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Evaluation of Mechanical and Antibacterial Properties of Nano Zinc Oxide and E-Glass Fiber Reinforced Epoxy Composite

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Abstract: Composites are made by combining different materials with varying properties to create a new material with specific characteristics. This study aimed to develop a composite material using nano zinc oxide (ZnO), E-glass fibers, and epoxy resin. Epoxy resins have a wide range of uses in various industries due to their customizable nature. By incorporating different additives and nano materials, the versatility of epoxy can be further expanded to meet different application needs, including antibacterial, antimicrobial, anticorrosive and high mechanical properties. A series of samples with different concentrations of nano zinc oxide (0.5wt.%, 1wt.%, 1.5wt.%, and 2wt.%) were prepared using the hand layup method, while maintaining a consistent composition ratio of Epoxy and E-glass Fibers in all the other variants and is cured at room temperature. The mechanical and antibacterial properties of the developed specimens are evaluated and discussed.

The developed composite is assessed for its hardness and antibacterial effectiveness against Escherichia coli and Bacillus subtilis. Analysis of obtained results indicate that the highest hardness was observed at 1.5wt.% nano zinc oxide concentration, while the highest antibacterial rates for both the bacteria were recorded at 2wt.% nano zinc oxide concentration. Overall, the experimental findings show that addition of nano zinc oxide enhances both the mechanical and antibacterial properties of the composite material.

Keywords: Mechanical, Antibacterial, Hand layup, Room temperature.

I. INTRODUCTION

1.1 Composite Materials

Composite material consists of two or more materials with similar or dissimilar chemical or physical properties. One of the materials is known as matrix, serves as a binder, holding together the other materials, called as reinforcements or fibers. This combination allows composites to exhibit a blend of properties from the individual components, resulting in new properties that surpass those of the original materials. For instance, in mud bricks, mud and straw or aggregate fulfill the roles of matrix and reinforcement respectively. Similarly, in wood, cellulose and lignin play these roles. Concrete is another well-known composite, where small stones or gravel (aggregate) are bound together by cement. Concrete demonstrates good strength under compression and can be reinforced under tension by incorporating metal rods, wires, mesh, or cables (thus forming reinforced concrete).

In recent years, numerous new composites with valuable properties have been developed. By thoughtfully choosing the reinforcement, matrix, and manufacturing process, tailoring of properties can be achieved to meet the specific requirements. For example, they can enhance strength in one direction by aligning fibers accordingly while sacrificing strength in less critical directions. Additionally, Characteristics like heat resistance, chemical resilience and weather durability can be customized by selecting a suitable matrix material.

Composite materials have become essential in various industries including aerospace, automotive, marine, electronics, and domestic sectors, offering alternatives to traditional engineering materials. Modern composite materials are optimized to strike a balance of properties suitable for specific applications. In recent years, polymeric nanocomposites and fiber-reinforced composites have gained attention from both academia and industry. Numerous scientific studies are dedicated to investigate the thermo-mechanical characteristics of thermoplastic and thermosetting matrices modified with nanomaterials and concluded that nanostructured materials enhance different attributes of polymers, such as mechanical strength, dimensional consistency, barrier properties, and thermal resistance.

1.2 Fiber Reinforced Polymer Composites

Fiber Reinforced Composites are composed polymer matrix combined with embedded fibers. Fiber reinforcing agents are chosen based on the specific properties desired for the composite, such as asbestos, aluminum oxide, carbon fiber, graphite fibers, glass fibers and natural fibers utilized. Commonly used matrix materials include epoxy, vinyl ester, polyester, phenolic, etc. The function of resin is to provide support and transfer force between the fibers, protecting them from environmental factors like moisture, insects, heat, and wind. Simultaneously, the fibers provide stiffness and structural support to the flexible plastic, resulting in a composite material with an outstanding strength-to-weight ratio. The main objective of this is creating a material possessing properties such as strong and rigid and low density. Commercially available materials commonly contain glass or carbon fibers embedded in polymer matrices such as epoxy or polyester resins. Alternatively, thermoplastic polymers can be preferred for their mold ability after initial process. Other composite categories include matrix made of metal or ceramic, but these are mostly in a developmental phase, facing challenges such as high manufacturing costs. Additionally, the reasons for incorporating fibers is often diverse, aiming to enhance properties such as fracture toughness, wear resistance, creep resistance, and thermal stability.

1.3 Nano composites

Nano composites are a specific type of particle reinforcement composites that uses nanoparticles as reinforcements within any composite matrix. In a nano composite, two or more materials, either in the matrix or as fillers, interact at the nano level, typically within a range of 1 to 100 nanometers. Nano fillers are materials with distinctive properties that are finely tuned at the nano scale. These composites constitute multiphase solid materials, in which one, two, or three dimensions in one of the phase measures less than 100 nanometers, or structures with nano scale repeat distances between the various phases comprising the material. The concept underlying nano composites is to utilize building blocks with nano meter-sized dimensions to engineer and develop new materials with unparalleled flexibility and enhancements in their physical properties. Nano composites are engineered to demonstrate properties that often surpass, sometimes significantly, the capabilities of their individual components. The properties such as thermal, electrical, mechanical, electrochemical, optical and catalytic properties of nano composites typically exhibit marked differences from those of the constituent materials.

1.4 Hand layup technique

Hand layup technique is one of the simplest method of processing composites, involving a manual fabrication process utilizing open contact molding. This method requires minimal infrastructure, and has a significant advantage that is it does not require a skilled labour thus saving labour cost. Initially, a mould release wax is applied mold surface to prevent the polymer from adhering to the mould. In order to obtain superior surface finish of material a thin plastic sheets are employed on top and bottom plates of the mould. Reinforcement, typically in the form of mats are cut as per the required dimension and positioned on the surface of the mould. Following this, polymer matrix in liquid form is mixed with a suitable hardener and poured onto the surface of the previously laid mat within the mould. A second layer of mat is then placed over and rolled uniformly with gentle pressure. This process is repeated sequentially for each layer of polymer and mat until the desired thickness of material is attained. Subsequently, curing of the material at room temperature, and is further sent for post processing like finishing.etc. Commonly used matrix materials include epoxy, polyester, polyvinyl ester, phenolic resin and that of reinforcements are Glass fibre, carbon fibre, natural fibres, aramid fibre etc.

1.5 Material Characterization

Material characterization is the most basic crucial procedure in material science for analyzing and measuring properties of the material, this provides the foundation for scientific understanding of materials. The definition of characterization varies considerably; some interpretations limit its scope to microstructure analysis, while others extend it to other examination process for materials, such as density calculation, mechanical testing, and thermal analysis. The material characterization techniques can investigate properties at both the atomic and macroscopic levels ranging from angstroms, as used in evaluating chemical bonds and individual atoms, to centimeters, as used in imaging of coarse grain structures in metals.

1.5.1 Hardness

Hardness is defined as the resistance of a material to permanent deformation, indentation, or scratching when subjected to mechanical forces. This characteristic is of great importance in a wide range of fields including engineering, metallurgy, and materials science, as it helps in evaluating a material's suitability for particular applications where mechanical strength and durability are crucial. Types of hardness tests include Vickers, Rockwell, or Brinell hardness tests, utilized to precisely measure mechanical hardness.

The micro Vickers hardness test is a method used to measure the hardness of materials, particularly metals or ceramics at a very small scale. It involves applying known force into the surface of the test sample through diamond shaped intender and measuring the size of the intender.

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The hardness value is then measured based on the dimension of the indentation.This test is particularly useful for evaluating the hardness of thin coatings, small parts, or materials with fine microstructures. The micro Vickers hardness test is widely used in materials science, metallurgy, and engineering for evaluating the hardness of different materials. It provides valuable information about material properties, including high strength, wear resistance, and deformation behaviour, at localized regions.

1.5.2 Anti bacterial test

An antibacterial test is performed for evaluating the ability of different materials to inhibit or promote the growth of bacteria upon contact. These tests are very crucial in various industries, such as healthcare, food processing, and consumer products for preventing microbial contamination and transmission. Factors such as material selection, design considerations, and manufacturing processes play a major role in enhancing antibacterial performance and minimizing microbial contamination risks. This antibacterial test helps in selection and optimization of materials for antibacterial applications for preventing bacterial growth or contamination.

II. MATERIALS AND METHODOLOGY

2.1 Material selection

Compositions of composites include the following materials:

1. Nano Zinc Oxide.
2. E-Glass Fibre (350 GSM) Chopped Strand Mat.
3. Epoxy Resin Lapox L12 and Hardener K6.

Nano Zinc Oxide: Zinc is classified as block D, period 4 element, combines with oxygen, block P, period 2 element, to form these nanoparticles. Zinc Oxide nanoparticles (ZnO NPs) are metal oxide nanoparticles found in both powder and dispersion forms. These nanoparticles exhibit a broad range of properties, encompassing antimicrobial, antibacterial, anticorrosive, UV-filtering, regenerative, and mechanical effects. ZnO NPs are widely used in numerous fields, including materials science, agriculture, the food industry, cosmetics, medicine, and diagnostics.These Zinc Oxide Nanoparticles are dissolved in ethanol because dispersing zinc oxide nanoparticles is essential for unlocking their full potential and harnessing their unique properties in various applications, from advanced materials to biomedical and environmental technologies. Proper dispersion techniques and optimization are critical to achieving desired performance and ensuring the success of nanoparticle based products and formulations.

E-glass Fiber: E-glass fiber is a widely utilized reinforcement material in fiber-reinforced polymer composite industry. It is made up of oxides of silicon, aluminum, calcium, magnesium, and boron. In this work E-glass chopped strand mat is used which consists of randomly dispersed chopped strands of E-glass fibers bind together by an adhesive. These mats provide exceptional strength and rigidity to composite structures, making them suitable for diverse applications such as in automotive components, marine products, construction materials, and consumer goods. The chopped arrangement of fibers facilitates optimal resin saturation and ensures uniform reinforcement dispersion throughout the composite matrix. E-glass chopped strand mats are recognized for their cost-effectiveness in enhancing the mechanical characteristics and durability while maintaining a lightweight profile of composite materials.

Epoxy Resin: Lapox L12 stands as a medium-viscosity liquid epoxy resin, adaptable for creating glass fiber reinforced composites alongside different hardeners. The selection of hardener depends upon the intended processing technique and desired properties of the final composite. Hardener K6 emerges as a liquid with low viscosity, capable of curing at room temperature. Primarily utilized for hand layup applications, its high reactivity ensures a short pot life and rapid curing under normal ambient conditions. The resulting laminates exhibit resilience to operating temperatures up to 100°C.

2.2 Methodology

The materials obtained for preparation of composite material include Epoxy resin, Nano zinc oxide, and E-glass fiber, used in specific proportions to produce the desired composite material. The different weight percentages of zinc oxide nanoparticles desired are accurately measured and dissolved with appropriate amount of ethanol using ultrasonicator to obtain a stable and homogeneous dispersion. The dissolved ZnO Nanoparticles are dispersed in to epoxy resin using a magnetic stirrer, along with subsequent amount of resin hardener. Initially the epoxy resin is smeared onto the surface of the mold, similar to painting a wall using a brush. The E-glass chopped strand mat cut according to the required dimensions is laid over the resin layer. Again resin is reapplied over the fiber layer using and then second layer of mat is placed on top of the polymer surface. Trapped air and excess of polymer is removed rolling a roller with gentle pressure. This process is repeated for each layer of polymer and mat until the desired thickness is achieved. Finally, release wax is applied to the inner surface of the thin plastic sheet and top mold plate is placed on the stacked layers, and pressure is applied. The material is allowed to cure at room temperature, after curing the composite is taken out and further are cut to required dimensions as per ASTM standards using water jet cutting machine for the conduction of different tests.

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III. EXPERIMENTATION

3.1 Material composition

The work is been carried out for different concentrations of zinc oxide nanoparticles while maintaining a constant composition of Epoxy resin and each consisting of four layers of E-glass fibres chopped strand mat. Consequently, tests were conducted to evaluate the performance of different compositions. Table 1 shows the specimen composition of different composites.

Specimen No.	1	2	3	4	5
Nano ZnO %	0	0.5	1	1.5	2

Table 1 Specimen Composition of Different Composites

3.2 Testing

The prepared composite specimen are subjected to Hardness test conducted using micro Vickers hardness tester as per ASTM E384 standards and Antibacterial test performed through culture test as per ASTM E2180.

Hardness Test

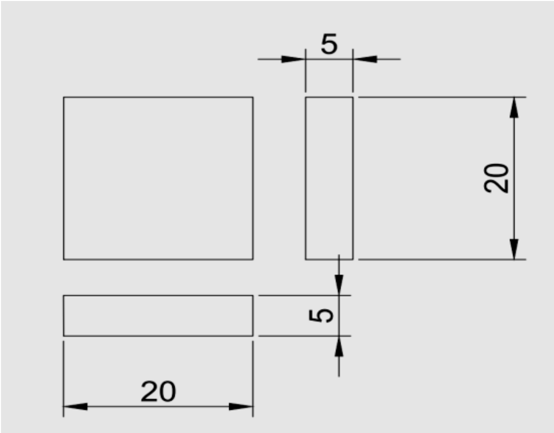

Fig 1 Geometry of Hardness Test Sample (All Dimensions are in mm)

The geometry of hardness test specimen is shown in Fig 1 as per ASTM E384 standards. Specimen length is 20mm, breadth is 20mm and thickness is 5mm.

Micro vickers hardness test is performed for characterizing the mechanical properties of materials at a microscopic scale, providing valuable insights into their performance and suitability for various applications.

Antibacterial Test

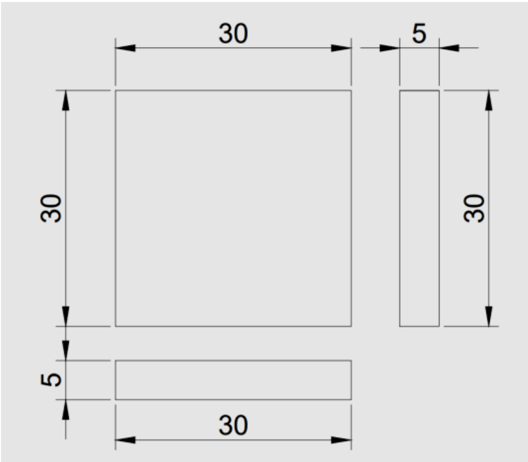

Fig 2 Geometry of Antibacterial Test Specimen (All Dimensions are in mm)

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The geometry of antibacterial test specimen is shown in Fig 2 as per ASTM E384 standards. Specimen length is 30mm, breadth is 30mm and thickness is 5mm.

The antibacterial test was conducted based on culture test in accordance with ASTM E2180, for determining the antibacterial efficacy of antimicrobial agents incorporated in polymeric materials. The antibacterial test aims to assess the susceptibility of composite materials to microbial colonization of Escherichia coli and Bacillus subtilis species.

IV. RESULTS AND DISCUSSIONS

4.1 Hardness Test Results

The hardness test results of the developed composites are shown in the Table 2 and Fig 3.

Specimen No.	1	2	3	4	5
VHN	31.9	34.1	38.7	50.5	35

Table 2 Hardness Test Results

The micro-vickers hardness value (VHN) of the developed composite materials with different concentrations of ZnO is shown in Table 2 and Fig 3. By analyzing hardness test results of prepared composites, it is observed that the hardness value of materials has been observed to increase gradually with increasing weight percentage of ZnO up to 1.5wt% and then decreases. For sample having 1.5wt.% of ZnO, exhibits highest hardness value of 50.5 VHN of all other composites. It is due to homogeneous dispersion, leads to effective load transfer and reinforcement throughout the material, enhancing its hardness, also may be due to the increased adhesion between matrix and reinforcement, and decreased porosity. The increase in the concentration of fillers in FRP composites, which results in increased hardness due to reduced inter particle distances and decrease in hardness at 2% maybe due to addition of excessive ZnO nanoparticles, which leads to various effects such as agglomeration or clustering instead of uniform dispersing of nanoparticles throughout the matrix which leads to weakness within the material, weak interfacial bonding between the nanoparticles and the matrix that reduces the effectiveness of load transfer and also due to formation of voids or gaps between nanoparticles and matrix material, these voids acts as stress concentrators, causing localized deformation and thereby reducing the overall hardness of the material.

4.2 Anti bacterial test

The antibacterial test results of the composite specimen are shown in Table 3 and Fig 4.

Specimen No.		1	2	3	4	5
Anti bacterial rate	**Escherichia coli (CFU)**	0	10	19	55	72
	Bacillus subtilius (CFU)	0	6	12	44	61

Table 3 Antibacterial Test Results

The data from the above Fig 4 demonstrates a clear trend of increasing antibacterial activity against both Escherichia coli and Bacillus subtilis with increasing concentration of the nano zinc oxide across the specimens. Escherichia coli exhibits highest antibacterial rate at 2% nano Zinc oxide with a reduction of 72 CFU. Similarly, Bacillus subtilis exhibits highest antibacterial rate of 61 CFU at 2% nano Zno content.

The antibacterial activity of ZnO may be due to generation of reactive oxygen species (ROS) of ZnO nanoparticles, when these highly reactive ROS's such as hydroxyl radicals and superoxide ions when exposed to light or moisture damages bacterial cell membranes, proteins, and DNA, leading to death of bacterial cell. From the Fig 4 There is an evidence of the decreasing colony-forming unit (CFU) counts observed for both bacterial strains. Furthermore, there is a notable threshold effect observed between Specimens 3 and 4, where there is a significant reduction in CFU counts.

This suggests that there may be a critical concentration of the antibacterial agent, beyond which further increases do not significantly enhance antibacterial activity. Understanding this threshold effect is essential for optimizing the efficacy of antibacterial agents. It implies that simply increasing the concentration of the antibacterial agent may not always result in better outcome, as it could also decrease antibacterial effectiveness beyond a particular threshold. Therefore, the optimal concentration of zinc oxide nanoparticles is 2wt.% that maximizes antibacterial activity reducing negative effects.

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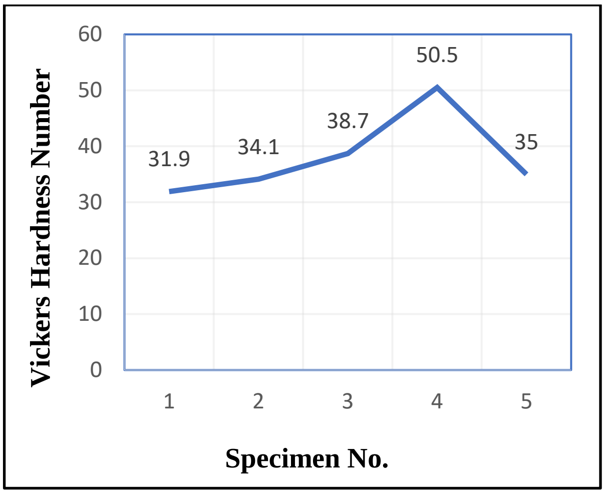

Fig 3 Hardness Test Result

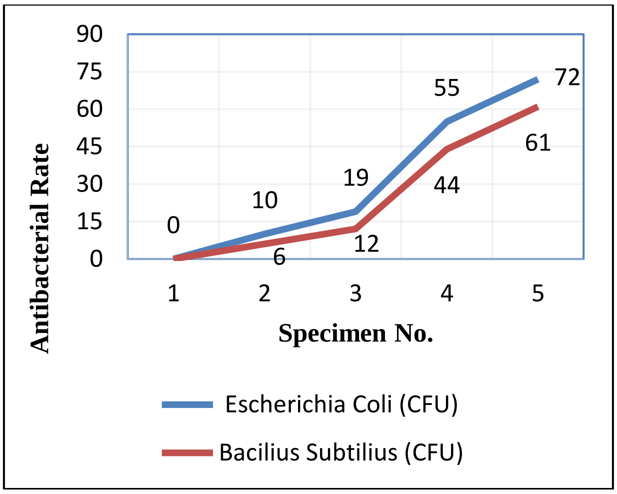

Fig 4 Antibacterial Test Results

V. CONCLUSION

In conclusion, the study demonstrates the feasibility and potential of nano zinc oxide and E-glass fiber reinforced epoxy-based composite materials in achieving synergistic improvements in mechanical performance and antibacterial efficacy.

Conclusions drawn from the study are as follows:

- The dispersion of fillers significantly impacts both mechanical and antibacterial properties of the composite.
- The density of the material increased by 5% for 2% of nano zinc oxide content.
- The hardness of the material is enhanced by increasing the filler loading upto 1.5wt% of nano zinc oxide by 58%.
- The antibacterial efficacy against Escherichia coli increases by 72% with a 2% rise in nano zinc oxide content.
- Similarly, the antibacterial effectiveness against Bacillus subtilis increases by 61% with a 2% rise in nano zinc oxide content.
- These findings contribute to the advancement of composite materials with enhanced functionalities, opening up new avenues for innovation and application in various industries.

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