IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Revue des Composites et des Matériaux Avancés-Journal of Composite and Advanced Materials
Vol. 35, No. 1, February, 2025, pp. 21-26
Journal homepage: http://iieta.org/journals/rcma

Effect of Zirconia-Alumina Additives on Some Mechanical and Physical Properties of Epoxy Resin for Industrial Applications

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https://doi.org/10.18280/rcma.350103

Received: 19 September 2024
Revised: 6 October 2024
Accepted: 17 January 2025
Available online: 28 February 2025

Keywords:
epoxy, zirconia. alumina, composite, tensile, impact, hardness, density, water absorption

ABSTRACT

The performance of the composite is improved by the addition of ceramic particles to the polymer resin, making such materials useful in the automotive and aerospace sectors. In order to evaluate the properties of epoxy resins, zirconia and alumina are combined in this study at weight percentages of 5%, 10%, 20%, and 30%. The main goal is to use the "hand lay-up" method to assess how various ceramic additions affect the mechanical and physical characteristics of the epoxy matrix, including its tensile test, impact test, hardness test, density and water absorption test. Alumina adds hardness and wear resistance, whereas zirconia is well-known for its high fracture toughness and energy absorption capacity. It is believed that mixing these fillers would increase composite performance synergistically. The most appropriate ratios to optimize the reinforcing effects are investigated in this study. The best mean values of the tensile strength and impact strength (8.35MPa, 22.37KJ/m^2) were at the samples (Epoxy-10% zirconia-alumina). By raising the concentration of the weight fractions of zirconia-alumina in epoxy up to 10%, the percentage of water absorption values increased; the samples with 10% zirconia-alumina in epoxy had the optimum water absorption percentage (0.253%). The results emphasize the importance that interfacial bonding and appropriate filler distribution are to obtaining excellent mechanical characteristics.

1. INTRODUCTION

The creation of durable composite materials, also known as composites, is the primary task for most material scientists. Composites are engineering materials composed of two or more constituent materials that, at the macroscopic level, remain distinct and separate while forming a single component [1].

The backbone of the composites industries is polymer matrix composites (PMCS). They are reasonably priced and have good room temperature properties. Polymers that are thermoplastic and thermosetting resins make up the matrix. The majority of composites include a reinforcement component in the form of whiskers, flakes, particles, and small-diameter fibers [2]. Even now, there is a great deal of research and development being done on particle filled polymers, despite the tremendous interest in advanced composite materials. particle filled polymers are utilised in extremely large amounts in a variety of applications. Scientists have been interested in ceramic particles filled with polymer composites because of scientific study that has demonstrated the benefits of polymer composite materials as a type of engineering material with better corrosion and friction properties [3].

One of the most popular thermosetting plastics, epoxy resin has many useful uses, such as adhesives, surface coatings, electrical laminates, aircraft components, and building materials. Epoxy can withstand the effects of harsh solvents while maintaining its mechanical and physical characteristics because of its excellent dielectric strength, minimal shrinkage, excellent adhesion, superior chemical resistance, and other qualities. Additionally, epoxy resins adhere to a variety of materials, including plastics, metals, stone, wood, and glass [4].

The filler concentration or volume fraction or, the type of reinforcing used in the particles, the size, shape, and interfacial adhesion between the particles and the matrix are the main factors influencing the mechanical properties of the particulate composite [5]. Because of their superior mechanical and thermal conductivity over carbon-based materials and metal particles, ceramic particles have been the subject of extensive research [6]. Alumina is a viable filler in industrial applications because Al_2O_3 materials have been extensively researched in composites because of its cheap cost, and steady chemical characteristics [7, 8]. Alumina fillers in epoxy resin composites can improve the material's strength and elastic modulus for product moulding [9, 10].

Currently, research on ZrO_2's effect on epoxy resin nanocomposites has been conducted by Dorigato et al. [11]. ZrO_2 nanoparticles, on the other hand, have great wear resistance, excellent chemical resistance, high strength, high fracture toughness, and high hardness, making them a potentially useful candidate for polymer reinforcement [11].

Long et al. [12] added b-Al_2O_3 to epoxy resin to prepare 0.5 wt% b- Al_2O_3/EP composites, 30wt% b-Al_2O_3/EP composites, and 70wt% b-Al_2O_3/EP composites, as the experimental results present the thermal conductivity of 70% filled b-Al_2O_3/EP composites is 1.13W/(mK), which exceeds the value of pure epoxy resin by an excess of seven.

In this study, the traditional fillers zirconia (ZrO_2) and aluminum oxide (Al_2O_3) are used to produce the epoxy composites. The mechanical properties (tensile, impact, and hardness) and physical properties (water absorption and density) of composite materials that can be utilized for industries that depend on epoxy composites, especially in applications requiring better mechanical characteristics like aerospace, automotive, and construction, are affected by the weight percentage and type of reinforcing particles.

Furthermore, we explicitly articulate the specific research gap addressed by our investigation. While previous studies have explored the individual effects of ceramic reinforcements, limited research has focused on the combined impact of zirconia (ZrO_2) and alumina (Al_2O_3) in epoxy composites and the optimal loading percentages for enhancing mechanical performance. This research aims to fill that gap by evaluating the mechanical and physical properties of epoxy composites reinforced with varying weight percentages of these ceramics.

2. MATERIALS AND METHODS

2.1 Materials used

The epoxy resin from Sikadur®-52, obtained from SikaTM, is utilized as the matrix phase in the current work. Alumina AL_2O_3 and zirconia ZrO_2, which were purchased from Sigma Aldrich Pvt. Ltd. in India, are the particles used as reinforcement materials (micro size particles).

2.2 Preparation of samples

The conventional approach (Hand lay-up) was utilised in this study to create the specimens needed for the research utilising a ready to cast mould made up of silicon, as indicated in Figure 1. By combining epoxy in various ratios (5, 10, 20, 30)% with the particles zirconia (ZrO_2) and alumina (AL_2O_3), pure and composite samples were created. For 8 to 10 minutes, the hardener was combined with both particles using an ultrasonic homogeniser (Soniprep 150 MSE) to achieve the optimal dispersion of ZrO_2 and AL_2O_3 particles inside the resin matrix. This is a crucial requirement for the theory of epoxy composite reinforcing. After that, the mixture was poured into the mould in a continuous and steady flow. After being cast for 24 hours at room temperature, the samples were demolding, and they were then heated in an oven to finish the polymerisation process and remove any internal tensions that had occurred during the casting process. After the specimens were prepared into five groups, they were all cured at 50°C for two hours. The composition of epoxy composite samples at 0%, 5%, 10%, 20%, and 30% weight percentages of alumina (Al_2O_3) and zirconia (ZrO_2) reinforcements is shown in Table 1. The specific weight percentages of both particles were selected based on previous research showing notable mechanical enhancement at lower loading. Furthermore, evaluating the composites' mechanical properties systematically through testing a range of percentages (0%, 5%, 10%, 20%, and 30%) allows for the discovery of the ideal formulation while reducing the possibility of problems with brittleness and particle agglomeration.

Figure 1. Silicon mould for preparing samples

Table 1. A description of the sample's composition

Composition	Designation
Pure Epoxy	0%
Epoxy/2.5% AL_2O_3/2.5% ZrO_2	5%
Epoxy/5% AL_2O_3/5% ZrO_2	10%
Epoxy/10% AL_2O_3/10 ZrO_2	20%
Epoxy/15% AL_2O_3/15% ZrO_2	30%

3. CHARACTERIZATION

3.1 Tensile test

This test, which was carried out in compliance with ASTM D 638 guidelines [13], was used to assess epoxy composites' tensile properties experimentally. Specimens in the shape of dog bones were cast directly. Tensile tests were performed using an Instron-type universal testing equipment in displacement control mode at a crosshead speed of 5mm/min. For every type of epoxy composite, testing was done on at least three samples.

3.2 Impact test

In accordance with ASTM D4812 or ISO-180, this test is performed at room temperature using an Izod impact tester (XJU series pendulum Izod/Charpy impact tester). The sample must be broken up immediately from the equipment in order for energy to be absorbed. The sample was positioned vertically using the Izod method, and the pendulum was raised to its maximum point in accordance with the testing procedure of the instrument, secured firmly, and then allowed to strike the sample to transform its potential energy into kinetic energy [14].

3.3 Hardness test

For the purpose of testing the hardness, the sample's surface needs to be straight, smooth, and uncomplicated. As per the ASTM D2240 by Dorumeter hardness test [15], the sample has a 50mm diameter and a 4mm thickness. A force of 50N was applied during this test, which used a hardness device type (Shore D). The measurement depressing time was approximately (15) seconds.

3.4 Density test

The samples have been prepared in accordance with the ASTM D792. Any practical size specimen can be utilized in this test, however the volume shouldn't be less than 1cm³. Additionally, the specimens' edges and surfaces must be smooth and devoid of any extraneous materials such as oil or grease. The samples underwent testing, and they need to be weighed both in the open and after being submerged in room-temperature distilled water [16].

3.5 Water absorption test

The water absorption in this test was determined by the ASTM D570 standard [17]. Models must have a cut interest that is 40mm in diameter and 5mm in thickness.

4. RESULT AND DISCUSSION

4.1 Tensile test results

A useful tool for examining the effects of reinforcing weight percentage (wt%) is the stress-strain curve. Figure 2 displays the typical stress-strain curves of ZrO_2 and Al_2O_3 reinforced epoxy resin composites. Figures 3 and 4 illustrate the effects of alumina and zirconia percents (0-30 wt%) on the tensile strength and elastic modulus, respectively. The results appeared an improvement in stress-strain curves, as well as tensile strength and elastic modulus of the composites when a reinforcement phase was compared to the pure epoxy sample. This improvement in these properties was achieved in composites containing 10 weight percent of ZrO_2 and Al_2O_3 particles improve by around 32% and 50%, respectively, in comparison to those of the neat epoxy resin.

The average strain values at break for the prepared epoxy samples (epoxy- 0%, 5%, 10%, 20% and 30% wt. zirconia and alumina) are shown in Figure 3. The average strain values at break for the pure epoxy samples (4.88) and samples (epoxy-5%, 10%, 20%, 30% zirconia and alumina) are (5.09, 7.3, 6, 5.81%) respectively.

The enhancement of the tensile strength is attributed to the homogeneous distribution of ZrO_2 and Al_2O_3 particles into the epoxy resin and interfacial bonding which is between epoxy matrix and the ceramic fillers. This interfacial bonding is essential for effective load transfer and improved tensile strength.

The highest results were in the percentage (10%wt.) additives consist from (5% Al_2O_3 and 5% ZrO_2). Because when both alumina and zirconia added to an epoxy can provide a synergistic reinforcement effect. Zirconia improves toughness and tensile strength, while alumina enhances hardness and wear resistance. However, tensile strength and elasticity modulus somewhat decrease as the particle content is increased beyond 10 weight percent. This could be explained by the extreme particle aggregation found in composite materials. It notices from Figure 4 that the value of the elasticity coefficient increases as the additive (ZrO_2 and Al_2O_3) concentration increased, up to a percentage of (10% wt.), and it is good at (20% wt.), and then it decreases at (30% wt.). The resistance that the fillers provide to the mobility of polymer chains is demonstrated by the increase in stiffness (Young's modulus) of epoxy, alumina, and zirconia composites.

The results demonstrate that the mechanical characteristics of epoxy composites containing ZrO_2 and Al_2O_3 particles are due to enhanced interface bonding performances, since it improves the adhesion strength and interfacial stiffness [18]. Due to their relatively small sizes, high specific surface area, higher strength, stiffness, and toughness over the epoxy resin matrix, as well as their improved adhesion at the particle/matrix interface, ZrO_2 particles can improve mechanical attributes [4]. It is evident that effective dispersion results in a high surface area and a well-bonded contact, which allows for some stress transfer and greatly improves the tensile characteristics. However, an overly high particle content causes massive agglomerates in the composites, which lead to poor interfacial adhesion, structural failure, and performance loss.

Consequently, the good dispersion and reinforcing influence of the alumina zirconia particles are responsible for the increase in elongation at lower weight fractions. Higher weight fractions cause an ensuing decrease because of particle agglomeration, limited polymer chain mobility, and maybe even flaws in the composite [19, 20].

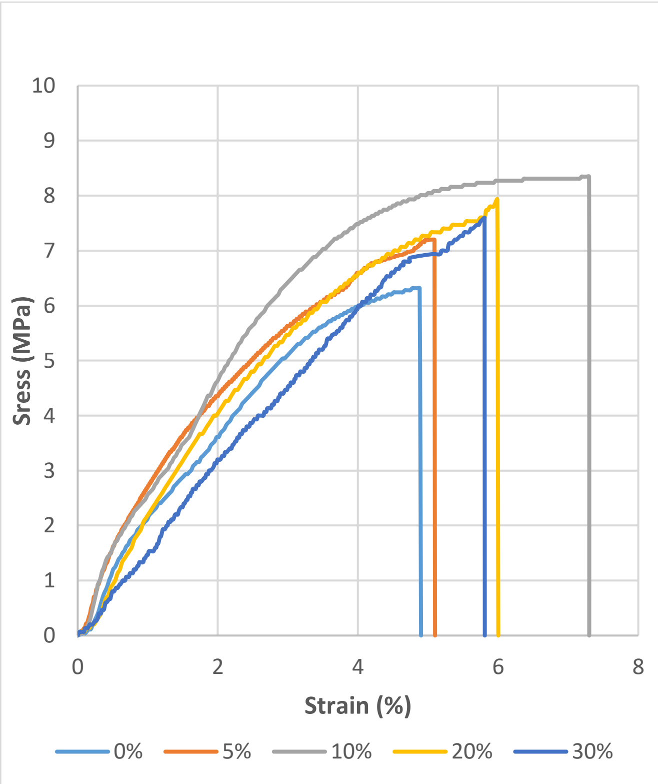

Figure 2. Effect of additive concentration on the stress-strain curve

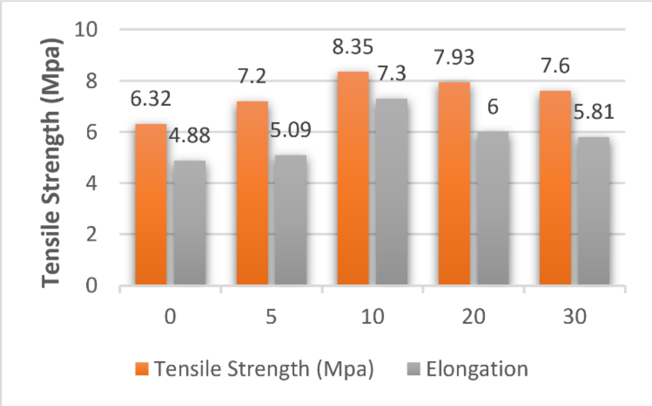

Figure 3. Effect of additive concentration on the tensile strength and elongation

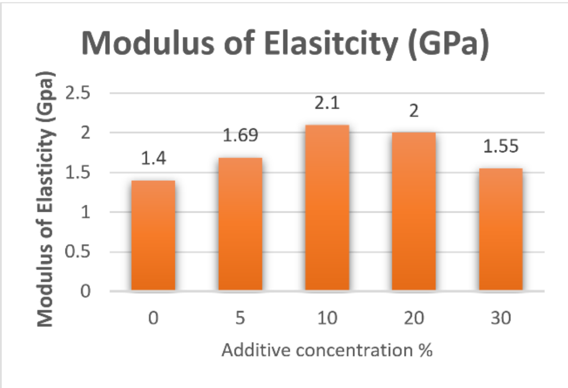

Figure 4. Effect of additive concentration on the modulus of elasticity

4.2 Results of impact test

The impact resistance and fracture toughness curves for composite specimens are displayed in Figures 5 and 6. They clearly show how the addition of zirconia and alumina to an epoxy composite can enhance its impact strength by combining the toughening effect of zirconia with the hardness of alumina. The impact resistance and fracture toughness increase with the weight fraction up to 10% which contain (5% ZrO_2 and 5% Al_2O_3). Moreover, a well-balanced zirconia and alumina mixture can enhance the composite's capacity to absorb and disperse impact energy, resulting in increased impact strength.

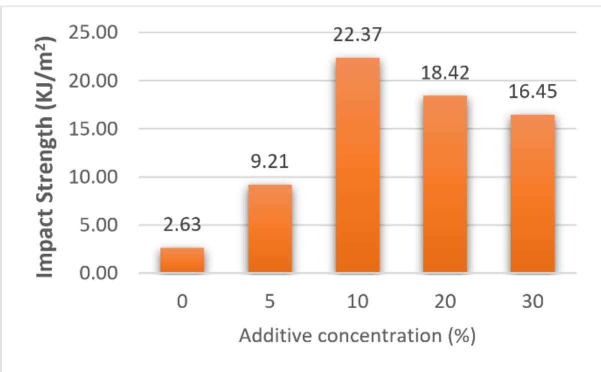

Figure 5. Effect of additive concentration on the impact strength

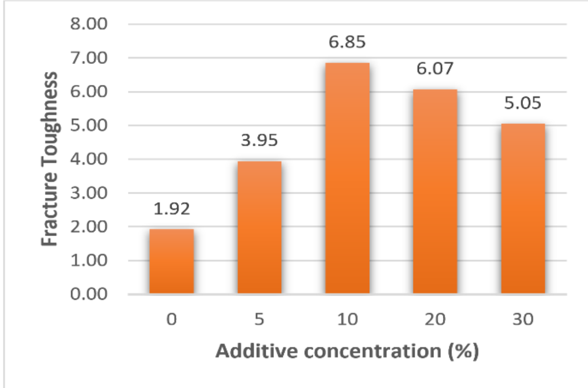

Figure 6. Effect of additive concentration on fracture toughness

In Figure 5 the impact strength increases from (2.63KJ/m^2) for pure epoxy to about (22.37KJ/m^2) for the addition 10% wt of zirconia and alumina composite and then the value of the impact strength starts to decreases as the weight percentage of the particles increase and reach to (18.42 and 16.45KJ/m^2) with the addition 20% and 30% wt zirconia and alumina respectively. As 10% weight of zirconia and alumina composite was added, the fracture toughness of pure epoxy in Figure 6 improved to (6.85Mpa. $m^{1/2}$) from (1.92Mpa. $m^{1/2}$).

The increase in impact strength indicates that when the particle content increases, brittleness appears, giving the material strength while also making it brittle. Brittle material is defined as that which breaks suddenly and permits the spread of cracks. Additionally, these composites usually show poor resistance to fracture formation and lightning strikes. The low rate of impact resistance in additives (20% and 30% weight percentages of zirconia and alumina) is due to particle agglomeration; these particles act as pressure focus points in the epoxy resin, weakening the adhesive strength and increasing brittleness [21]. The significant improvement in fracture toughness with 10wt.% addition is likely due to the material's increased ductility and its capacity to withstand greater plastic deformation before failing.

4.3 Hardness test results

Figure 7 illustrates the relationship between the hardness and weight fraction of the additives applied to the epoxy. As can be seen, the hardness improved from (49) Shore D without additive to (56) Shore D with 10% weight of alumina and zirconia. This is because the strengthening is caused by the load-carrying ability of the zirconia and alumina particles, which have extremely high hardness.

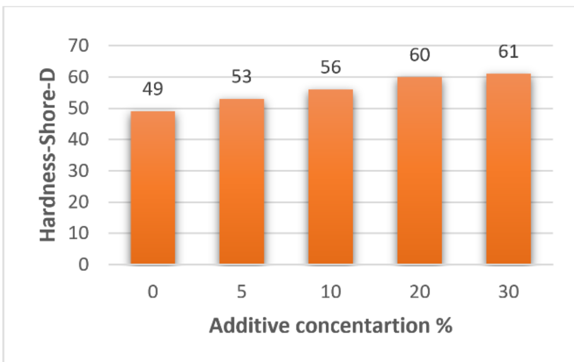

Figure 7. Effect of additive concentration on the hardness

The improvement in the hardness is due the presence of the hard ceramic particles, which have a much stronger phase compared to the polymer matrix. The hardness is enhanced when particles are included into the polymeric matrix because they increase the link density between the polymer chains [22].

Additionally, the uniform dispersion of ZrO_2 and Al_2O_3 particles and the decrease in interparticle distance with increased particle loading in the matrix contribute to the overall hardness increase. Based on the acquired data, the hardness of the composites is observed to rise with an increase in ZrO_2 and Al_2O_3 addition [23].

4.4 Density test results

It is noticed from Figure 8 that the density of composite decreased initially as the weight fractions of particles increases, reaching (0.311g/cm^3) for 10% wt of zirconia and alumina composite. The density starts to rise as well when the weight percentage increased more than 10% wt because of better particle packing and smaller void areas, this is because the density of zirconia and alumina become higher as compared with epoxy reaching (0.572g/cm^3) for 30% wt of zirconia and alumina composite. The initial decrease in density at 10% wt. is likely due to the uniform dispersion of ceramic particles within the epoxy matrix, which contributes to the formation of microvoids, thus reducing the overall composite density.

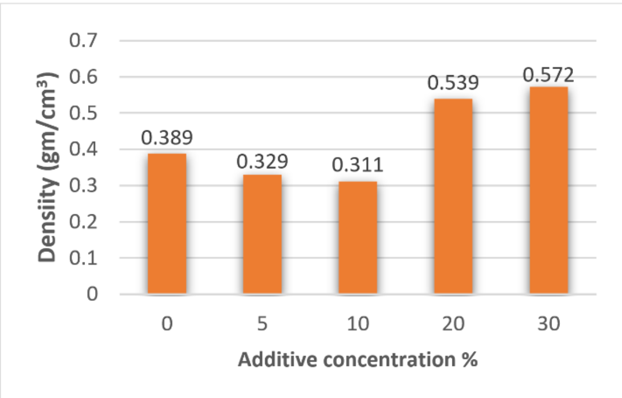

Figure 8. Effect of additive concentration on the density

4.5 Water absorption test results

The mean water absorption values for the epoxy composites reinforced by zirconia-alumina are shown in Figure 9. As more of these particles were added, it was observed that the water absorption of epoxy composites dropped, reaching 0.253% for 10% weight percentage zirconia-alumina. The zirconia and alumina additions' increased barrier qualities are responsible for the initial drop in water absorption. The reason for this phenomena is that the presence of particles blocks the diffusion of water molecules through the composites by creating a barrier [24]. By increasing the density of the composite and decreasing its free volume, these additions limit the amount of space that water molecules can occupy within the material. Nevertheless, the water absorption starts to rise when the weight percentage of these compounds beyond a particular level. This pattern indicates that while adding zirconia and alumina in moderation might improve epoxy composites' water resistance, adding too much of either can result in increased porosity or other structural alterations that make water uptake easier.

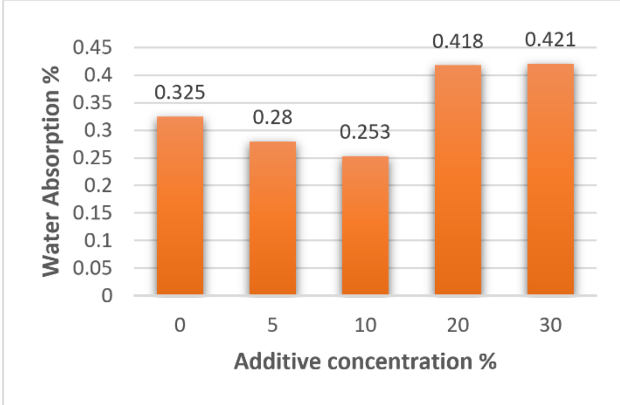

Figure 9. Effect of additive concentration on the water absorption

5. CONCLUSIONS

The research verifies that adding alumina (Al_2O_3) and zirconia (ZrO_2) to epoxy at different weight percentages (0, 5%, 10%, 20%, and 30%) improves its characteristics, with the best results seen at a 10% wt. At this concentration, alumina boosts hardness and wear resistance, whereas zirconia enhances energy absorption and fracture toughness. When combined, these fillers increase impact strength to about 22.37kJ/m², tensile strength to about 8.35Mpa, and modulus of elasticity to about 2.1Gpa. These characteristics, however, deteriorate as the particle weight percentage rises above 10%. These results imply that epoxy composites reinforced with zirconia and alumina show promise for use in the automotive, aerospace, and structural engineering industries, among other sectors, where materials with improved impact strength, wear resistance, and toughness are needed. Achieving optimal performance requires careful control of filler content, uniform particle dispersion, and strong interfacial bonding.

Environmental and economic impacts, limitations, and future research

Epoxy composites with alumina and zirconia added provide increased mechanical performance and durability, which could lower waste and material consumption in the automotive and aerospace industries. However, one should take into account the greater initial expenditures as well as the environmental impact of producing and disposing of ceramic particles. Particle agglomeration at greater weight percentages, which alters material properties, is one of the study's limitations. Subsequent investigations may concentrate on enhancing particle dispersion, refining filler ratios, and examining the long-term efficacy of these composite materials under diverse circumstances.

ACKNOWLEDGMENT

The authors would like to express their gratitude to the University of Technology-Iraq for its support of this research.

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