Investigation of Nanoparticle-Added Natural Fiber Reinforced Composites Under Low-Velocity Impact Loading

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***Abstract*—Textile-reinforced composites hold significant promise for structural applications in vehicles, buildings, industrial machinery, and household appliances—primarily due to their low weight-to-volume ratio and cost-effectiveness. Growing environmental concerns have increased interest in using natural fibers; however, to match the mechanical performance of synthetic fiber-reinforced composites, nanoparticles such as TiO_2 and ZnO can be introduced into the matrix to enhance the mechanical properties of these natural fiber-based materials. In this study, natural fabric-reinforced composite plates were produced using plain woven linen fabric. The fabrics were subjected to alkali treatment before composite production to improve their interface properties. Epoxy resin served as the matrix material, suitable for reinforcing both natural and synthetic fibers. To enhance the composites, three types of fillers were incorporated: TiO_2 , ZnO, and silica powder. TiO2 and ZnO fillers were reduced to nano fillers in a ball milling machine. Epoxy resin was mixed with 2% and 6%w of fillers TiO2 and ZnO, and 2%, and 3%w of Silica using an ultrasonication process. The hand lay-up technique was used for fabric-reinforced composite production. The samples were tested for impact response using a drop weight impact tester under low-velocity impact loading at a kinetic energy level of 20 J. The results revealed that the addition of fillers enhanced energy absorption (up to 121.69%), with the increase correlating positively with filler concentration. The load-displacement curves demonstrated that with the addition of filler, the ductility and toughness of the material increased, and it absorbed more energy.**

***Keywords*— Linen fabric, Low-velocity impact, Nanoparticles, Natural fiber reinforced (NFC) composite, Silica, TiO2, ZnO**

I. INTRODUCTION

In recent years, textile-reinforced composites have gained significant attention due to their advantageous properties, particularly their strength-to-weight ratio, design flexibility, and cost-effectiveness. These materials are increasingly used in a wide range of structural applications, including the automotive industry, construction, aerospace components, industrial machinery, and household appliances. Their versatility and performance make them an attractive alternative to conventional materials, especially in applications where lightweight and durable structures are essential.

To better understand the performance and sustainability aspects of textile-reinforced composites, it is important to consider the types of fibers used in their production. In general, the fibers incorporated into these composites fall into two primary categories: synthetic fibers and natural fibers.

Composites reinforced with synthetic fibers are manufactured from man-made materials that undergo various chemical and thermal processing steps [1]. These fibers have been widely preferred in engineering applications due to their superior mechanical performance. However, growing environmental concerns and sustainability goals require more sustainable alternatives compared to the synthetic counterparts.

In response to increasing environmental awareness and global sustainability goals, natural fibers have emerged as an alternative to their synthetic counterparts. Natural fiber-reinforced composites, being composed of fibers obtained from renewable sources, are biodegradable, more environmentally benign, and often produced with lower energy input, making them favorable options for eco-conscious material design [2]. As a result, the development of natural fiber composites for applications such as automotive or construction works has gained considerable interest, as they contribute to reducing the carbon footprint of final products and promote the adoption of more sustainable manufacturing practices [2], [3].

Despite their ecological advantages, natural fibers also pose certain limitations when used as reinforcing materials. Compared to synthetic fibers, they tend to exhibit lower mechanical strength, greater variability in quality, and higher moisture absorption, which can compromise the performance and durability of resulting composites [4], [5]. Addressing these challenges is crucial for enabling the effective and widespread use of natural fiber-reinforced composites across diverse industrial sectors.

In light of the growing demand for sustainable yet high-performance composite materials, this study aims to investigate the enhancement of natural fiber-reinforced

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composites through nanoparticle enhancement. Specifically, it focuses on the incorporation of titanium dioxide (TiO_2) and zinc oxide (ZnO) nanoparticles, and silica powder into the polymer matrix to analyze their impact on mechanical properties and optimize nanoparticle concentration in the matrix material. By exploring the mechanical properties of composites using these nanoparticles, the study aims to contribute to the development of more durable and environmentally responsible composite materials suitable for various application areas.

II. LITERATURE REVIEW

Textile-reinforced composite materials are engineered structures that integrate textile forms, such as woven, knitted, or braided fabrics, with matrix materials like polymers, metals, or ceramics to enhance mechanical performance. While synthetic fibers offer high strength, they pose challenges in terms of recyclability. In contrast, natural fibers provide a sustainable alternative with comparable mechanical properties and lower environmental impact [6].

Natural fibers, composed mainly of cellulose, hemicellulose, and lignin, can be sourced from bast, seed, grass, or core plants [7]. They are compatible with both thermoset and thermoplastic matrices, offering advantages such as low cost, light weight, biodegradability, and renewability [8].

Despite their benefits, natural fibers are inherently hydrophilic and prone to moisture adsorption, which can weaken fiber-matrix adhesion. To address this, surface treatments, such as alkaline modification, acetylation, and graft copolymerization, are commonly applied to improve interfacial bonding [9]. Additionally, hybridization strategies involving the combination of flax with synthetic fibers like Kevlar and glass have been explored to enhance the mechanical performance of natural fiber composites [10].

To improve the mechanical performance of natural fiber polymer composites, several enhancement strategies have been developed, tailored to different application needs. Among the most commonly used techniques are surface modification, polymer blending, compatibilization, nanoparticle incorporation, and hybridization. Surface modification, whether chemical, physical, or biological, aims to improve fiber-matrix adhesion by altering the fiber surface and removing non-cellulosic components [11].

Polymer blending allows for the combination of two or more polymers in order to improve the qualities of the goods and reduce costs [12]. On the other hand, compatibilization is the process of introducing a new chemical component into a mix that is immiscible or phase separated, to enhance its stability. They are also known as coupling agents.

Nanoparticle incorporation has emerged as an effective strategy to enhance both mechanical and thermal properties of natural fiber polymer composites [13]. Nanoparticles, typically less than 100 nm in size, offer a high surface area-to-volume ratio [14]. This leads to remarkable mechanical properties such as increased strength, hardness, and elasticity [15]. Additionally, nanoparticles can be surface-functionalized to interact selectively with either the fiber or matrix, or act as compatibilizers by bridging both phases [16], [17]. Common nanoparticles include nanoclays, silica, and carbon-based materials, which contribute to better dispersion and dimensional stability of the composites [18].

Lastly, hybrid composites, formed by combining different kinds, forms, or sizes of reinforcement inside a single composite material.

These techniques, often used in combination, continue to expand the applicability and performance of sustainable composite materials in various engineering domains.

III. EXPERIMENTAL WORK AND ANALYSIS

This section outlines the material selection and the experimental procedures conducted for the development and characterization of natural fabric-reinforced composite plates. The methodology comprises six main steps: (A) material selection, (B) alkali treatment of linen fabrics to enhance fiber-matrix adhesion, (C) characterization of reinforcement fabrics with standardized tests, (D) preparation and fabrication of composite plates using nanoparticle-modified epoxy resin, (E) physical and mechanical evaluation of the composite specimens including density and void content analysis, and low-velocity impact testing to assess the structural performance under dynamic loading. Each step is detailed in the following subsections.

A. *Material Selection*

In the present study, composite plates were fabricated using plain woven fabrics made of linen fibers as natural fabric reinforcements. The linen fabric was supplied by Koza Tekstil (Türkiye).

As the matrix material, an epoxy resin system consisting of F-1564 epoxy resin and F-3486 hardener, both supplied by Kompozistan (Türkiye), was utilized. This epoxy system is compatible with both natural and synthetic fiber reinforcements.

To enhance the mechanical performance and functionality of the composites, three types of inorganic fillers were incorporated into the epoxy matrix TiO_2(IV) in anatase form (molecular weight: 79.87 g/mol, particle size ~325 mesh <44 µm, purity ≥99%, Sigma Aldrich), ZnO (molecular weight: 81.39 g/mol, particle size <5 µm, purity ≥99%, Sigma Aldrich), and silica powder with a specific surface area of 200 m^2/g (AEROSIL® 200, Evonik). These fillers were selected based on their proven ability to improve the composite's mechanical strength, thermal stability, and durability.

B. *Alkali Treatment of Reinforcement Fabrics*

To enhance interfacial adhesion between the fibers and the matrix, alkali treatment was applied to linen fabrics prior to composite fabrication. Initially, the fabrics were washed with non-ionic detergent (SDC ECE Phosphate-Free Detergent A) at 60°C for 1 hour to remove surface impurities such as wax and dirt. Subsequently, the fabrics were treated with a 4% NaOH solution (99% purity, Emplura, Germany) at room temperature for 30 minutes. After treatment, the fabrics were rinsed with distilled water, neutralized using a 2% acetic acid solution, rinsed again, and then dried in an oven at 80°C until constant weight was achieved.

C. *Testing of Reinforcement Fabrics*

Before composite fabrication, the physical and mechanical properties of the reinforcement fabrics were characterized to ensure material consistency and suitability for composite production.

Fabric thickness was measured using a James H. Heal thickness tester following BS EN ISO 5084.

Mass per unit area was determined following the ASTM D3776/D3776M-20 standard.

Tensile strength was evaluated in both warp and weft directions using a James H. Titan 710 strength tester, at a cross-head speed of 100 mm/min, according to TS EN ISO 13934-1.

D. *Composite Fabrication*

In the initial step, TiO_2 and ZnO fillers were mechanically reduced to nano-size using a ball milling process. These fillers were then dispersed in epoxy resin at concentrations of 2% and 6%w, while silica powder was added at 2% and 3%w using an ultrasonication process to ensure homogeneity.

Composite plates were produced using the hand lay-up method. Epoxy resin was applied layer by layer onto the fabrics at room temperature using a silicone roller, which facilitated even distribution and eliminated entrapped air and voids. The epoxy-to-hardener ratio was maintained at 3:1, as per the supplier’s recommendation. The samples were cured at room temperature for 24 hours.

E. *Testing of Composite Plates*

Following the fabrication of composite plates, a series of physical and mechanical tests were performed to evaluate their structural integrity and overall performance. These tests were focused on determining fiber content, void fraction, density, and impact behavior of the composites.

Fiber weight and volume ratios were calculated using the following equations:

$$Wf = \frac{wf}{wf + wm} \, x\, 100 \qquad (1)$$

$$Vf = \frac{Wf/\rho f}{(Wf/\rho f) + (Wm/\rho m)} \, x\, 100 \qquad (2)$$

where w_f and w_m are the fiber and matrix weight ratios, respectively; p_f and p_m are the respective densities.

Void fraction was determined according to ASTM D2734-94 using:

$$Void\ fraction\ (\%) = \frac{\rho ct - \rho ex}{\rho ct} \, x\, 100 \qquad (3)$$

Theoretical density was calculated using:

$$\rho ct = \frac{1}{(Wf/\rho f\,) + (Wm/\rho m\,)} \, x\, 100 \qquad (4)$$

Experimental density was obtained by dividing the sample’s measured mass by its volume, determined using Archimedes’ method. Measurements were performed with a digital caliper and precision balance.

For calculations, material densities were assumed as follows: linen fiber: 1.50 g/m^3; epoxy resin: 1.15 g/cm^3; hardener: 1.00 g/cm^3.

F. *Impact Testing*

In order to evaluate the impact response of the composite samples, a drop weight impact tester (Besmak) equipped with a 16 mm hemispherical weight impactor and a dynamic force sensor was used, following ASTM D7136. Tests were performed at a kinetic energy level of 20 J. Impact performance was assessed in terms of: impact energy absorption, maximum displacement, and impact strength. Visual inspection was used to evaluate post-impact damage characteristics.

IV. RESULTS

This section firstly presents the properties of the reinforcing fabrics used in the production of the composite plates, followed by the results of the composite plates testing.

Table I demonstrates the properties of linen reinforcing fabrics in terms of weave type, weight, tensile strength, and elongation.

TABLE I: PROPERTIES OF REINFORCING FABRICS USED IN COMPOSITE PRODUCTION

Weave Type	Weight (g/m^2)	Warp (ends/cm)	Weft (picks/cm)	Tensile Strength (N)		Elongation (%)	
				Warp	Weft	Warp	Weft
Plain	255	16	12	509	453.51	10.22	17.62

Depending on the type and concentration of fillers, silica powder, ZnO, and TiO_2 , applied at 0%, 2%, 3%, and 6% by weight, the resulting composite specimens exhibited weights and thicknesses within specific measurable ranges. The properties of the composites are given in Table II.

TABLE II: PROPERTIES OF COMPOSITES

Sample Code	Fabric Weight (g)	Composite Weight (g)	Composite Thickness (mm)	Matrix Weight (g)	Fiber Density (g/cm^3)	Matrix Density (g/cm^3)	Fiber Weight Ratio (%)
K0	33.13	84.44	3.70	51.31	1.50	1.11	39.23
KT2	33.49	82.47	3.50	48.99	1.50	1.11	40.60
KT6	33.64	84.10	3.82	50.46	1.50	1.11	40.00
KZ2	32.95	84.06	3.50	51.12	1.50	1.11	39.20
KZ6	33.07	81.97	3.48	48.90	1.50	1.11	40.35
KS2	33.02	84.69	3.45	51.67	1.50	1.11	38.98
KS3	33.13	81.89	3.33	48.77	1.50	1.11	40.45

TABLE II (CONTINUED): PROPERTIES OF COMPOSITES

Sample Code	Matrix Weight Ratio (%)	Fiber Volume Ratio (%)	Matrix Volume Ratio (%)	Theoretical Density (g/cm^3)	Experimental Density (g/cm^3)	Void Fraction (%)
K0	60.77	32.33	67.67	1.24	1.60	29.40
KT2	59.40	33.59	66.41	1.24	1.60	29.08
KT6	60.00	33.04	66.96	1.24	1.86	50.29
KZ2	60.80	32.30	67.70	1.24	1.33	7.69
KZ6	59.65	33.35	66.65	1.24	1.57	26.96
KS2	61.02	32.10	67.90	1.24	1.47	18.78
KS3	59.55	33.45	66.55	1.24	1.55	24.84

In the sample codes, K refers to linen fabric, 0 refers to no filler, and 2, 3, and 6 refer to the percent concentration of the filler. T refers to TiO_2 filler, Z refers to ZnO filler, and S refers to silica powder. It is seen that the fiber weight ratio of composites varies around 40% while the matrix weight ratio varies around 60%. The fiber volume ratio varied slightly, with the values between 32.10% and 33.59%. Similarly, the matrix volume ratio ranged from 66.41% to 67.90%, showing a minor variation influenced by the type of filler and its concentration. Experimental densities varied between 1.33 g/cm^3 to 1.86 g/cm^3. The void fraction was affected by the type and concentration of the filler. At lower filler concentrations (2 wt%), the void fraction generally decreased, with ZnO showing the most pronounced decrease (7.69%). In contrast, higher filler concentrations (6 wt%) tended to increase the void fraction, an effect most evident for TiO_2, which exhibited the highest value (50.29% for KT6). Regarding filler type, ZnO at low filling levels demonstrated to greatest capability to reduce void content, while TiO_2 at high filling levels resulted in a substantial increase. Silica produced intermediate void fraction values at both 2 wt% and 3 wt%, indicating a moderate influence on porosity relative to TiO_2 and ZnO.

After characterization of the composite samples, the impact performance was assessed in terms of impact energy absorption, maximum displacement, and impact strength. Table III demonstrates the absorbed energy values for each sample.

TABLE III: ABSORBED ENERGY VALUES

Sample	Absorbed Energy (J)	Increase Rate Compared to Reference Sample (%)
K0	1.328	--
KT2	1.823	37.27
KT6	1.320	-0.60
KZ2	1.834	38.10
KZ6	2.230	67.92
KS2	2.944	121.69
KS3	2.163	62.88

When the results are examined, it is seen that the addition of fillers generally enhanced the absorbed energy of the composites compared to the reference sample (K0), except KT6, which exhibited a slight decrease (-0.60%). At lower filler concentrations (2 wt%), all three filler types improved energy absorption, with silica (KS2) producing the most significant increase (121.69%), followed by ZnO (KZ2, 38.10%) and TiO_2 (KT2, 37.27%). Increasing the filler content to higher levels yielded different trends depending on the filler type. Silica exhibited the highest energy absorption at 2 wt%, but its performance declined at 3 wt% (62.88%), though still remaining well above the reference value (1.328 J). For TiO_2, the absorbed energy decreased markedly at 6 wt% (67.92%), indicating a negative correlation between filler content and impact performance for this material. Overall, ZnO demonstrated consistent gains with increasing concentration, silica powder and TiO_2 showed diminished performance at high filling, and silica achieved the greatest single improvement (121.69%) at low filling.

Following the energy absorption assessment, post-impact damage characteristics were evaluated through visual inspection, focusing on the type and zones of the load-displacement curves. These curves are generally classified into two types, closed and open. In closed curves, the impactor rebounds and the displacement return to zero at the end of unloading, whereas in open curves, the specimen is penetrated or perforated by the impactor. Load-displacement curves can be divided into three distinct zones: elastic response, damage initiation and propagation, and unloading. Figures 1 and 2 present the load-displacement curves of linen fabric-reinforced composites fillers in comparison with the reference sample without a filler.

In the present study, all recorded curves were of the open type. Examination of the graphs in Fig. 1 revealed that all composites exhibited similar trends with an initial linear increase in load, reaching a peak, and then a gradual decline as displacement increases. The reference composite (K) shows moderate peak load (~500 N). KT2 and KZ2 reach similar peak loads but slightly lower than K, suggesting that TiO_2 and ZnO fillers at 2 wt% do not significantly enhance load-bearing capacity. On the other hand, KS2 (silica filler) demonstrated the highest displacement at failure (≈10 mm), indicating improved ductility compared to other composites, though its peak load is slightly below the reference. In Fig. 2, KT6 (6 wt% TiO_2) showed the largest displacement at failure (≈14–15 mm) and sustained the load over a long post-peak region, indicating enhanced toughness/energy absorption. KZ6 (6 wt% ZnO) attained a high peak load but failed at a smaller displacement (≈10 mm), suggesting higher strength with lower ductility than KT6. KS3 (3 wt% silica) exhibited the lowest peak load and earlier failure, implying embrittlement at this filler level.

When the zones of the load-displacement curves were observed, it was seen that the initial slopes of all curves are nearly identical, indicating that the specimens possessed similar stiffness under the applied impact energy. However, while the reference sample showed a sudden load drop following damage initiation, a greater extent of damage development was observed in KS2, KZ6, and KT6 samples. Overall, the addition of TiO_2 filler at 6% appears to enhance the ductility and toughness of the composites, enabling them to absorb more impact energy.

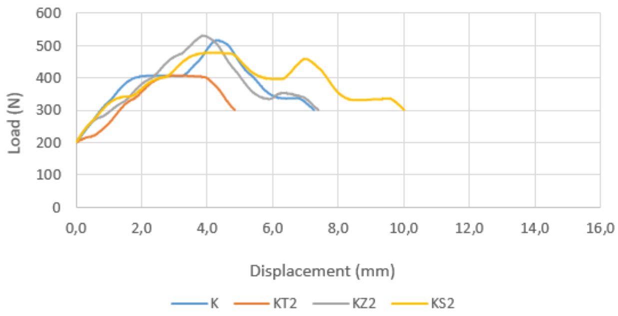

Fig. 1. Load-displacement graphs of linen fabric-reinforced composites with 2wt% filler.

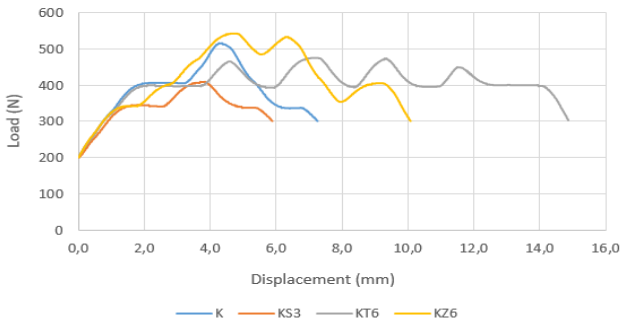

Fig. 2. Load-displacement graphs of linen fabric-reinforced composites with 3wt% silica filler and 6wt% TiO_2 and ZnO filler.

In summary of all the results, impact testing demonstrated that the incorporation of nanoparticle fillers generally improved the energy absorption capacity of linen fabric-reinforced epoxy composites, with the most pronounced enhancement achieved by 2 wt% silica (121.69% increase over the reference sample). ZnO exhibited a consistent positive trend with increasing filler content, while TiO_2 and silica showed reduced performance at higher concentrations. Load-displacement analysis confirmed that all specimens exhibited open-type curves with similar initial stiffness, but TiO_2 at 6 wt% provided the most favorable balance between load capacity and displacement and extended damage propagation, indicating enhanced ductility and toughness. Overall, the results suggest that appropriate filler selection and optimization of filler content are critical for maximizing impact performance.

V. CONCLUSION

Textile-reinforced composites remain highly attractive for structural applications due to their favorable weight-to-volume ratio and cost efficiency. In response to increasing environmental demands, the use of natural fibers has gained prominence; however, achieving mechanical properties comparable to those of synthetic fiber composites often requires modification of the matrix with nanoparticles.

In this study, plain-woven linen fabric pre-treated with an alkali process to improve fiber-matrix adhesion was used as reinforcement, with epoxy resin serving as the matrix. To further enhance performance, TiO_2, ZnO, and silica powder fillers were incorporated. The results demonstrated that these fillers can substantially improve the impact performance of linen fabric-reinforced epoxy composites. Low-velocity impact tests revealed increases in energy absorption of up to 121.69%, with responses varying according to filler type and concentration. Load-displacement curve analysis confirmed that filler addition enhanced ductility and toughness, enabling composites to better withstand and dissipate impact energy.

While this study focused on impact response, future research should extend the investigation to other mechanical properties, including static and fatigue performance under tensile, compressive, and bending loads. Further work could also examine the effect of combining fillers such as TiO_2, ZnO, and silica powder to enhance mechanical, thermal, and UV-resistance properties while optimizing filler type, ratio, and concentration.

In conclusion, and in light of the growing demand for sustainable yet high-performance composite materials, this study demonstrates the potential of nanoparticle incorporation to enhance the properties of natural fiber-reinforced composites. The findings on impact performance highlight the feasibility of producing more durable and environmentally responsible composites, supporting their applicability across a range of structural and functional applications.

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