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Improving the Mechanical Properties of a Car Bumper by Using Glass Fiber Reinforced Composite Laminates and Nano-ceramic Filler

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Abstract

In this study, mechanical tests were performed on a Chinese car bumper of the Chery model, which was chosen for examination due to its widespread use in Iraqi streets. It was also compared to the best specimens obtained in these study stages. Glass fiber mats and nanoparticles have been mixed with the unsaturated polyester resin (UPE) in two stages. In the first stage, the fibers have been mixed with a volume fraction of 14% and the mechanical properties have been calculated. In the second stage, different weight fractions of nanoparticles of zirconium oxide (ZrO_2) were added to the mixture, and the mechanical tests were recalculated. The experimental test's results illustrated that the tensile strength, fracture toughness, and damping ratio of the composite material were enhanced when mixing 14% vf of glass fiber mats with unsaturated polyester resin by about (285.85%, 207.56%, and 100%) respectively, compared to the car bumper, while the ratio of impact resistance decreased by about (-24.55%). The same tests were repeated after adding different weight fractions (1%, 2%, 2.5%, 3%, 3.5%, 4%) of (ZrO_2) and it was observed that adding the nanoparticles had a significant effect on the mechanical properties since at first, it improved them until the nanoparticles ratio reached 2.5 wt.%, but any higher addition than this ratio caused a decrease in the enhancement of the mechanical properties. Thus, it was found that adding 2.5 wt.% nanoparticles gave us the best improvement in the tensile strength, impact resistance, fracture toughness, and damping ratio by about (436.32%, 47.28%, 438.66%, and 52.3%) respectively, compared to the car bumper properties.

1. Introduction

As traditional metals, alloys, and ceramic materials cannot keep up with the demands of technological development, the need for compounds with better properties to fit in with developed applications such as aerospace, underwater, and transportation applications has resulted in the use of new or alternative composite materials as a foundation in the modification and development of engineering designs for many goods and industrial products [1,2]. In recent years, polymeric materials have been widely used in different methods to satisfy the requirements of industries. Such an important interest in the materials has been driven by several factors, involving their ease of processing, light weight, low cost, high productivity, good corrosion-resistance, low

electrical characteristics, a moderate thermal expansion coefficient (CTE), and good customizability for these properties by different structural designs [3,4]. Because fiber-reinforced plastics have proven themselves as matrix materials for composites in many applications and well-established markets, and most composites based on other classes of matrix materials are still primarily in the development stage, most people assumed that composite materials consist of a polymer matrix reinforced by fibers, and they forgot that fibers can be used to reinforce all classes of materials [5]. Many thermosets are limited in their application regions given the low fracture toughness, so chemical modifications or the use of specific additives such as liquid rubbers, elastomers, or fiber reinforcing agents have been used to enhance the polymer's fracture toughness [6]. Thermosetting polymers, which are amorphous and have excellent bonding properties, are frequently utilized as adhesive materials [7]. Fiber reinforcement has become a significant way of improving the strength, modulus, and impact toughness of thermoset resins, which are typically liquid in their uncured condition. Fibers are commonly utilized for reinforcing thermosetting resins [8]. Modern techniques study the reinforcement of polymers with nanoparticles. These nanoparticles are defined as particles with a size smaller than a one-micron meter, where 0.1 µm equals one-micron meter (100 nm). Nanoparticles are directly proportional to their volume; as particle size drops, the volume/surface ratio rises, making surface characteristics increasingly important [9]. The use of nanofillers such as (nanofibers, nanoparticles, or both combined) to reinforce polymers is referred to as "polymeric nanocomposites," owing to the small distance between particles and large surface area [10]. Zirconium oxide nanoparticles have chemical stability, hardness properties, low thermal conductivity, excellent weather resistance, good strength, and fracture toughness [11]. Many studies have found that adding fibers and nanoparticles to polymer composites improves their mechanical characteristics. Sousa et al. (2017) studied the unsaturated polyester-based PMs modified by the nanoparticles (ZrO_2, and $Al2O_3$) and their effects on the mechanical properties. The results showed that the compressive strength, flexural strength, and Shore D hardness tests were improved by adding the nanoparticles. Also, it was noticed that adding ZrO_2 gave higher mechanical properties than $Al2O_3$ [12]. P. Prabhu et al. (2018) investigated the addition of various weight fractions of nanoclay particles (0, 1, 2, 3, 4, and 5%) to glass fiber-reinforced polyester composite (GFRP) and its effect on the mechanical properties. It was observed that adding nanoclay to a GFRP composite improved the tensile strength, impact strength, and fracture toughness. Also, it was found that 3 wt.% of nanoclay gave the optimum enhancement [13]. Reem et al. (2020) investigated the unsaturated polyester resin reinforced by 4% mat fiber of polypropylene with different weight fractions of zirconia nanoparticles (1, 2, 3, and 4%). An enhancement in the mechanical and physical properties was observed by adding the nanoparticles of zirconia [14]. M. D. Stanciu et al. (2021) studied the mechanical properties of glass fiber reinforced polyester (GFRP) of two types of glass fibers. The first type was plain fabric (GFRP-RT500), and the second was chopped strand mat (GFRPMAT450). The results showed that the addition of glass fiber leads to improvements in both the tensile and compression strength, and the improvement in the first type of glass fiber (GFRP-RT500) gave higher mechanical properties compared to the chopped strand mat (GFRPMAT450) [15].

Previous research found that reinforcing the matrix phase with fibers improved the mechanical properties of a composite material. Further improvement was obtained through adding nanoparticles to the composite materials.

2. Experimental Procedure

2.1. Materials

The unsaturated polyester resin (UPE), a product of the polyester group, was the matrix material employed in the current investigation and was provided by the company Saudi Industrial Resins Limited (SIR). This UPE resin, a thermoset resin, was combined with (2–4%) of the same company's hardener, methyl ethyl ketone peroxide (MEKP), at ambient temperature. This interaction is called an "addition reaction". Table (1) illustrates the mechanical and physical properties of polyester. As for reinforcement materials, two major advantages must be available to enhance the material matrix; the high strength and low ductility, which represent a good example of it. Glass fiber mats (E-glass) with a thickness of about 1 mm (as manufactured) are used in this study. The mechanical properties of glass fiber are shown in Table (2). The zirconium oxide nanoparticles were supplied by (intelligent material Pvt. Ltd. (nanoshell) in white colour powder and 30 nm in size. The characteristics of zirconium oxide nanoparticles are shown in Table (3).

Table (1). Mechanical and physical properties of UPE.

Test method	The dry value	The wet value
Density (g/cm^3)	1.15	-
Tensile strength (MPa)	91.5	88.3
Tensile strength coefficient (GPa)	9.30	7.71
Flexural strength (MPa)	176	164
Flexural strength coefficient (GPa)	7.32	6.59
Young's modulus (Gpa)	3	-
Elongation (%)	2	-
Poisson's ratio	0.38	-
Glass content (%)	27.4	-

Table (2). Mechanical properties of glass fiber [16].

Material	Density g/cm^3	Modulus of elastic (GPa)	Strength (MPa)	Poisson's ratio
E-glass	2.54	72.4	3450	0.2

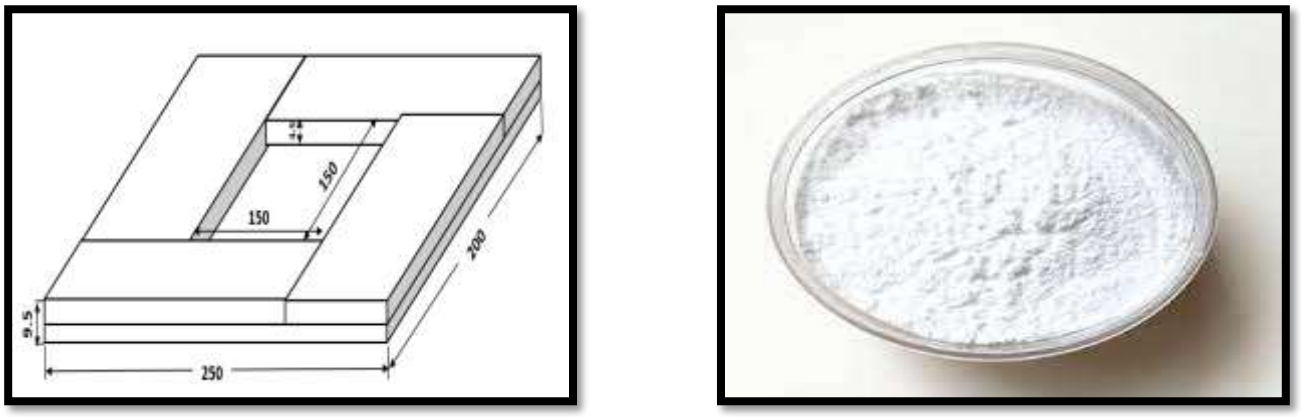
Table (3). Characteristics of Zirconium Oxide Nanoparticles.

properties	Density (g/cm^3)	Molecular formula	Solubility	appearance	purity	odor	ASP
values	5.68	ZrO_2	Insoluble in water	White powder	99.9%	odorless	30 nm

2.2. Preparation of Molds and Specimens

The mold is manufactured of acrylic material because of its moderate strength and toughness, so that the samples would not stick to the mold, thus making it easy to remove and safer than glass in usage because it does not break easily. If it breaks, it does not scatter into small harmful pieces. The mold is made with dimensions of (150 × 150 × 4.5) mm as shown in the Figure (1 a), and is used to make a plate of composite material, which is cut into ASTM standards for each test.

The specimens were made by the hand lay-up molding method, where a plane place must be chosen, then all sides of the mold in contact with specimens are cleaned and lubricated with wax to remove the polymeric material easily and guarantee the guarantee of obtaining a regular distribution, smooth surface, and defect-free specimen. First, polyester resin is mixed with zirconium oxide nanoparticles (ZrO_2), which are shown in Figure (2 b) at different weight percentages (1, 2, 2.5, 3, 3.5, and 4%). The mixture was stirred well for at least half an hour to ensure the homogeneity of the two materials together and then distributed in the mold. After that, a dry layer of glass fiber mat is placed in the mold, and then a brush is used to apply the resin matrix on the reinforcing material from one side only to remove the entrapped air. Then, the process is repeated until the pre-planned thickness is reached, after which the mold is covered with a piece manufactured of acrylic material (same as the mold material) and pressed well. Then, the weight of 5 kg is placed on it to level the surface, expel the excess resin, and force air bubbles out of the mold. The mixture is left for 24 hours until it solidifies at room temperature. Then, the material is taken out of the mold and cut to size according to the ASTM standard for the tensile, impact, hardness, and damping tests.



(a) (b)

Figure (1). (a) The Dimension of Prepared Mold & (b) Zirconium Oxide.

2.3. Mechanical Tests

2.3.1. Tensile Test

The tensile test was done by using the machine of Instron Universal (Tinius Olsen U.K., model HKT 50 KN). The specimens were cut into dog bone shapes with a cross-sectional area of (10 x 5 mm) and were used for the test according to ASTM-D638, and it is shown in the Figure (2), the device fixed the sample from its ends. While its lower jaw is stationary, the upper jaw of the device moves up at a constant rate of 2 mm/min, applying a hydraulic force to the sample gradually until the sample fails and breaks. Tensile strength is obtained from the stress-strain curve.

Figure (2). Tensile Test's Specimen.

2.3.2. Impact Test

The test was done by using the Izod impact test instrument (Testing Machines, INC., MITYVILLE, New York). Firstly, the specimen of size (10 x 4.5 x 55mm) according to ASTM-ISO-179 illustrated in Figure (3) is placed on the machine supports, then a hummer of 5 joules is released in such a way that the edge of the striking will hit the specimen's exposed part. The absorbed energy (fracture energy) by the specimen was read in a joule unit from the energy scale, where the impact resistance can be obtained from the mathematical relationship.

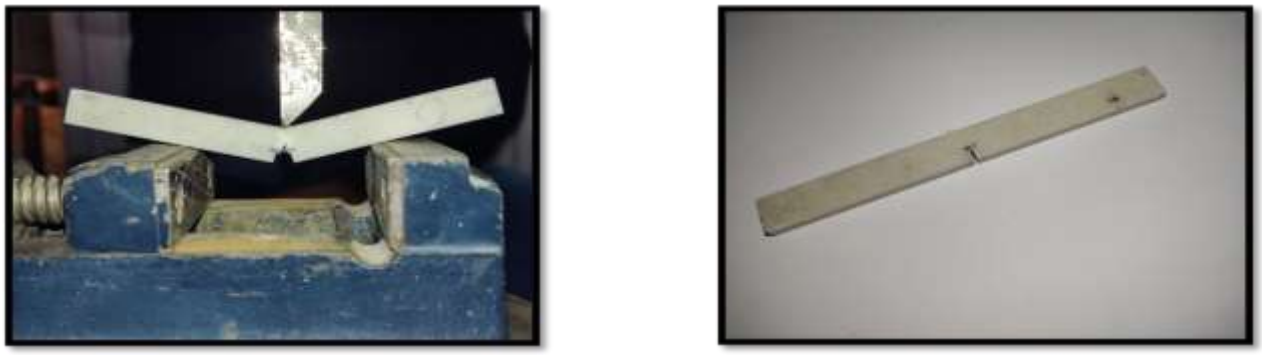
$$I.S = (U/A) * 1000 \quad (1)$$

Where U: is the energy of fracture measured by (J) that obtained from the Izod impact test scale, A: is the specimen's cross-sectional area measured by (m^2), and I.S: Impact strength measured by (KJ/ m^2).

Figure (3). Impact Test Specimen.

2.3.3. Fracture Toughness Test

A fracture toughness test was done by using the machine from Instron Universal (Tinius Olsen U.K., model HKT 50 KN), as shown in Figure (4 a). This test was executed at the University of Technology/Materials Engineering Department. Specimens of size (10 x 4.5 x 100 mm) with a notch of 4 mm were placed in the specimen's center according to ASTM-D4045 was used for the test as illustrated in Figure (4 b). It was placed on two supports that were set 40 mm apart, and a load pin with a constant rate of 2 mm/min was lowered from above to the center of the specimen until it failed.



(a) (b)

Figure (4). (a) Fracture toughness test instrument & (b) Fracture toughness specimen.

2.3.4. Damping Test

The damping test was done using the logarithmic decrement method, which incorporated a system of instruments and software programs, as Figure (5 a) illustrates. This test was executed at the University of Babylon/Mechanical Engineering Department. Specimens of the size (4.5 × 45 × 145 mm) as illustrated in Figure (5 b) were used in the test. The specimens are considered cantilever beam configurations with length enough to fix the cantilever beam.

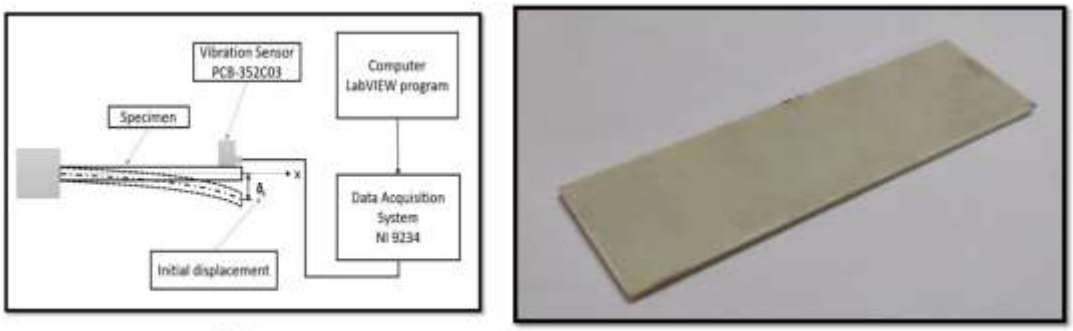


Figure (5). (a) Damping test setup with assembled specimen & (b) Damping specimen.

3. Results and Discussion

This section discusses the obtained results and represents them in curves and graphics to recognize the material's mechanical properties.

3.1. Tensile Test Results

Tensile tests were done on the specimens prepared from fiber-reinforced polyester before and after adding the fibers. As illustrated in the Figure (6) tensile strength has increased by about (74.04%) after adding 14% vf of glass fiber mats as compared to the neat specimen. This increase is due to the fiber present, which enhances the performance of bonding between interfaces and adhesion strength, which plays a major role in improving the mechanical properties of composite materials.

Adding the different weight ratios (1, 2, 2.5, 3, 3.5, and 4%) of zirconium oxide nanoparticles to the resultant composite gave a further enhancement in tensile strength by about (8.8%, 25.06%, 38.98%, 31.78%, 21.64%, and 16.26%), respectively, compared to the specimen of fiber-reinforced polyester. This enhancement is due to the good characteristics and homogeneous distribution of nano zirconium oxide, which improve the adhesion between the particles and resin, which in turn allows the transfer of the applied pressure. Also, from figure (7), we can say that a composite of 14% fibers and 2.5% nano ZrO_2 owns the maximum tensile strength and shows the best enhancement.

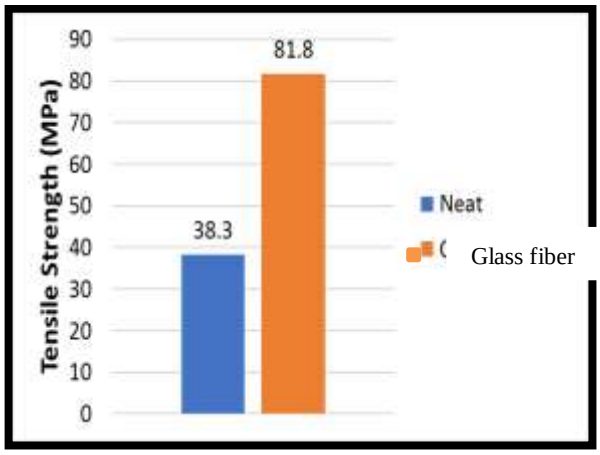


Figure (6). Effect adding 14% vf of glass fibers mat on tensile strength**.**

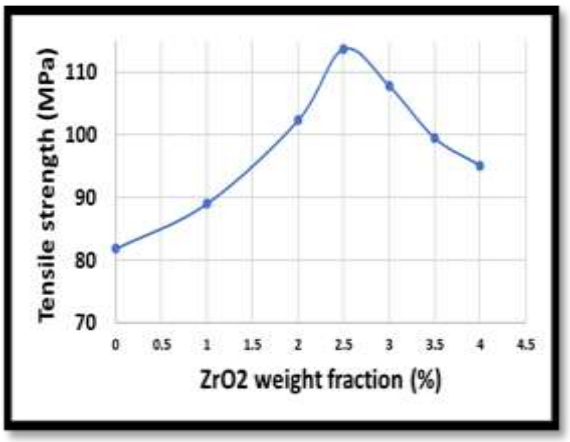


Figure (7). Effect of ZrO_2 weight fraction on tensile strength.

3.2. Impact Test Results

Figure (8) illustrates the experimental results obtained from the Izod impact instrument through equation (1). A rise was observed of about (574.5%) in impact resistance when a 14% vf of glass fiber mat was added to the resin. This increase is attributed to the fibers, as the fibers carry the maximum portion of the impact energy placed on the specimen.

Figure (9) shows that adding the different weight ratios (1, 2, 2.5, 3, 3.5, and 4%) of nanoparticles to the resultant composite gave a further enhancement in impact resistance by about (16.8%, 59.7%, 95.2%, 80.5%, 56.3%, 40.3%) respectively. As a result, the resulting composite absorbs and disperses a load of impact energy before fracture, especially at the composite of 14% fibers +2.5% zirconium oxide, which absorbs and disperses the highest load.

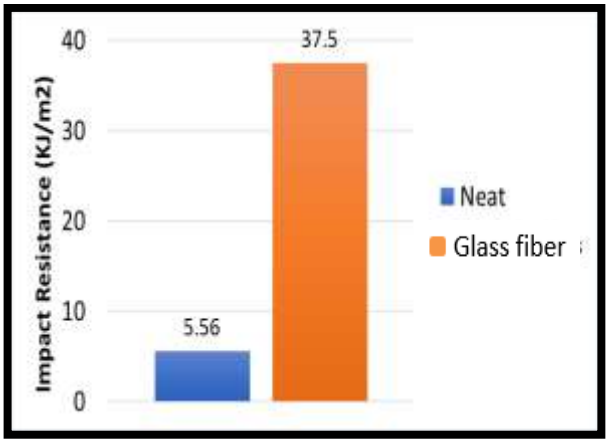


Figure (8). Effect of 14% of glass fiber mats on impact resistance.

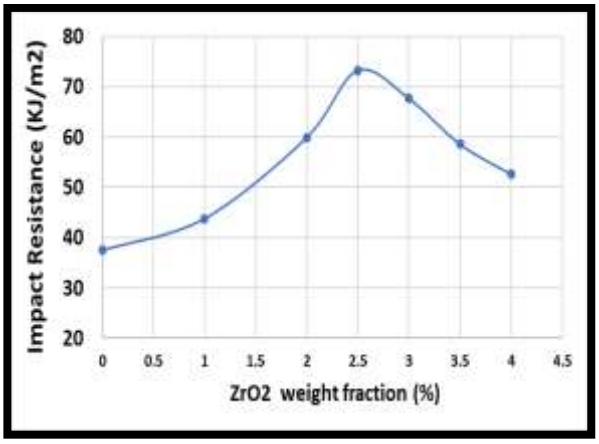


Figure (9). Effect of ZrO_2 weight fraction on impact resistance.

3.3. Fracture Toughness Test Results

Figure (10) shows an enhancement in the experimental results of the fracture toughness test, where they increased by about 4218.26% after adding 14% vf of glass fiber mats. This increase is attributed to the existing fibers, which may operate as an obstruction to crack development and thus increase the fracture resistance.

It has also been noticed that adding different weight fractions (1, 2, 2.5, 3, 3.5, and 4) of nano-ZrO_2 to the polyester reinforced fiber caused an enhancement in the fracture toughness values, which increased by about (37.43%, 65.57%, 75.14%, 69.4%, 66.12%, 53.01%) respectively. This enhancement is because the particles are fragile (brittle) and there is no sliding characteristic between the used nano-particle molecules, so they enhance the brittleness and toughness of the material.

Figure (11) depicts the composite with the highest fracture resistance (14% vf of fibers and 2.5 wt.% nanoparticles).

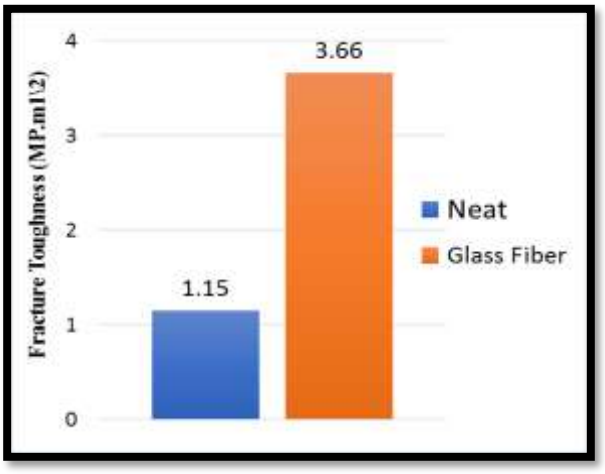


Figure (10). Effect of 14% of glass fiber mats on Fracture toughness

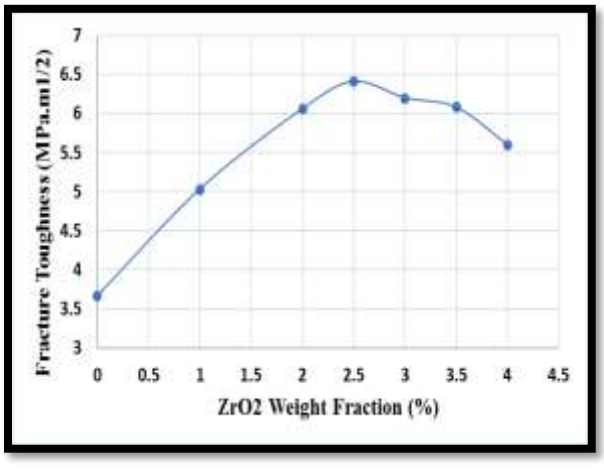


Figure (11). Effect of ZrO_2 weight fraction on Fracture toughness

3.4. Damping Test

Figure (12) shows a reduction in the experimental results of the damping ratio, where they decreased by about (-23.18%) after adding 14% vf of glass fiber mats. This decrease is due to the presence of fibers in the polyester resin, which increases the toughness of the composites and results in less sliding across surfaces. As a result, less energy is dissipated and the damping ratio is reduced.

It has also been noticed that adding different weight fractions (1, 2, 2.5, 3, 3.5, 4) of nano-ZrO_2 to the polyester reinforced fiber caused an enhancement in the fracture toughness values, which decreased by about (-8.05%, -17.53%, -23.85%, -28.74%, -40.23%, -54.02%) respectively. These reductions are due to the fact that the good particle dispersion in the matrix resulted in higher adhesion between particles and the matrix, which influenced the stiffness increase of composite materials and led to lower sliding between interfaces, allowing less energy to be dissipated and the damping ratio to be reduced.

According to Figure (13), the composite (14% vf fibers and 2.5 wt.% nanoparticles) has the lowest damping ratio.

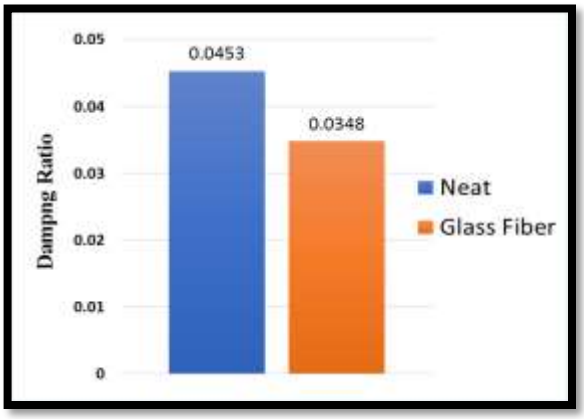


Figure (12). Effect of 14% of glass fiber mats on damping ratio.

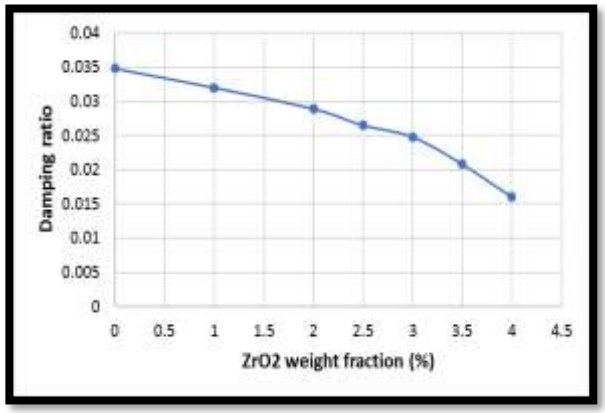


Figure (13). Effect of ZrO_2 weight fraction on damping ratio.

3.5. Choosing the Best Specimen Compared to the Car Bumper.

All the previous mechanical tests have been repeated on a car bumper of the model Chery, and compared with the composite materials that were produced in the study stages. It was found that the compound (UPE+14% GF) enhances tensile strength, fracture toughness, and damping ratio by about (285.85%, 207.56%, and 100%) respectively while reducing the impact by about (-24.55%) compared to the car bumper. while the composite (UPE+14% GF+2.5% ZrO_2) enhances all the mechanical properties by about (436.32%, 47.28%, 438.66%, and 52.3%), respectively. From the foregoing, it was concluded that the composite (UPE+14% GF+2.5% ZrO_2) is the best composite material compared to the bumper properties illustrated in Table (4).

Table (4). The mechanical properties of Chery bumper.

Material	Tensile Strength (MPa)	Impact Resistance (KJ/m^2)	Hardness	Fracture Toughness ($MPa.m^{1/2}$)	Damping Ratio
Chery Bumper	21.2	49.7	70.7	1.19	0.0556

4. Conclusions

From the foregoing, it was concluded that adding 14% of glass fiber mats and different weight fractions of nanoparticles (zirconium oxide) to the unsaturated polyester (UPE) increases the mechanical properties of the

composite such as tensile strength, impact resistance, and fracture toughness, while it decreases the damping ratio. It has been also observed that adding nanoparticles with a percentage greater than (2.5 wt.%) will reduce the enhancement in the composite material as a result of the agglomeration of nanoparticles with each other, forming stress concentration zones. The composite (UPE+14% GF+2.5% ZrO_2) was the best composite material compared to the Chery bumper's mechanical properties, which enhanced all the mechanical properties by about (436.32%, 47.28%, 438.66%, and 52.3%) respectively.

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