in Fig. 3; The printing parameters were: 0.2 mm layer height, 40% fill density, the fill pattern was set to rectilinear, the minimum skirt loop was 4, and the skirt type was set to inner edge and outside, the width of the skirt was 5 mm; Furthermore, the piece had no supports and the printing speed was set to 50 mm/s.

Fig. 3. Real-scale 3D printed blade model.

Then the mold was manufactured using 8 kg of plaster mixed with water in a 1:2 ratio; It was left to dry for two days before placing a plastic sheet to pour the top mold. This was left to dry for one day and then detached from the lower mold to let it dry one more day separately, as seen in Fig.4.

a) b)

Fig.4. Plaster mold of the blade: a) Upper face, b) Lower face.

Subsequently, after the construction of the blade mold, it was manufactured by manual impregnation using the previously characterized biocomposite; To do this, two layers of fique were cut with the geometry of the mold. Then, 100 grams of resin prepared with 40 drops of catalyst were applied to both sides of the two layers, until they were completely covered. It was left to cure for 48 hours before being removed from the mold to obtain the blade.

Fig. 5. Shaft mold.

For the axle mold, the design was made in Inventor (Student Version 2023b) **to** print it in 3D with PLA as seen in Fig. 5, and then assemble the manufactured blades in the mold slots and then pour resin to build the shaft and finally get the rotor.

3. Results

As shown in Fig. 1, the curve represents the properties obtained from the tensile test carried out on the biocomposite of polyester resin and fique fiber; a linear-elastic behavior is observed, until reaching a maximum stress point of 70.15 MPa; Subsequently, the stress drops significantly indicating fracture of the material. The elastic modulus was calculated from the elastic zone which is represented by the initial line of the curve, the value obtained is 6.02 GPa. On the other hand, the maximum deformation was approximately 10% in the elastic regime.

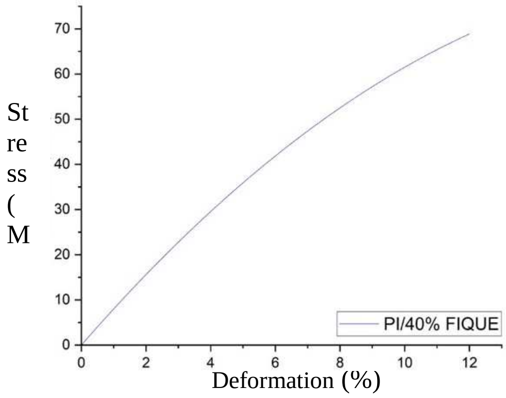

Fig. 1. Tensile stress vs strain diagram, 40% Fique biocomposite

Then the density was calculated considering the density of the resin as 1.2 g/cm^3 and that of the fiber as 0.8 $g/cm^{3,}$ applying equation 3, resulting in a density of the biocomposite of 1.08 $g/cm^{3.}$

According to Fig. 2, the biocomposite exhibits elastic behavior under bending. The key parameters in this analysis are the modulus at break and the elastic modulus.

The modulus at break, which is the maximum resistance that the material can withstand before breaking, is 113.62 MPa. This value indicates the material's ability to resist deformation under load. On the other hand, the elastic modulus in bending, which is represented by the initial slope in the graph, is 14.81 GPa. This value is a measure of the material's stiffness and describes how the material deforms elastically (i.e., temporarily) when a force is applied to it.

These values indicate that the biocomposite has good strength and stiffness, which could make it suitable for applications that require these properties.

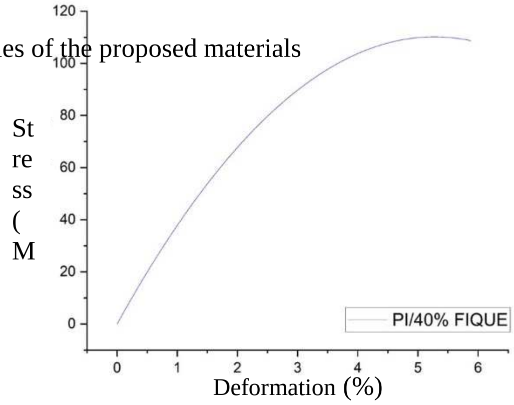

Fig. 2. Tensile stress vs strain diagram, 40% Fique biocomposite

Table I were considered, which summarizes the physical and mechanical properties of four potential materials for the manufacture of hydraulic turbine rotors, with the aim of contrasting the characteristics of the developed biocomposite against conventional materials. Initially the density is compared; where, the biocomposite with polyester resin and fique fiber shows the lowest density (1.08 g/cm^3), even lower than that of aluminum (2.7 g/cm^3) [20], which agrees with previous studies that recommend the use of lightweight materials to increase the efficiency of the turbines.

Regarding tensile strength, the biocomposite withstood 70.15 MPa, less than stainless steel.

(515 MPa) but like fiberglass composite (100 MPa); indicating, an adequate level of resistance for the desired function; In addition, the tensile elastic modulus also has a value of 6.02 GPa, lower than that of fiberglass (15 GPa) but sufficient for the intended use.

The results of resistance and flexural modulus are analogous, with 113.62 MPa and 14.81 GPa respectively, which makes them suitable in comparison with the glass fiber composite. Regarding cost, the biocomposite is 4 times cheaper than the other alternatives, with a price of 120,000 COP/m^2; In addition, having natural fibers makes it totally environmentally friendly.

Regarding the mechanical properties, it is observed that the results of resistance and flexural modulus are analogous, with 113.62 MPa and 14.81 GPa, respectively. This makes them suitable compared to fiberglass composite. Strength and flexural modulus are key indicators of the material's durability and stiffness, suggesting that the biocomposite can withstand considerable loads without permanently deforming.

Table I- Physical and mechanical properties of the proposed materials

Material name	Density (g/cm^3)	Tensile strength (MPa)	Tensile modulus of elasticity (GPa)	% maximum tensile elongation	Flexural strength (MPa)	Modulus of elasticity in bending (GPa)	Cost (COP/m^2)	Environmentally friendly
Aluminum	2.70	90.00	70.00	30.00	240.00	70.00	850000.00	No
Stainless steel	8.00	515.00	190.00	40.00	300.00	190.00	1000000.00	Yeah
Fiberglass composite	1.60	100.00	15.00	5.00	200.00	15.00	250000.00	No
Biocomposite	1.08	70.15	6.02	10.00	113.62	14.81	120000.00	Yeah

Table II- Scores obtained after applying the selection method.

Resin name	Density Weight=30 %	Tensile strength Weight=5%	Modulus of elasticity Weight=10%	% elongation Weight=5%	Flexural strength Weight=10%	Modulus of elasticity Weight=5%	Cost Weight=20%	Environment ally friendly Weight=15%	Total score Weight=100 %
Aluminum	2.30	0.02	0.35	0.36	0.68	0.16	0.34	0.00	4.20
Stainless steel	0.00	0.50	1.00	0.50	1.00	0.50	0.00	1.50	5.00
Fiberglass composite	2.77	0.03	0.05	0.00	0.46	0.00	1.70	0.00	5.03
Biocomposite PI/40% FIQUE	3.00	0.00	0.00	0.07	0.00	0.00	2.00	1.50	6.57

Table III- Scores obtained after applying the selection method.

In relation to costs, the biocomposite is significantly cheaper than the other alternatives, with a price of 120,000 COP/m^2. This is approximately 4 times cheaper, making it an economically attractive option. Furthermore, the fact that the biocomposite is composed of natural fibers makes it partially environmentally friendly, which adds additional value in terms of sustainability and ecological responsibility.

For a better understanding of how the conclusion in Table II was reached, it is important to highlight that a method of selecting the best material was applied. In this method, different weights were assigned to the material properties, with density having the greatest weight, at 30%, due to its direct relationship with the turbine efficiency.

The manufacturing cost is next in importance, with 20%. Based on these properties and the assigned weights, the biocomposite manages to obtain the highest overall rating, reaching 6.57 points out of 10 possible.

This indicates that the biocomposite optimally meets the characteristics required to manufacture the rotor, standing out for its low density, cost, and renewable origin. Regarding the manufacture of the blade, it was necessary to conduct post-processing machining with polishing to eliminate excess material. Subsequently, it was coated with resin to prevent the formation of air bubbles, which could allow water to enter and deteriorate the material. In Fig. 3 you can see the blade after these processes.

Fig. 3. Final blade.

Finally, the blades were joined to the shaft and thus obtained the prototype of the final rotor as seen in Fig. 4.

Fig. 4. Rotor prototype.

4. Conclusions

In the present research, a composite material based on a thermostable unsaturated polyester resin reinforced with a natural fique fiber is proposed, as an alternative for the construction of a rotor of a gravitational vortex turbine; The manufacture of laminates using the manual impregnation method, which combined unsaturated polyester resin with three layers of fique fiber, resulted in a composite material with promising mechanical properties. This process was essential to obtain a material with the desired characteristics for its application in the construction of the turbine rotor. Furthermore, the estimation of the density of the biocomposite proved to be a crucial aspect. Its lightness, compared to conventional materials such as aluminum and stainless steel, positions it as an attractive alternative to improve the efficiency of hydraulic turbines.

Tensile and bending tests performed on the bio composites provided promising values, supporting the viability of the biocomposite as an alternative to conventional materials in the manufacture of turbine rotor blades (Page 7).

The meticulous selection of resin and fique fiber for the creation of the biocomposite turned out to be successful. The resulting material met the characteristics required for the manufacture of the rotor, standing out for its low density, competitive cost, and environmental sustainability. Finally, the manufacture of the rotor from the biocomposite proposed in the study represents an important milestone in the practical application of this material in the construction of gravitational vortex turbines. This ultimate step demonstrates the feasibility and effectiveness of the biocomposite in the production of structural components for hydroelectric power generation.

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