Evaluation of properties and characterization of wood-based Epoxy composite for Wind Turbine Blade Material

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Abstract-*Epoxy composites play a good role in wind energy sector. The majority of epoxy resins found in the energy sector are used in manufacturing blade of wind turbines. In the present study wood-based epoxy composite is studied for application in blade material. In this study wood dust size less than 710 micron have been taken in to consideration for fabrication of wood-based epoxy composite and the mechanical and thermal properties were evaluated. The outcome was that different properties combined together resulted in attributes such as extremely light weight, relatively high strength, easy fabrication, resistance to corrosion, excellent impact strength, tensile strength, flexural strength, good thermal strength etc. , thus indicating that wood-based epoxy composite can be utilized in blade material for wind turbine.*

Keywords: Wood-based epoxy composite, Tensile Strength, Flexural strength, Impact strength

1. INTRODUCTION

Global energy policy places major emphasis/priority on the development and growth of alternative energy thereby resulting in the reduction of greenhouse gases emission. Despite the high initial investment, wind technology proves to be advantageous for economies as it generates local added value, as well as creates a favourable impact on the market by reducing unit price of electricity since the wind does not cost us anything. Thus, those producing wind energy do provide energy at a lesser cost when compared with other forms of energy such as fossil fuel technologies [1].

Blades are the most vital as well as the most costly component of a wind turbine. The blades play vital role in overall performance, reliability, and cost of a wind turbine system. Most of the blades are made with fibre glass-reinforced polyester or epoxy. But the processing and disposal of the blades involves non-renewability and negative impact on the environment which in turn forced the researchers to search for some biodegradable and light weight natural plant fibres for reinforcement in polymeric resin to produce required polymer composites.

Wind turbine blades are critical load-bearing components that operate under complex aerodynamic, gravitational, and cyclic stresses throughout their service life [2]. The choice of blade material strongly influences the structural reliability, efficiency, and economic viability of wind energy systems. Glass fiber reinforced polymer (GFRP) composites with epoxy matrices are widely used due to their favorable mechanical properties and established manufacturing practices [3], [6]. Nevertheless, increasing environmental concerns, disposal challenges, and sustainability requirements have encouraged the exploration of alternative blade materials.

Wood-based epoxy composites represent a promising sustainable alternative by combining renewable ligno-cellulosic reinforcements with high-performance thermosetting matrices [3]. Historically, such materials were used in early wind turbine blade designs; however, limitations in standardization and large-scale manufacturing led to their replacement by synthetic fiber composites [2]. Recent advancements in material processing and characterization have renewed interest in wood–epoxy systems, particularly for small and medium-scale wind turbine applications [4], [8]

Wind turbine blade materials must exhibit high specific strength, adequate stiffness to control deflection, excellent fatigue resistance, and durability under harsh environmental conditions [6]. Wood-based epoxy composites achieve these requirements through epoxy impregnation, which improves stress transfer, enhances moisture resistance, and increases structural integrity [3].

Experimental investigations indicate that wood–epoxy composites demonstrate significant improvements in tensile, flexural, and compressive properties compared to untreated wood [3], [5]. Tensile strength values typically range from 40 to 120 MPa, while flexural strength may reach up to 200 MPa depending on reinforcement configuration and resin content [4]. These properties, although lower than those of GFRP and CFRP, are sufficient for certain wind turbine blade designs [8].

Fatigue behavior is a critical consideration for blade materials due to long-term cyclic loading. Wood-based composites exhibit favorable fatigue performance at moderate stress levels owing to their cellular microstructure, which dissipates energy and delays crack propagation [6], [7]. In addition, epoxy matrices enhance damage tolerance by reducing defect sensitivity [6].

Environmental durability remains a key challenge for wood-based composites because of the hygroscopic nature of wood. While epoxy matrices significantly reduce moisture uptake, prolonged exposure may still cause degradation in mechanical properties [10]. Surface treatments and protective coatings are therefore essential to improve long-term performance [7].

Comparative studies reveal that wood–epoxy composites offer advantages in terms of low density, cost-effectiveness, and sustainability when compared with GFRP and CFRP materials [4], [9]. However, their lower stiffness and strength limit their application primarily to small-scale wind turbines or hybrid composite systems [8].

In summary, wood-based epoxy composites provide a viable, environmentally responsible alternative for wind turbine blade materials in specific applications. Continued research focusing on hybridization, moisture resistance, and fatigue performance is required to enhance their structural capability and broaden their practical adoption [11].

For a material which can be employed as blade material for wind turbine, some basic properties are like greater specific stiffness and tensile strength, low density, deflection resistance and endurance under extreme climatic condition without any fracture and bending. Natural fibre reinforced polymer composites fulfils the basic material criteria and provides a sustainable environment for rotor blades. Natural fibre reinforced polymer composites potential as a blade material for rotor has to be taken up on high priority as per the suggestions of literature background and that the determination of its strength is need of the hour.

The blades are that component of the wind turbine which take up energy from wind and convert it into mechanical power (via torque) and further into electrical energy. The overall performance, reliability, and cost of a wind turbine system are very much dependent on the efficacy of the blades and thus blades form a critical component of the system. Longer blades sweep a greater area and thus result in higher energy yield of a turbine system. However, the blade needs to contain more material and has greater strength which comes at increased costs.

Both glass and carbon fibres are essential and major constituents of blade manufacturing. E-glass (a borosilicate glass, or also known as Electric glass due to the high electrical resistance) is the principle reinforcement utilized for manufacturing wind turbine blades. Increase in volume content of the fibres results in proportionate increase in the mechanical properties. However, beyond around 65% fibre volume fraction, there is a higher possibility that dry areas would become more prominent resulting in negative impact on the fatigue performance [12].

Different materials to manufacture wind turbine using Multiple Attribute Decision Making (MADM) were investigated. Modelling of turbine was done using Catia and FEM was used for analysis. Analysis was done for steel, aluminium, Glass E, Carbon, Aramid. It was concluded that composite materials such as carbon fibres offer high stiffness, low density, and high fatigue life [13].

Investigation of the performance and cost reduction obtained by using composite materials as wind turbine blades was carried out. It was found that composite called intelligent composites can replace the conventionally used glass fibres offering advantages like decrease in danger factor, control of structural vibration, increase in efficiency etc [14]

Various blade profiles and blade materials that yield higher electrical parameters that is higher efficiency were discussed. Height to radius ratio 1 is obtained as an optimum profile. On comparing materials like aluminium, carbon fibre, stainless steel as blade material in terms of strength, cost velocity, deformation etc, aluminium was found to be the best material [15]

FE analysis of a bamboo-based VAWT blade under static loading was undertaken. Investigation of the improvement of structural behavior of symmetrical and asymmetrical profiles in blade deformation with the optimum stacking combination was also conducted.[16]

Excellent performance and good reliability in many tough conditions and demanding applications have been found in epoxy composites which makes them suitable for use in components for wind turbine blades. Significant stresses are developed in wind turbine blades during operation due to their own movement, wind flow, temperature cyclic reversals, humidity and bird strikes.

In the recent past there have been several efforts to replace synthetic fibres with natural wood powder reinforced composites, mainly because of more awareness about climate and gradual decline in the amount of oil resources. The fact that wood powders are available cheaply and in abundance, being biodegradable, very light weight and low density, has inspired several researchers all over the world to investigate their application potential in various industrial sectors including in wind turbine technology.

Wood working operations such as sawing, sanding, milling, planning, and routing result in production of wood dust or saw dust as a by-product or waste product. Its constituents are small chips of wood. The operations mentioned above are carried out by woodworking machinery, portable power tools or by use of hand tools.

In general, composites are formed from two different types of materials:-

Matrix materials:- Matrix material is a pure polymer which is generally more ductile but has lower strength and rigidity.

Reinforcement materials:-
Reinforcement material is generally in the form of fibres or natural powders that have less ductile but rigid and stronger properties. Here matrix material is used as epoxy resin and reinforcement material is used as wood powder.

2. EXPERIMENTAL PROCEDURE

Fabrication Process:

(a) In order to develop wood- based epoxy composites, epoxy resin was purchased from the local market and wood saw dusts were collected from local wood mill and less than 710-micron size particles (Fig.1a)were separated by using a sieve of opening size 710 micron. Then the wood dust was dried in a hot air oven at 105^{0}C for 4 hrs for reinforcement with Epoxy.

Fig. 1a Preparation of Wood Powder

(b)Epoxy Resin Sheet

For comparing the properties of Epoxy with wood based epoxy composite, at first Epoxy sheet without reinforcing was prepared by taking 150 ml (187.5 g) of standard epoxy resin in a big bowl and then 1.2 ml cobalt was added as an initiator and stirred properly. After that 4.8 ml of epoxy hardener was added to the epoxy resin and both were uniformly mixed together by continuous stirring.Whole mixture was quickly poured on a square steel plate coated with wax & covered by another plate with weight on it. Then the assembly was kept for 24 hours for proper curing(Fig. 1b).

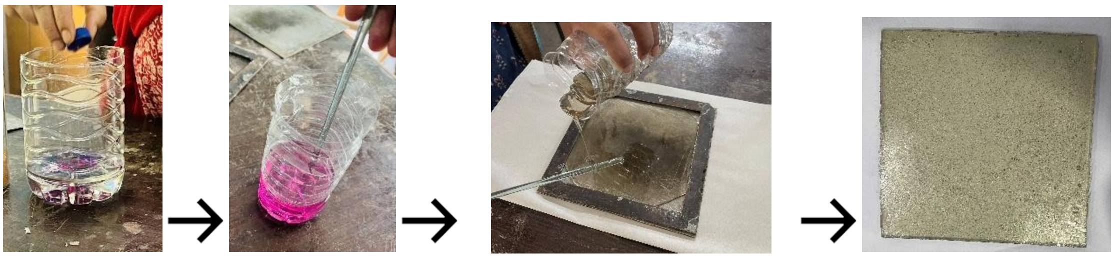


Fig 1b (i) Fig 1b (ii) Fig 1b (iii) Fig 1b (iv)

Fig. 1b (i) to 1b (iv): Preparation of Epoxy Sheet

(c)Preparation of Wood Based Epoxy Composite Sheet (10 % reinforcement):

For preparation of wood based epoxy composite, 150 ml (187.5 g) of standard epoxy resin &1.2 ml cobalt was taken in a big bowl with continuous stirring. Then 15gm of dry wood powder of size less than 710 micron was mixed with the above epoxy resin and mixed properly. Then 4.8 ml of standard epoxy hardener was added to the mixture and again stirred properly so that the hardener and the epoxy and wood powder mixed uniformly. Whole mixture was then quickly poured on a square steel plate whose surface was precoated with wax for easy removal of sheet. Then it was covered with another steel sheet and fixed weight was applied on the top plate. The whole assembly was kept for 24 hours so that the curing process could occur properly thereby leading the whole mass to solidify and form a strong and hard sheet. The whole process was done at a room temperature (27 ± 2^{0}C) as shown in Fig. 1c.

Fig 1c(i) Fig 1c(ii) Fig 1c(iii) Fig 1c(iv)

Fig. 1c (i) to Fig 1c (iv):- Preparation of Wood Based Epoxy Composite Sheet

3. TESTS, RESULTS AND DISCUSSION

i. Mechanical Testing

Tensile Strength and Elongation Measurement

For determining the effect of wood dust on the epoxy-based composites, 5 samples of pure epoxy resin & epoxy-based composites were tested. Dumbbell shape samples were cut out to prepare test samples for tensile test (Fig. 2a &2b). For each group, 5 tensile test samples were tested on Universal Testing Machine as per Test Method: ASTMD 638(Fig. 2c). This test methodology was designed to produce data of tensile property in order to control and generate proper specification of plastic materials.The experimental data are shown in Fig 2d & 2e.

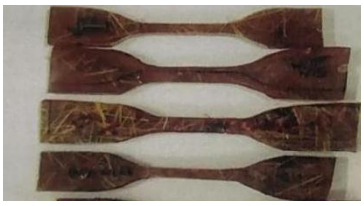
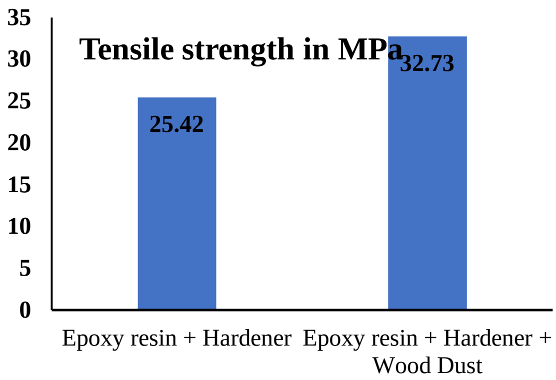


Fig.: 2a Tensile sample of epoxy Fig :-2b Tensile sample of 10 % wood + epoxy Fig: 2c Tensile testing

RESULTS OF TENSILE PROPERTY

From experimental tensile test data presented in Fig. 2d & 2e, it is clear that the average tensile strength of the pure epoxy resin is 25.42 MPa & for 10% wood based epoxy composite is 32.73MPa. The elongation at break for epoxy resin is 14.53 % & for 10% wood based epoxy composite is 18.35%. The value of tensile strength and elongation at break of the epoxy resin increases after incorporation of 10 % wood dust of size less than 710 micron.



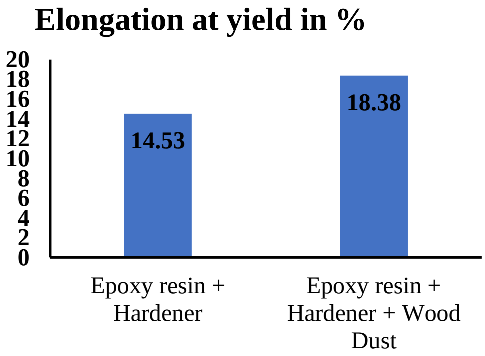


Fig. 2d : Tensile strength of epoxy & wood based epoxy **Fig. 2e : Elongation at yield of epoxy & wood based epoxy**

Impact (Izod) Strength Measurement

In order to determine the effect of sudden load on the composites, 5 samples of pure epoxy resin & epoxy-based composites were tested for impact strength. Rectangular sample of length 65 mm, width 12.7 mm & central notch of 2.54 mm were cut to test the impact strength(Fig. 3a). For each group, 5 Impact test samples were tested on Digital Pendulum Impact Tester (Fig 3b) as per Test Method: ASTMD 256. The experimental data are shown in Fig 3c .

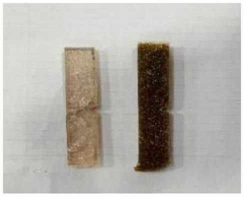


Fig 3 a:-Izod Impact sample after notching **Fig.3 b:- Izod Impact Testing**

Results of Impact Resistance Test

From experimental data presented in Fig. 3c it was observed that the average impact strength of the pure epoxy resin was 5.51 KJ/m^2& for 10% wood- based epoxy composite was 8.41 KJ/m^2. After addition of wood dust of size less than 710 micron, the Izod impact strength increases.

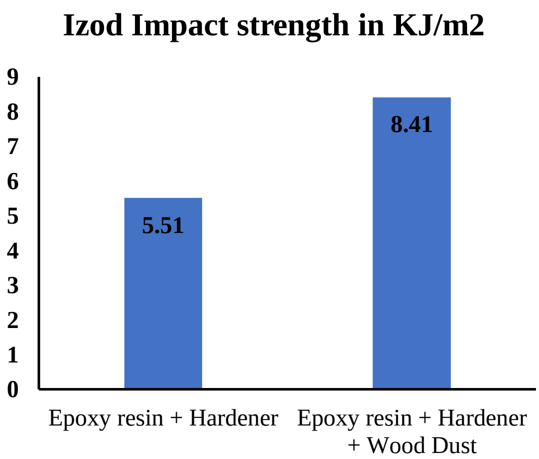


Fig. 3c:- Izod Impact strength of epoxy & 10 % wood based epoxy Flexural Property

To determine the bending strength of the composites, 5 samples of pure epoxy resin & epoxy-based composites were tested for flexural strength. Rectangular sample of Length 100 mm, width 15 mm & thickness of 4.0 to 5.5 mm were prepared for flexural strength test (Fig. 4a). For each group 5 flexural test samples were tested on Universal Testing Machine (Fig 4b) as per Test Method: ASTMD 790. The experimental data are shown in Fig. 4c .

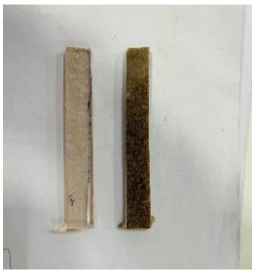
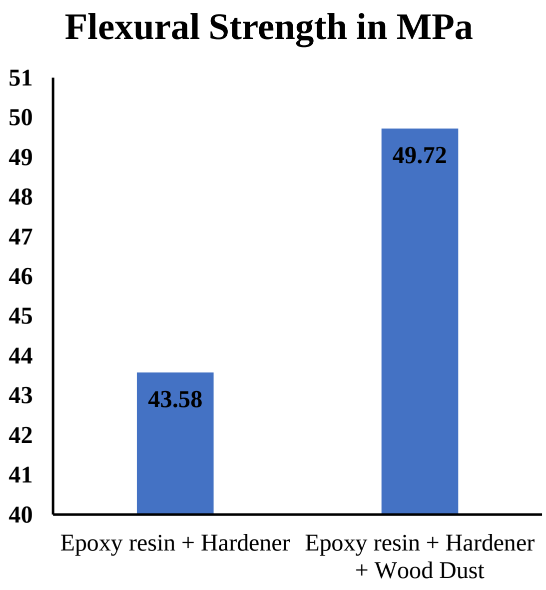


Fig (4 a):-Samples for Flexural property determination **Fig (4 b):- Flexural property determination**

Results of Flexural property

From the experimental data presented in Fig. 4c and 4d, it was observed that the average flexural strength & flexural modulus of the pure epoxy resin was 43.58 MPa and 1412 MPa respectively. However, the same for 10% wood-based epoxy composite was 49.72 MPa & 1734 MPa. From this experiment it was observed that after addition of wood dust of size less than 710micron, the flexural property increases.



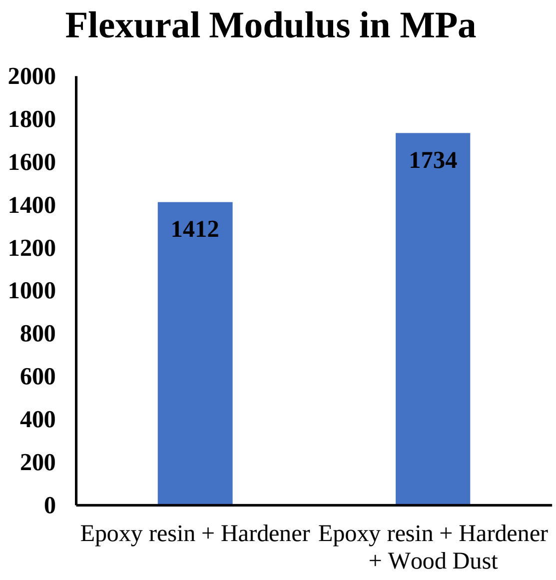


Fig. 4 c: Flexural strength for epoxy resin & 10% wood based epoxy composite **Fig. 4d Flexural modulus for epoxy resin & 10% wood-based epoxy composite**

Density Test

In order to know the mass with respect to volume, density of epoxy & wood - based composites were checked. 5 samples of pure epoxy resin & epoxy-based composites were prepared (Fig. 5a). For each group 5 samples were tested on density tester (Fig. 5b) as per ASTMD 792 (Displacement method). Water was taken as Immersion liquid. The experimental data are shown in Fig 5c .

Fig (5a):-Samples for density determination **Fig (5b):- Density Test**

Result of Density Test

From the experimental data shown in Fig. 5c it was observed that the average density of the pure epoxy resin was 1.23 g/cc and for wood based epoxy composite density was 1.27 g/cc. From this experiment is was observed that after addition of wood dust of size less than 710 micron, the density remains almost the same.

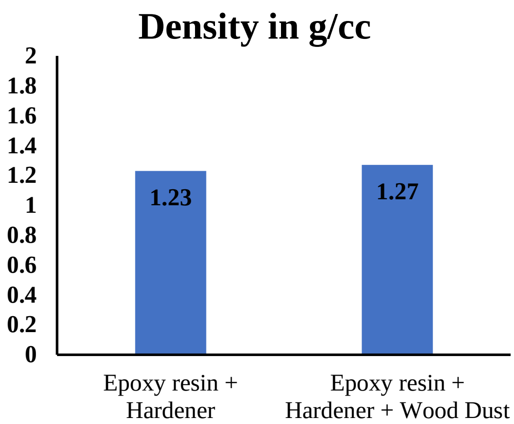


Fig. 5c: Density of Epoxy & wood- based epoxy composite

(ii)Thermal Property

Heat Deflection Temperature (HDT)

To determine the thermal strength of the composites, 2 samples of pure epoxy resin & epoxy-based composites were tested for Heat Deflection Temperature (HDT). Rectangular sample of length 127 mm, width 13 mm & thickness of 4.0 mm were prepared for HDT test (Fig. 6a). For each group, 2 test samples were taken for test on HDT Machine (Fig.6b) as per ASTMD 648. The test specimen was loaded in three – point bending in the edgewise direction. The outer fiber stress used for testing was 0.455MPa, and the temperature was increased at the rate of 20^0 C/min until the specimen deflects 0.01 inch. The data from experiments are shown in Fig. 6c

Fig. (6a) HDT Test Samples **Fig:(6b) HDT Testing**

Result of Heat Deflection Temperature (HDT)

From the experimental data shown in Fig. 6c it was observed that, the heat deflection temperature. (HDT) of the pure epoxy resin was 37.5^0 C and for wood-based epoxy composite HDT was 48^0 C. Addition of wood dust of size less than 750 micron increases thermal property.

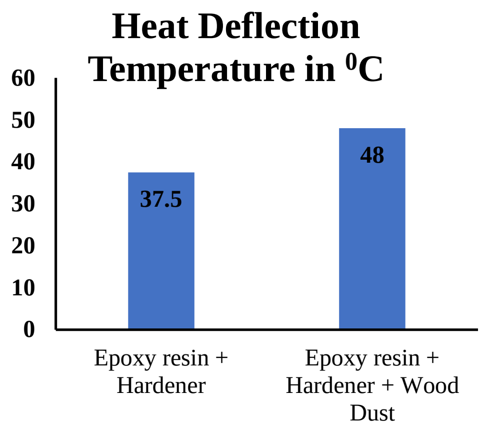


Fig:(6c) HDT test results for epoxy resin & wood- based epoxy composite

(iii) Water Absorption

Materials durability and performance can be evaluated by measuring how much water a substance can absorb. For that water absorption test was conducted for both the epoxy resin as well as for 10% wood-based epoxy-based composite as per test method ASTMD 570. Test was conducted at temperature 23 ^{0}C by immersing test samples in water for 10 Days.

Result of water absorption

From the experimental data in Fig. 7, it was observed that water absorbed by epoxy resin was 1.26 % & by wood-based epoxy composite was 2.05 % after 10 days of immersion in water

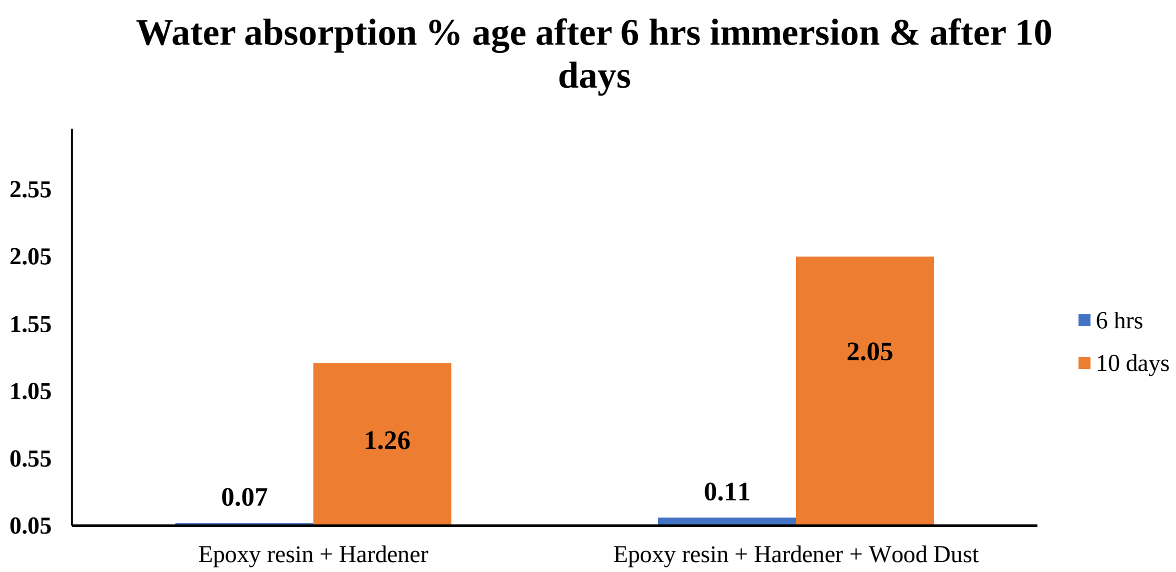


Fig. 7 : Results of water absorption

Effect of 10% wood dust additive on mechanical and thermal properties of epoxy

The effect of 10% wood dust of particle size less than 710 micron on mechanical & thermal properties of epoxy are compared in Table 1

Table 1:- Change in Mechanical & Thermal property properties of 10% wood-based composite with pure epoxy

Tensile Strength	Elongation	Impact Resistance	Flexural Strength	Flexural Modulus	Heat Deflection Temp. (HDT)
28.76 % increase	26.50 % increases	52.8 % increase	14.09 % increase	22 .80 % increase	28 % increase

It was observed that reinforcement of wood powder of particle size less than 710 micron with epoxy resin improves mechanical & thermal property. Addition of 10% of wood dust of size less than 710 micron increases the mechanical strength like tensile strength of the base epoxy by about 29%, Elongation by 27 %, Impact resistance by 53 %, Flexural strength by 14% and Flexural modulus by 23 %. However thermal property like HDT increases by about 28 %.

4. CONCLUSION

The present study was undertaken with an objective to search an option for wind turbine rotor blade material with reduced environmental impact.The present study reports the comparison of properties of epoxy with the wood-based epoxy composite which was made from wood dust of less than 710-micron particle size.

It was observed that reinforcement of wood powder of particle size less than 710 micron with epoxy resin improve mechanical and thermal properties. Addition of 10% of wood dust of size less than 710 micron increases the mechanical strength like tensile strength, elongation, impact resistance, flexural strength and flexural modulus. Thermal property like HDT also increases. Hence wood based epoxy composite can be an option for wind turbine rotor blade material

Materials used for wind turbine blades must be of lower mass per unit volume and possess high strength and damage tolerance. It was observed that wood-based epoxy composite possesses low density i.e 1.27 g/cc with good mechanical and thermal strength.

The wind turbine blades are always exposed to rain & extreme environmental condition. So, one of the major properties of the blade turbine material is that it should have low water absorption because it will reduce the strength of the blade. Epoxy resin always shows excellent resistance to water absorption. From this study it was observed that water absorption of epoxy &wood-based epoxy composite almost remained same. 1.26 % water absorbed by epoxy and 2.05 % by wood-based epoxy composite after 10 days of immersion in water.

Using natural fiber as reinforcement, the mechanical & thermal performance is met in an eco-friendly manner. They are reducing the environmental impact of composite materials. Additionally, natural fibres are renewable resources that can be easily sourced and biodegradable, making them a sustainable alternative to synthetic fibers. This composite is lesser in price, light weight and environmentally superior to glass fiber or other synthetic fiber composites in general. Hence it is suggested that wood-based epoxy composite can be a potential alternative to traditional reinforcement materials that can be used for rotor blades in a wind turbine.

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Conflict of Interest: All authors declare that they have no conflicts of interest