ISSN 1392-1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 30, No. 1. 2024

Studies on Mechanical and Dielectric Properties of the $Ni(OH)_2$ Filler Reinforced Polymer Composite Materials for Structural Application

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http://doi.org/10.5755/j02.ms.34793

Received 4 August 2023; accepted 29 September 2023

Polymer composite materials play a vital role in many automotive and wind turbine industries because of their high mechanical properties. The present work emphasises the improvement of polymer composites used for different environmental conditions. The glass and basalt fibers with epoxy and vinyl ester matrix have been prepared individually with 3 % $Ni(OH)_2$ filler. The mechanical and dielectric properties were investigated separately for each material. The mechanical properties of the glass fiber with vinyl ester and $Ni(OH)_2$ filler showed better results. The dielectric strength of the glass fiber with vinyl ester and $Ni(OH)_2$ filler material in a saline environment showed only a 38.16 % reduced dielectric value before saline treatment. The FE validation was also validated using Digimat- FE software for evaluating the void stress in the filler matrix. From the validation the glass fiber with epoxy resin and $Ni(OH)_2$ filler showed the lowest von-Mises stress and shear stress values compared to the other materials. The overall results highlight the improvement of mechanical and electrical properties after the addition of $Ni(OH)_2$ filler materials in offshore environment to meet the demands of the wind turbine industry.

Keywords: dielectric strength, mechanical strength, water absorption, thermal stability, nickel hydroxide, environmental fatigue.

1. INTRODUCTION

Wind turbines were considered the most efficient conventional source of energy generation compared to other non-conventional power generation methods, such as thermal power and nuclear-based power generation. The increase in demand for power generation entails the gap between the actual power requirements from the conventional energy sources. The main setback in wind energy is due to the lightening effect that could cause structural damage in wind turbine blades to fail. The wind energy generation system is clubbed within the electrical system, where the charge has to be stored during the running condition of the blades. The majority of wind turbine damages have been identified from lightning. The main source documents are found from the claims for insurance due to the effects of the lightning. Normally the turbine blades are manufactured using E-glass fiber, which is an electrically resistive material, where no electric current can pass through the system. The blade lightning protection system deals with the materials that are used normally in wind turbine blades. The temperature generated during the lightening may reach up to 30,000K, thus producing a shock wave [1].

Wenjing et.al explained the usage of the $Ni(OH)_2$ filler for improving the dielectric property of the material. The $Ni(OH)_2$ based composite material is filled with an enormous number of hydroxide groups thus making the material insulated from the external electrical field. The application involved in improving the dielectric medium has been drastically increasing in the current days [2]. Due to the high breakdown and flexural strength with the addition of the fillers, the study of dielectric strength in composite materials has increased for various applications [3, 4]. The research aims for the novel development of the material, especially for wind turbine applications. Although the material plays a vital role in increasing the dielectric strength, the shape of the filler infused in the matrix also originates an effect for increasing the electrical properties [5]. The platelet-shaped filler was found to be experiencing high dielectric strength with 5 to 20 % of the filler weight. The results were tested with $Ni(OH)_2$ and poly vinylidene fluoride (PVDF). Sasidhar et.al experimented with the effect of surface engineered nano composites with suitable coupling agents for excellent dispersion and particle interaction characteristics, it has also improved the dielectric characteristics of the epoxy resin [6]. The best solution for improving the life expectancy of the material is by adding a suitable filler, which enables the material to withstand the electrical and moisture by which the reliability of the turbine blades can be increased in the offshore environment.

The effect of electrical conductivity also depends on the moisture on the surface of the composite materials. The recently trending offshore structures are exposed to high humidity and saline environments. The effect of the addition of fillers in the composite materials was examined for effective usage in the dry, humid, and saline conditions especially in an offshore environment. Arlt et. al have explained the size of the grains has a direct interaction with the dielectric strength and other mechanical properties [7]. Junwei et. al experimented importance of blending the

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chemical salts with thermoset plastics for improving the dielectric strength using electrospinning technology [8]. Dalong et. al investigated the blends of molybdenum disulfide and PVDF fillers to improve the dielectric characteristics of the composite material [9]. Shaohui et. al have studied the composite fillers with higher flexural and dielectric characteristics with surface modification of the oxide fillers with the poly(vinylidene fluoride) polymer with improved dispersion effects on the composite materials [10]. The literature study clearly shows that the material in the saline environment decreases the storage modulus due to the water absorption characteristics of the composite material. The increased immersion of the composite material in the moisture conditions leads to the deterioration of the matrix and the fiber interaction. Zhiping et. al validated that molding temperature during manufacturing of the composite materials also affects on the tensile behavior of the materials. At higher temperatures, the material tends to degrade significantly thus reducing the material properties [11].

The current research mainly focuses on the development of suitable composite materials with better mechanical and dielectric properties. The Digimat-FE module was also used to validate the particle distribution of $Ni(OH)_2$ with fiber and matrix for identifying the void stresses on the composite material.

2. MATERIALS AND METHODS

The experimental section consists of the preparation of the composite materials with fillers. The materials required for the fabrication are shown in Table 1.

Table 1. Materials used for preparing the samples

Description	Material	Grade
Fiber	E-Glass Fiber	300 GSM
	Basalt Fiber	320 GSM
Matrix Resin	Resin-Araldite Hardener-Aradur Resin-Vinyl Ester Accelerator-Cobalt Catalyst-MEKP	AY-556 HY-951
Filler	Nickel Hydroxide $Ni(OH)_2$	Hexagonal structure

The composite laminates were prepared using a vacuum infusion process (VIP). The VIP process has been preferred as it has been presently used in composite manufacturing industries. A 200 GSM mat was trimmed into (300 mm × 300 mm) sheet and a suitable amount of resin pertaining to the fiber weight equal amount of resin was taken with 10 % of hardener was mixed to the resin for epoxy, whereas for vinyl ester the accelerator and catalyst were added to 3 % to the original weight with 3 % of the $Ni(OH)_2$ filler from the overall weight of the resin. Further, the resin with filler was sonicated at 60 °C for 1 h and has been kept in the resin container by adding a suitable quantity of the hardener. The resin has been sucked inside the mat using vacuum pressure and excess resin has been collected to the catch pot, the laminate is then removed from the base plate and kept in the oven at 60 °C for removing moisture. The specimens were prepared by the water jet cutting. The specimen of size $175 \times 25 \times 3$ mm^3 was prepared and a gauge length of 115 mm was maintained as per the ASTM D 3039 for tensile test. The flexural test has been conducted as per the ASTM D 790. The tensile and flexural test has been carried out using a 10-ton servo-hydraulic UTM machine (Make: Instron, Model: 3382). The crosshead speed was maintained at 1mm/min for evaluating the tensile strength of the composite material. The dielectric test was done using ASTM D149 with a 3 mm thickness slab of 50 mm square between the electrodes with an oil bath. The impact test has been carried out using ASTM D256 with a notch on the specimen. The impact test has been carried out using a pendulum hammer that impacts the specimen directly to determine the impact strength of the specimens.

3. RESULTS AND DISCUSSION

3.1. Tensile and flexural test

The comparative tensile results from Table 2 illustrates the material with vinyl ester and glass fiber showed better mechanical property related to the tensile behavior with the addition of $Ni(OH)_2$ fillers. The other samples also showed appreciable results with the same filler proportions of epoxy resin.

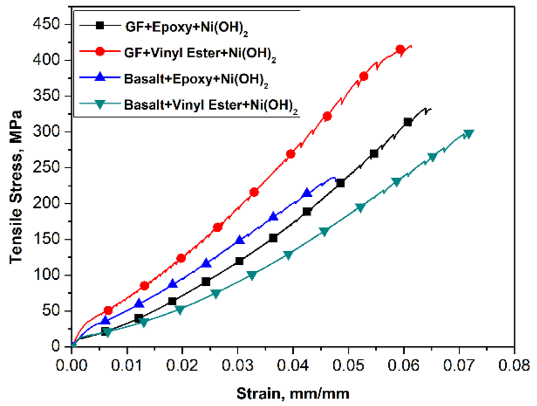
Table 2. Tensile properties of the $Ni(OH)_2$ filled samples

Sample	Tensile strength, MPa	Modulus, MPa
GF+Vinyl ester+$Ni(OH)_2$	420	6830
GF+Epoxy+$Ni(OH)_2$	332	5132
Basalt+Vinylester+$Ni(OH)_2$	299	4158
Basalt+Epoxy+$Ni(OH)_2$	236	4447

The basalt fiber showed reduced elastic modulus with the addition of fillers. The change in the properties may be due to the interference of the filler in the matrix with different viscosity levels of the matrix. The higher viscosity level will ease the amalgamation of the filler into the matrix to enhance the strength of the composite material. The GF with epoxy has been used as a primary material for offshore structural applications, but the addition of $Ni(OH)_2$ particles in GF and vinyl ester improved the modulus. A 15 % increased value was obtained from the filled material to the unfilled material of the GF epoxy and $Ni(OH)_2$ blend. A 44 % incremental tensile value was obtained from the filled $Ni(OH)_2$ with GF and vinyl ester resin [12]. The overall mechanical properties of the basalt fiber were reduced by 12 – 15 % of the unfilled material. The tensile properties of the samples are shown in Fig. 1.

3.2. Dielectric and impact test

The dielectric strength of the material has been defined by estimating the ultimate voltage that a material can withstand before it becomes electrically conductive. The dielectric strength is calculated by dividing the thickness of the specimen by the breakdown voltage. The breakdown voltage is the actual output from the machine from which the dielectric strength of the material can be determined. Santosha et.al estimated the interference of the filler size has a direct interaction in the matrix. The reduced size of the filler shows less stress levels in the voids, as per the Digimat software [13]. The saline water treatment test was the primary motivation for determining the material behavior of offshore turbine blades. The sample was treated in saline water for a period of 24 h until there was a saturation in the mass, then the saturated samples were dried and kept in the oven for one hour at 50 °C.



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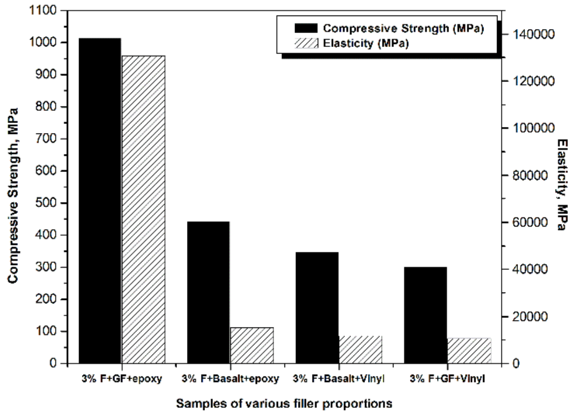

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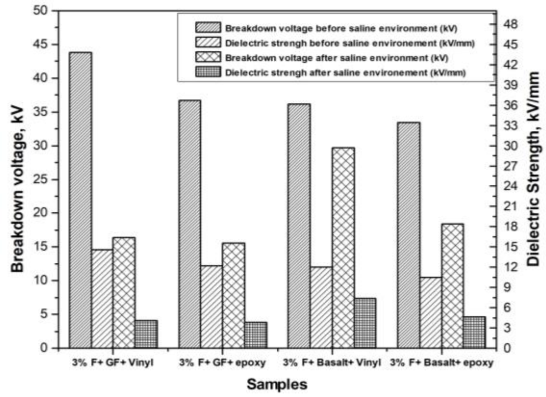
Fig. 1. a – stress-strain curve of the sample with 3% Filled $Ni(OH)_2$ filler; b – compressive strength and elasticity of $Ni(OH)_2$ filled samples *(F- $Ni(OH)_2$ filler)

Then the prepared samples were tested for the breakdown voltage, Table 3 clearly explains the reduction in the dielectric strength after saline treatment, however, the sample with basalt fiber showed an average of 47 % reduction in the dielectric strength, whereas glass fibers showed 70 % of reduction from the original value.

Table 3. Dielectric behavior of the samples before and after saline water treatment

Sample	Dielectric strength, kV/mm	
	Before saline environment	After saline environment
GF+Epoxy+$Ni(OH)_2$	12.2	3.80
GF+Vinyl ester+$Ni(OH)_2$	14.6	4.10
Basalt+Epoxy+$Ni(OH)_2$	10.4	4.60
Basalt+Vinylester+$Ni(OH)_2$	12.0	7.42

Based on the results, the addition of $Ni(OH)_2$ fillers in two different fabrics and matrix showed two different behaviors related to the electrical insulation [14]. This may be due to the viscosity factor of the resin with the filler and also due to the agglomeration factors causing the fillers to form clusters in some specific region. The percentage of the filler comprises the total dielectric strength of the material, the electrical resistive nature of the filler with limited proportion makes the material actively resist electricity to some extent but at the same time, a slight increase in the filler proportion may also increase the dielectric strength with improved matrix filler mixture. The dielectric strength and impact characteristics of the samples are shown in Fig. 2.



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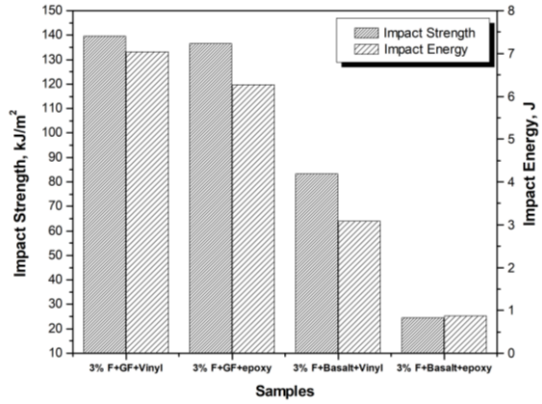

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Fig. 2. a – dielectric strength with and without saline water treatment with 3% Filled $Ni(OH)_2$; b – impact characteristics of 3% Filled $Ni(OH)_2$ *(F- $Ni(OH)_2$ filler)

3.3. Mechanical validation of the composite material with filler using Digimat-FE

The Digimat analysis was carried out to determine the stress concentration in the areas near the filler and the matrix. The analysis provides information related to the material shear characteristics and interlaminar stress for determining the interior behavior of the composite materials with $Ni(OH)_2$ filler. The Representative Volume Element approach (RVE) model was used for determining the stress and strain fields of the $Ni(OH)_2$ filled polymer matrix composite materials. Hazrati clearly defined the von-Mises stress and shear stress values of the composite materials were compared and were in good agreement with the theoretical values experimented for the silicon composites [15]. The utilization of the exact finite element model for the composite material will considerably reduce the cost and designing time for real-time fabrication, thus enabling to obtaining the processed output [16]. The matrix filled material geometry is shown in Fig. 3.

The model was prepared using the Digimat FE modeler and analysis was carried out in the same module. The RVE method was adapted for the material preparation with basic parameter as input such as density and Young‘s modulus of the fiber, matrix and filler. After the input, the model was generated with the filler as per the RVE method. The boundary conditions have been given as mixed constraint from the Digimat modeler. An incremental tensile and shear load was applied individually to determine the von-Mises stress and shear stress of the material. The material combinations of four types with two different matrices epoxy and vinyl ester with glass and basalt fibers were used for the analysis with $Ni(OH)_2$ filler as the common filler. The FEA validation results have been shown in Table 4 and Fig. 4 a and Fig. 4 b. show the von-Mises stress and shear stress results. The result shows that the maximum von-Mises stress was concentrated on the $Ni(OH)_2$ filler and the least stress concentration was found in the fibers.

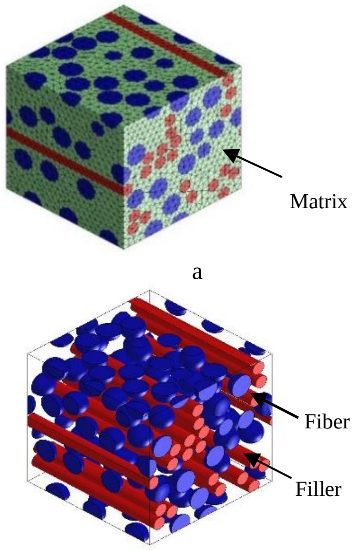


Fig. 3. Model of the composite structure: a – with matrix; b – without matrix showing fiber and the fillers

This may be due to the high interference of the matrix and the filler material for absorbing the external load. The effect of particle size also played a vital role in maintaining the mechanical characteristics of the material [17]. The variations in the stress values were due to the change in the elastic modulus of the individual material. The FE validation also proves that the von-Mises stress and shear stress have been reduced for the glass fiber epoxy with $Ni(OH)_2$ filler. The effect of addition of the filler has the effect of improving the load transfer over the material. From Fig. 1 b, the elastic modulus of the GFRP with epoxy and $Ni(OH)_2$ showed better results enabling the external load transfer from the matrix to the filler.

Table 4. Finite element validation results of the samples

Sample	von-Mises stress in the voids of the filler and matrix, GPa	Shear stress in the voids of the filler and matrix, GPa
GF+Epoxy+$Ni(OH)_2$	7.30	5.08
GF+Vinyl ester+$Ni(OH)_2$	7.85	5.83
Basalt+Epoxy+$Ni(OH)_2$	7.81	5.10
Basalt+Vinyl ester+$Ni(OH)_2$	8.80	5.26

3.4. Surface morphology and contact angle analysis

The surface morphology of the samples was carried out after analysing the impact behaviour of the material. The effect of the addition of $Ni(OH)_2$ particles has been analysed using SEM. Fig. 5 a shows the micrograph of the fiber void after breakage. The nominal elastic modulus makes the material brittle towards the lateral zone, this may be due to the irregularity in the curing temperature over the surface of the material. The effect tends to fiber to fracture along the surface of the matrix. The interfacial bonding with the filler and matrix has to be bonded well in order to achieve better results for withstanding the external loads.

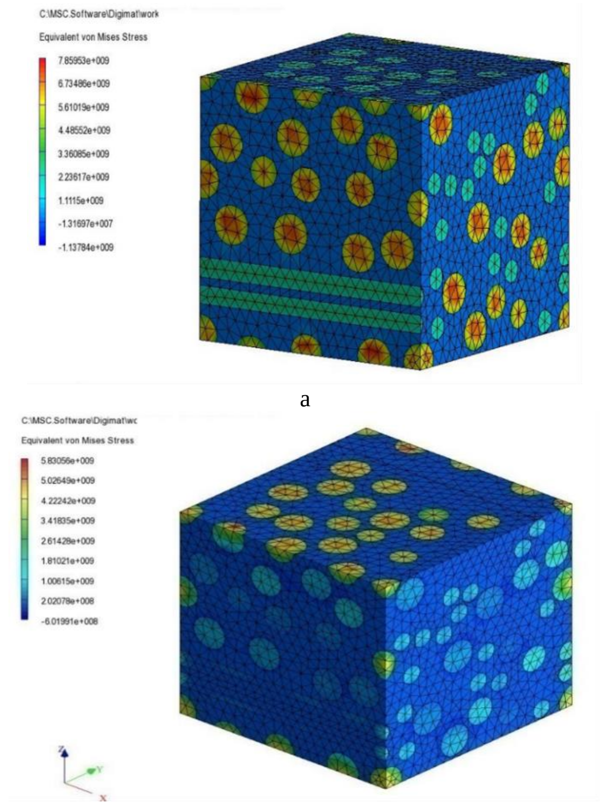


Fig. 4. FEA results of the Glass fiber with Vinyl ester $Ni(OH)_2$ filler: a – von-Mises stress of the composite model; b – shear stress of the composite

The bonding of the filler along the matrix makes the fiber stay integral avoiding the fiber slippage during loading. Fig. 5 b shows the matrix was found to be in the form of debris, this may be due to the sudden impact load causing the matrix to form in the shape of the roll. The matrix roll was dispersed, also the micro-particles were found to be finely embedded in the matrix, the resulting void formation after the impact was found to be normal from the SEM image. There is no evidence of the formation of the voids and the tight interaction of the particles to the matrix makes the glass fiber with vinyl ester composites attain better mechanical properties. This surface examination further substantiates the particle dispersion to the matrix by enhancing the electrical and mechanical behavior of the GFRP with $Ni(OH)_2$ filler. The surface wettability or contact angle of the samples has been evaluated for estimating the water absorption characteristics. The specimens prepared from glass and basalt fibers and epoxy and vinyl ester resins with $Ni(OH)_2$ filler were validated.

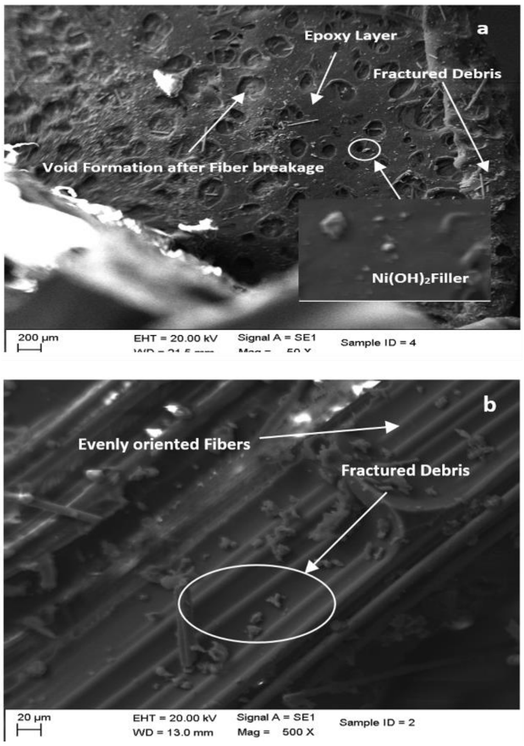
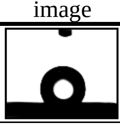
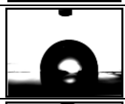
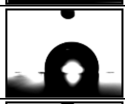
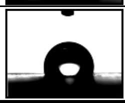


Fig. 5. Microstructure of impact fractured specimens: a – glass fiber with epoxy $Ni(OH)_2$ filler; b – glassfiber with epoxy $Ni(OH)_2$ filler

Table 5. The contact angle of the $Ni(OH)_2$ filled materials

Samples with $Ni(OH)_2$ fillers	Contact angle, °	Contact angle image
Basalt fiber with epoxy	124.53	
Glass fiber with epoxy	99.48	
Basalt fiber with vinylester	96.91	
Glass fiber with vinylester	95.1	

The contact angle results of basalt fiber with epoxy showed a higher contact angle compared to other GFRP mats. Generally, the epoxy resin is hydrophobic, with the addition of $Ni(OH)_2$ filler with the GFRP mat does not show any water absorption characteristics. The modified basalt fabric has shown improved flexural and impact properties [18]. The usage of basalt fiber with epoxy matrix showed a better hydrophobic nature with the $Ni(OH)_2$ filler. From the test, it is noted that the addition of the filler does not influenced the water absorption characteristics of the material. From Table 5, the majority of the samples showed hydrophobic nature, whereas the values are nearer to other materials . It is noted from the results, that the addition of $Ni(OH)_2$ filler to the matrix does not affect the water absorption characteristics of the material.

4. CONCLUSIONS

The comparison of the mechanical properties of the basalt fibers and glass fiber with epoxy and vinylester resins with 3 % $Ni(OH)_2$ filler showed superior values for the glass fiber. The tensile strength, tensile modulus, impact strength and dielectric strength for the glass fiber with vinyl ester and $Ni(OH)_2$ filler showed higher values compared to the other materials. The saline water treated basalt fiber with vinylester resin and $Ni(OH)_2$ filler showed a 38.16 % reduction in dielectric strength compared to the untreated sample. The Digimat-FE validation proves that the filler and the matrix interaction was better for basalt fiber with vinylester resin and $Ni(OH)_2$ filler compared to other materials. The improved dielectric strength of the basalt fiber in the saline environment showed good agreement for the usage in offshore wind turbine applications. The overall results highlight the improved properties of the $Ni(OH)_2$ filled specialized composite material for wind turbines as well as offshore structural applications.

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