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Sports balls made of nanocomposite: investigating how soccer balls motion and impact

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Abstract. The incorporation of nanoplatelets in composite and polymeric materials represents a recent and innovative approach, holding substantial promise for diverse property enhancements. This study focuses on the application of nanocomposites in the production of sports equipment, particularly soccer balls, aiming to bridge the gap between theoretical advancements and practical implications. Addressing the longstanding challenge of suboptimal interaction between carbon nanofillers and epoxy resin in epoxy composites, this research pioneers inventive solutions. Furthermore, the investigation extends into unexplored territory, examining the integration of glass fiber/epoxy composites with nanoparticles. The incorporation of nanomaterials, specifically expanded graphite and graphene, at a concentration of 25.0% by weight in both the epoxy structure and the composite with glass fibers demonstrates a marked increase in impact resistance compared to their nanomaterial-free counterparts. The research transcends laboratory experiments to explore the practical applications of nanocomposites in the design and production of sports equipment, with a particular emphasis on soccer balls. Analytical techniques such as infrared spectroscopy and scanning electron microscopy are employed to scrutinize the surface chemical structure and morphology of the epoxy nanocomposites. Additionally, an in-depth examination of the thermal, mechanical, viscoelastic, and conductive properties of these materials is conducted. Noteworthy findings include the efficacy of surface modification of carbon nanotubes in preventing accumulation and enhancing their distribution within the epoxy matrix. This optimization results in improved interfacial interactions, heightened thermal stability, superior mechanical properties, and enhanced electrical conductivity in the nanocomposite.

Keywords: glass fiber/epoxy composites; impact resistance; nanocomposites; nanoplatelets; soccer balls; sports equipment

1. Introduction

Nano platelets and nano composites have revolutionized the production of sports balls, offering a myriad of benefits that enhance performance, durability, and overall quality (Zhang *et al*. 2017, 2020, 2022a, b). By incorporating these advanced materials into the manufacturing process, sports equipment manufacturers are able to create products that exhibit superior strength-to-weight ratios, improved impact resistance, enhanced flexibility, and increased responsiveness (Cao *et al*. 2022, 2024, Huang *et al*. 2024, Wu *et al*. 2024a). This innovative approach not only elevates the playing experience for athletes but also pushes the boundaries of material science in sports technology. In this article, we will delve into the fascinating world of nano platelets and nano composites, exploring their applications and impact on the production of sports balls.

By observing nature, it has been discovered that materials such as wood, teeth, bone, and skin are composites with complex internal structures and favorable mechanical properties (Thostenson *et al*. 2005). Composite materials are one of the most important and widely used engineering materials. Composition, high strength, and lightweight push composites into new realms, but other properties have also been considered (Komarneni 1992). The thermal expansion coefficient of composites is low, their vibration-damping ability is favorable, and their fatigue strength is good (Krysko *et al*. 2017, 2019, 2021a, b, 2024). The flexibility in the design and production of these materials reduces the number of parts required for specific applications, thereby reducing the need for raw materials, bonding and packaging, and the time required for assembly (Dzenis 2008). Composites due to high temperatures, corrosion, and wear. They are resilient, especially in industrial environments, reducing replacement costs (So *et al*. 2007). Their annual world production exceeds ten million tons and in recent years the demand for this material has increased by 5-10% per year. Composite materials have a wide range of applications and are designed in such a way that they can be adapted to different conditions of use (Wei *et al*. 2022). One of the essential applications of polymers is their use in manufacturing polymer matrix composites (Wang *et al*. 2022, Jia *et al*. 2023, Zhang *et al*. 2023b, c, d, Yan *et al*. 2024). Polymer matrix composites (PMCs) are more advanced than the other two groups of composites, namely metal and ceramic composites (Kong *et al*. 2023). Aerospace, automotive, sports and entertainment equipment, electronics, and medicine depend on polymer composites. Two main groups of polymers (thermoset and thermoplastic) are used as matrices for polymer-based composites (Yang *et al*. 2022a). Thermosets are materials whose

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hardening reaction occurs during component manufacture, after which they harden and become dimensionally stable. Thermoplastics, however, are softened by heat and can be reshaped in many ways (Xiao *et al*. 2022). Thermoplastics are generally divided into several types: amorphous, crystalline, and liquid crystalline (Moniruzzaman and Winey 2006). There are many polymers in both groups. Thermoplastics are generally more resistant to solvents and corrosive environments than thermoplastics, but there are exceptions (Wu and Liao 2007). Resin selection is based on design requirements and manufacturing and cost considerations (He and Deng 2023, Li *et al*. 2023a, Su *et al*. 2023). Polymer matrices are viscoelastic materials that generally have relatively poor mechanical properties (Cui *et al*. 2020). The strength and stiffness of polymer-based composites derive mainly from the fiber phase (Dai *et al*. 2023, Song *et al*. 2023, Yang and Mao 2023, Ye *et al*. 2023). One of the most important considerations when choosing a chip is its maximum operating temperature (Ashfaq *et al*. 2022). As the temperature increases, the properties of the polymers decrease. One of the criteria for determining the relative temperature stability of polymers is the glass transition temperature (Tg). 'Tg' refers to the temperature at which a polymer changes from a hard and glassy consistency to a soft, rubbery consistency (Li *et al*. 2023b) At temperatures above the glass transition temperature, the strength and stiffness of polymers decrease significantly. New polymers with increased heat capacity, i.e., comparable to many metals, are being developed. For example, carbon fiber-reinforced polyimide composites have replaced titanium in aerospace gas turbine parts (Yang *et al*. 2021). A key consideration when selecting polymer matrices in polymer matrix composites is their sensitivity to moisture. Resins absorb water, leading to dimensional changes and loss of strength and stiffness at high temperatures (Paul and Robeson 2008). The level of moisture absorption, usually measured as a percentage of weight gain, depends on the polymer and the relative humidity. Resins placed in a dry environment will repel moisture (Feng *et al*. 2023). The degree of adsorption and desorption strongly depends on the temperature. The sensitivity of resins to moisture varies greatly, which is why some are very resistant (Vaia and Wagner 2004).

Familiar examples of these composites are fiber-reinforced panels, generally classified as high-performance polymer composites or long fiber or nonwoven micro composites. In other words, additives can be discontinuous. Polymer composites fall into two general categories (Gan *et al*. 2023, Jiang *et al*. 2023, Wang *et al*. 2023b, 2024, Li *et al*. 2024):

• Fiber Reinforced Composites, also known as fiber composites (Melinte *et al*. 2019). In this type of composite, the fiber is the reinforcing phase (Jin *et al*. 2023, Lau and Li 2023, Wang *et al*. 2023a). This category of composite materials (FRC) is commonly used for structural applications.

• Particle composites: The reinforcement phase comprises particles in this composite type (Lee *et al*. 2005). This category of composites is used in high-friction parts. From another point of view, polymer composites can be divided into glass, carbon, and aramid, depending on the type of reinforcement (Cheng *et al*. 2023, Fu *et al*. 2023, Li *et al*. 2023d, Zhang and Huang 2023).

Fiberglass-polymer composites include continuous or discontinuous glass fibers in the polymer field. In the future, more carbon will be used as a reinforcing fiber in the high Polymer Composite instead of glass because carbon fibers have the highest specific strength and modulus of any fiber reinforcement material (Petronella *et al*. 2017). Aramid fibers are high-strength, high-modulus materials introduced in the early 1970s. In polymer matrix composites, in addition to the three types of reinforcing fibers, glass, carbon, and aramid, boron, silicon carbide, and alumina are sometimes used to a limited extent (Li 2023, Li *et al*. 2023e, Zhang *et al*. 2023b). Boron fibers are used in military aircraft components, helicopter blades, and sports equipment (Vijayan *et al*. 2012). Silicon carbide and alumina fibers are used in tennis racquets, printed circuit boards, and rocket tips. Polymers have great strength and flexibility, but in industrial applications, they face disadvantages that limit their use (Guan 2023, Li *et al*. 2023c, Ma *et al*. 2023). Recently, polymer composite materials have been used in a variety of applications (Fito *et al*. 2022). Therefore, nanotechnology has been adopted as an essential technology to improve composite materials' properties (Aguilar-Ferrer *et al*. 2022). Nanoparticles with a specific surface area, large pore volume, and small size exhibit unique physical and chemical properties. This allows them to be added to polymers as fillers, producing polymer nanocomposites with unique and multifunctional properties (Omidi *et al*. 2013, Ghadiri *et al*. 2016c, Mousavi *et al*. 2017). They have a thermal, physical, mechanical, barrier, covering, electrical, absorbent, and vapor-permeable properties (Fan *et al*. 2013). They have better ignition than pure polymer. In addition, the nature of the polymer network and the fillers play an essential role in the properties of the nanocomposite (Azimi *et al*. 2016, Ghadiri *et al*. 2016a, b, Shafiei *et al*. 2016, 2017). As fillers, various nanomaterials such as carbon nanotubes, graphene, nano-silica, and reinforced fibers are added to the polymer network (Ajayan and Zhou 2001). This gives similar results. Graphene nanocomposites are suitable for oil and gas applications and are widely used in this area (Ebrahimi *et al*. 2017, Ghadiri *et al*. 2017c, Shahabinejad *et al*. 2018, Shafiei *et al*. 2020). Before the advent of polymer-based composites, sports equipment was mainly made of wood, steel, aluminum alloys, etc. Compared with these materials, fiber-reinforced composites have obvious advantages, including lightweight, excellent mechanical properties (such as strength, toughness, and fatigue resistance), simple construction and shaping, and low costs (Popov 2004). Polymer matrix composites make equipment such as tennis and squash racquets, golf clubs, fishing clubs, skis, and bicycles. For example, in the grip of a golf club, the carbon and boron fibers are arranged in different directions and at different angles (Petousis *et al*. 2023). Their strength and rigidity make the grip capable of withstanding all tensile, compressive, torsional, and bending forces (Dai 2002). The properties of the primer depend on the microstructure, the manufacturing method, and thermal and mechanical post-

treatment. The drape is a polymeric, metallic, or ceramic composite (Dresselhaus *et al*. 1995). Tokyo-based Maruman used Hanjo Chemicals fullerenes to make its golf clubs' ends (Haddon 2002). A new titanium fullerene material is used for the tips of New Majesty golf clubs. The new wood is 12% more flexible than conventional titanium. Its hardness is 36° higher, its head has 20% more flexibility, and its ball distance has increased by 15 meters (Ebbesen 1994). Another company has used nanotechnology to extend the life of a golf club. This wood was made by introducing nanoscale carbon and using carbon nanotubes (Lin *et al*. 2004). These sticks are usually made from fibers derived from graphite and carbon (Iijima 2002). This company has combined carbon nanotubes with ordinary carbon fibers to create strong golf clubs. This compound is five times stronger and more supple than traditional carbon (Sun *et al*. 2023). Although the flexing of the frame on impact slows the ball speed of a regular golf club, these golf clubs have a good response at that moment of the shot, thanks to the durable materials (Agasti *et al*. 2022). In this research, the toughness of the polymer composite was improved by using carbon nanotubes and glass fibers as reinforcement. The ultrasonic method was used to mix nanoparticles in the field, and glass fiber was also used by the manual layering method. The sample was prepared according to the 5045 standards, and the bending test was performed. The toughness of the composite was calculated using the calculations below the diagram and the relationships (Hua *et al*. 2022, Yang *et al*. 2022b, Liu *et al*. 2023, Zhao *et al*. 2023, Wu *et al*. 2024b). The results showed that unreinforced epoxy was brittle, and its breaking energy was 1.64 joules. By adding reinforcing nanoparticles to epoxy, the fracture energy increased. In the hybrid case (carbon nanotubes and glass fibers together), the highest failure rate was obtained (Ehyaei *et al*. 2017, Ghadiri *et al*. 2017a, b, Shivanian *et al*. 2017).

While the extensive literature review provides a comprehensive overview of polymer matrix composites (PMCs) and their various reinforcements, including glass, carbon, and aramid fibers, it is evident that a specific gap exists in the exploration of nanocomposite applications in sports equipment, particularly in the context of sports balls. The current body of knowledge primarily focuses on the traditional uses of PMCs in items like tennis racquets, golf clubs, and bicycles. However, the study falls short in addressing the nuances of nanocomposite-enhanced sports balls, specifically soccer balls, where the unique demands of motion and impact are paramount.

The existing research predominantly emphasizes the use of carbon nanotubes and graphene in enhancing the toughness of polymer composites, with applications extending to golf club manufacturing. Nevertheless, a clear gap emerges concerning the direct investigation of these nanocomposites in soccer ball production. The novelty of this work lies in its explicit examination of how nanocomposites, including carbon nanotubes and glass fibers, influence the toughness of polymer composites specifically tailored for soccer balls. By integrating ultrasonic mixing of nanoparticles and manual layering of glass fibers, this research pioneers a methodology to improve the toughness of polymer composites for sports balls, thereby addressing a distinct void in the literature and contributing to the advancement of nanotechnology in sports equipment design. The study's outcomes, as evidenced by the bending test results and fracture energy calculations, shed light on the practical implications of incorporating nanocomposites in sports ball production, bringing a fresh perspective to the field and paving the way for future developments in high-performance sports equipment.

2. Experimental

2.1 Materials and devices

In this experiment, epoxy resin under the brand name Iponat 503, a bisphenol-based resin, and a polyamine hardening agent named Iponat 565, manufactured by Bitex Turkey, were employed. The carbon nanotubes utilized were functional multi-walled carbon nanotubes sourced from the United States, boasting a purity level of 97%. This resin and hardener combination exhibits a gelation time of approximately 40 minutes, allowing for effective air bubble removal. To enhance the epoxy resin, short glass fibers of type E, with a diameter ranging from 16 to 24 micrometers and an average length of 5 mm, were incorporated. These glass fibers originated from Crystal Tar Company. Additionally, nano-silica powder with a commercial code of 200, a product of South Kisukre Company, characterized by a spherical geometric shape with a diameter ranging from 8 to 40 nanometers, was introduced. The nano-silica powder exhibited a surface area of 200 mg and a density ranging from 100 to 50. To facilitate the solubilization of carbon nanotubes in acetone and to ensure optimal dispersion of nanotube particles in the resin, an ultrasonic device equipped with a probe was employed (Fan *et al*. 2020, Sheng *et al*. 2021).

2.2 Calculation of the percentage of carbon nanotubes required

The carbon content incorporated into the composite was selected at weight percentages of 1%, 0.5%, and 0.25%, respectively. Following the determination of the required quantity of nanotubes through calculations, an epoxy sample without reinforcement was prepared to ascertain the corresponding weight percentage used.

2.3 Prototyping

Initially, the fibers and epoxy resin were manually mixed for a duration of 5 minutes before introducing the hardener, yielding glass fiber epoxy resin composite materials. Subsequently, the samples underwent a 25-minute vacuuming process to eliminate air bubbles formed within the mixture. In the samples containing nano-silica, the process involved mixing the nano-silica powder with epoxy resin, followed by stirring the mixture with an electric stirrer operating at a speed of 3000rpm for 20 minutes. The next step involved subjecting the mixture to

ultrasonic waves for 20 minutes using an ultrasonic device with a power of 150 kW/cm^2. This step aimed to ensure the well-dispersion of nanoparticles, resulting in the attainment of a homogeneous mixture.

2.4 Mixing nanotubes and resin

To blend the resin and carbon nanotubes, acetone was introduced to the carbon nanotubes to elevate their weight to five grams. Subsequently, the acetone solution and carbon nanotubes underwent mixing using an ultrasonic device set at a power level of 50, with the solution stirred for 5 minutes. Following this, the resin was added to the solution, and manual mixing ensued. The resultant solution underwent additional mixing in the ultrasonic device. The ultrasonic solution process comprised 5 cycles, each lasting 10 minutes, with a power setting of 100 watts.

2.5 Mold manufacturing

A standard mold is needed for loading and making samples. Among the features of a standard mold are resistance to erosion, no change in shape when the temperature rises, and ease of sample removal from the mold. Due to the high use of the mold and the effect of erosion, a metal frame was chosen to have the lowest amount of mold erosion. In addition, due to the large thickness of the sample and the ease of removing the sample from the mold, a two-piece mold was preferred. Before loading, the mold was cleaned, and the surface of the mold was lubricated so that the sample could be removed from the mold (Yang *et al*. 2021, Lu *et al*. 2022, Zhang *et al*. 2023a).

2.6 Fabrication of epoxy samples reinforced with glass fibers

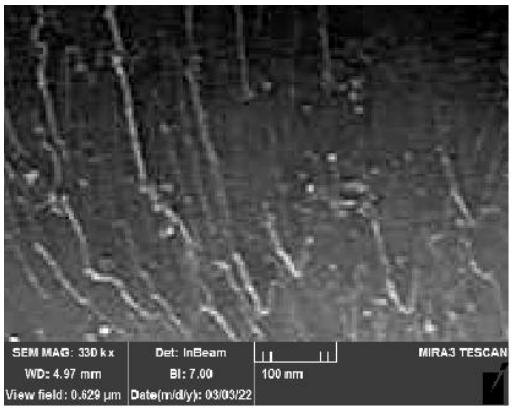
Once achieving a homogeneous solution of hardener and resin, a bottom solution layer was poured, followed by placing a layer of glass fiber upon it. The glass fiber layer was then coated with the solution using a distinctive roller. Subsequently, another layer of the solution was poured over the glass fiber, and another layer of glass fiber was added. This process continued iteratively until the mold was fully filled.

2.7 Making unreinforced epoxy samples

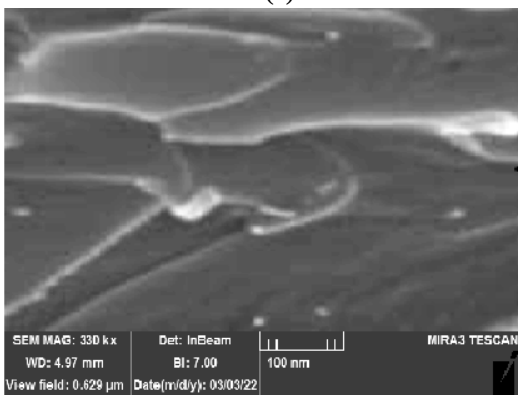
The resin and hardener were mixed manually with a ratio of 2:1, and after reaching a homogeneous solution, the solution was poured into the mold.

2.8 Exams

A cold-water bath was employed to prevent an increase in resin temperature during ultrasonic waves. Subsequently, the mentioned compound was blended with the hardener and placed in a vacuum for 20 minutes to assess the tensile properties of the glass fibers. Mechanical uniaxial tension was applied in the creation of the samples. In this testing process, nanoparticles were initially added to the field. After achieving widespread scattering, they underwent 20 minutes of ultrasound treatment facilitated by an electric stirrer to evaluate the mechanical properties of composite materials, including strength, stretching elastic modulus, and elongation until rupture. ASTM 3039 standards were followed, incorporating the addition of glass fibers to a metal mold, manually stirring to create tensile samples. Following the addition of the hardener, the resultant compound was designed and placed under vacuum for 20 minutes. This metal mold, constructed from steel, was positioned for the samples. The duration of sonication for the samples was determined through trial and error based on the mold's specifications. For curing, each sample was inverted after molding to secure the mold plate, accompanied by two other plates resembling shoes with three grooves each for the placement of thermal heaters, facilitating sample baking. The mold featured five rectangular holes measuring 2.5 cm x 25 cm and 2.5 mm thick. To regulate the heaters' temperature in the mold, an electric thermocouple and an automatic disconnect switch were utilized, enabling temperature adjustment up to 400 degrees. The German Zonic Roel model Z100 machine conducted the tensile test, with the moving speed of the movable jaw set at 2 mm/min. Additionally, to prevent potential sample slipping at the beginning of stretching, a preload of 1 Newton was applied to the machine, and the reported results represent the average of multiple measurements.



(a)



(b)

Fig. 1 SEM images of fracture surface (a) unreinforced epoxy (b) glass fiber epoxy

3. Results and discussion

3.1 Tensile strength

As seen from the scanning electron microscope images in Fig. 1, silica nanoparticles are well dispersed in the field. This uniform distribution and the filling of pores resulting from molecular defects by these nanoparticles have increased the tensile strength. The images indicate that by increasing the weight percentage of silica nanoparticles to 1% by weight, the tendency of nanoparticles to become lumpy causes the formation of clusters. These clusters can act as a defect. The concentration of stress due to the presence of clusters can reduce the tensile strength. This is while the glass fibers tend to come out of the ground due to their low adhesion and continuously reduce the tensile strength. Fig. 1(a) shows the fracture surface of unreinforced epoxy. The fracture surface obtained from this shape is smooth and without waves, which indicates a brittle fracture in the material. Fig. 1(b) is the fracture surface of epoxy reinforced with glass fibers. A rough and wavy surface around the glass fibers indicates a soft failure in this area. The fracture surface is undulating and smooth in areas with no glass fibers.

3.2 Examining the failure behavior of the samples

The displacement load diagram of the bending test for different epoxy composite samples can be seen in Fig. 2. In the unreinforced epoxy sample, the crack created in the sample grows with minimal force, and failure occurs. The graph of this material is crisp, and its elastic acceleration is high. After passing through the elastic zone, the sample fails and does not experience the plastic zone. In the sample reinforced with glass fibers, the crack grows by applying force, and fracture occurs. Due to the presence of glass fibers in the sample and the excellent bond that has been established between the fibers and the epoxy, it requires more energy than the empty epoxy to break the sample, as the force increases, the fiber breaks, and the sample breaks. The fracture of the sample is entirely elastic, and it breaks when it reaches the plastic part of the sample. Crack growth in the epoxy sample reinforced with 0.25% carbon nanotube needs more energy than the non-reinforced epoxy sample. The presence of nanoparticles and their dispersion in the field has caused the breaking behavior of the material to change from brittle to soft and the material to undergo plastic deformation. In the epoxy sample reinforced with 0.5% of carbon nanotubes, it can be seen that with the increase in the percentage of carbon, the material shows a softer behavior compared to the case of 0.25%. The increase in the plastic part of the diagram indicates the increase in the ability to change the shape of the material before the moment of failure. In the figure, the change of dimensions of the sample before failure is quite evident. By increasing the percentage of carbon nanotubes up to 1%, composite properties tend towards brittle behavior. As it is known, the plastic part of the diagram is reduced compared to other carbon nanotube epoxy samples, and the failure in the material is done in a brittle manner. The reason for this is the excessive use of carbon nanotubes, which causes the accumulation of nanoparticles and the formation of agglomerates. Agglomerates are considered high-energy and suitable places for crack growth, therefore, they help crack growth and cause brittle failure in the material. The material tends to soft fracture and plastic deformation in hybrid samples with two reinforcements. In fact, in Turkish hybrid composite, in addition to overcoming nanoparticles, it must also overcome glass fibers, therefore, double force is needed to break. Even with the crack growth in the material, the material is still resistant due to the presence of glass fibers, and the failure of the sample did not occur.

3.3 Elasticity

The slope of the elastic part in each material indicates the elasticity coefficient of that material. The higher this slope is, the more brittle the material is, and it breaks faster when the load is applied. The slope of the elastic part was calculated for the laboratory samples. It can be seen graphically in Fig. 3. According to the graph, it can be concluded that the highest slopes are related to glass fiber epoxy samples (EG) at the rate of 703 and unreinforced epoxy (E) at the rate of 553. The high degree of elasticity in these materials indicates their brittle behavior. The crack will grow in these samples, and failure will occur. With the addition of carbon nanotubes to unreinforced epoxy, we witness a significant decrease in the elastic slope. As the percentage of nanoparticles increases, the material becomes softer, and the slope decreases. Among the epoxy composite samples reinforced with carbon nanotubes, the lowest elastic slope is related to the epoxy composite sample with 0.5%, which occurs due to agglomerate formation. In the samples of hybrid composite (EG-CNT), the amount of slope reaches its lowest level, and it can be concluded that these materials have very high deformability.

3.4 Investigation of crack growth in samples

The nature of crack growth in samples can be altered before failure based on the type of failure, whether it is soft or brittle. In samples experiencing brittle failure, the crack grows minimally, and failure occurs suddenly. Conversely, in samples with a softer failure, the crack tends to grow more, spreading across the surface of the sample. As evident, the unreinforced sample exhibits only slight crack growth before failure. In contrast, the epoxy sample reinforced with 0.5% carbon nanotubes displays extensive crack propagation throughout the sample, affecting the surrounding crack area as well.

3.5 Calculation of fracture energy using the area under the diagram

Fracture energy is the amount of force that IC can withstand before breaking. In order to calculate fracture energy, a crack is formed on the sample, which is then bent to calculate the fracture energy. The fracture energy of each material depends on the type of fracture it is accelerated. Materials with brittle fractures have low fracture energy, the

Table 1 Fracture energy calculated using the area under the graph

Energy failure	Sample
1.56	Epoxy
4.753	Glass fiber epoxy
2.12	Epoxy 0.25% carbon nanotube
5.09	Epoxy 0.25% carbon nanotube + glass fiber
2.45	Epoxy 0.5% carbon nanotube
7.85	Epoxy 0.5% carbon nanotube + glass fiber
1.29	Epoxy 1% carbon nanotube

more brittle the fracture occurs, the higher the fracture energy. In this method, the surface under the load-displacement diagram was calculated. This work was done using Excel software, the results can be seen in Table 1.

The fracture energy calculated by both methods is compared in Fig. 4, where these two methods are as follows:

• The first method: using the area under the graph (Fig. 2).

• The second method: using relationships.

Calculating fracture energy requires dividing it into elastic and plastic parts using load-displacement relationships. In this case, the total fracture energy equals the sum of 'J_p+J_{el}'. Calculating the energy of the elastic part directly with Eq.(1) and calculating the energy of the plastic part directly with its mass is also possible.

$$J_{el} = K^2 \frac{(1 - \upsilon^2)}{E} \tag{1}$$

In this regard, 'K' is the toughness of the material, 'υ' is Poisson's ratio, which is considered equal to 0.5, and 'E' is the elastic modulus of the material. The fracture toughness of materials (K_Q) can be calculated using Eq. (2).

$$K_Q = \frac{P_Q S}{BW^{3/2}} f(a/w) \tag{2}$$

This relationship has 'P_Q' as the critical force at the point where the plastic part of the diagram begins, 'S' as the length of the sample (mm), 'B' as the width, 'W' as the thickness, and $f(\frac{a}{w})$ as the coefficient which calculated as follows:

$$f(a/w) = 6x^{0.5} \times [1.99 - x(1-x)(2.15 - 3.93x + 2.7x^2)] \times \frac{1}{(1+2x)} \times \frac{1}{(1-x)^{1.5}} \tag{3}$$

The coefficient $f(\frac{a}{w})$ is reported to be 2.66 in various sources, so the toughness of the material can be determined by having a critical value. As can be seen, the values obtained from both methods are close to each other. In both cases, unreinforced epoxy has the lowest amount of fracture energy. In glass fiber epoxy, the fracture energy increases due to the use of glass fiber as a reinforcement and the need for energy to break the fiber. The use of nanoparticles as reinforcement increases the softness and malleability of epoxy. The epoxy sample reinforced with a 1% carbon nanotube experiences a lower fracture energy than the non-reinforced epoxy sample due to the accumulation of nanoparticles and agglomerate formation. Hybrid samples have the highest amount of fracture energy, which is due to the simultaneous use of both reinforcements.

The reason for this increase in toughness is the use of glass fibers as a reinforcing phase. Glass fiber can withstand much stress and increases the toughness of the material.

4. Conclusions

In wrapping up this study, our focus has centered on the exploration of nanocomposite materials, specifically delving into their application in constructing golf clubs and their wider implications in the fabrication of physical education equipment. Employing advanced techniques like infrared spectroscopy and scanning electron microscopy, our examination has been thorough, scrutinizing the surface chemistry and morphology of epoxy nanocomposites. Additionally, a comprehensive analysis unfolded, assessing a spectrum of properties, encompassing thermal, mechanical, viscoelastic, and conductive facets of these nanocomposites. A notable milestone in our research is the successful prevention of carbon nanotube accumulation within the epoxy matrix, achieved through inventive surface modification techniques. This accomplishment not only averted accumulation but also enhanced the distribution of carbon nanotubes, promising substantial improvements in interfacial interactions, thermal stability, mechanical properties, and electrical conductivity.

The integration of functionalized nanoparticles, in conjunction with a dissolution process in acetone and the utilization of an ultrasonic stirrer, played pivotal roles in ensuring an optimal dispersion of nanoparticles within the resin. This meticulous approach contributed to uniformity and effectiveness in our composite material. The transformative impact of nanocomposites on the mechanical behavior of the epoxy resin is clearly evident, witnessed as the initial brittle characteristics underwent a notable transformation to a softer state with the addition of nanoparticles. This alteration effectively addressed the inherent brittleness and low toughness of the epoxy resin. Additionally, the synergy between glass fibers and nanoparticles emerged as a promising avenue to achieve peak material toughness.

An intriguing observation unfolded in the fracture surface characteristics. Initially displaying smooth features indicative of brittle fracture in unreinforced epoxy, the introduction of reinforcements induced a transition to a wavy state. This signifies a softer fracture with material deformation, underscoring the potential of nanocomposites to fundamentally alter the mechanical response of materials. In essence, this research contributes invaluable insights into the realm of nanocomposite materials, showcasing their transformative potential in elevating the mechanical and thermal properties of epoxy resins. The successful application of these materials in sports equipment, notably golf clubs,

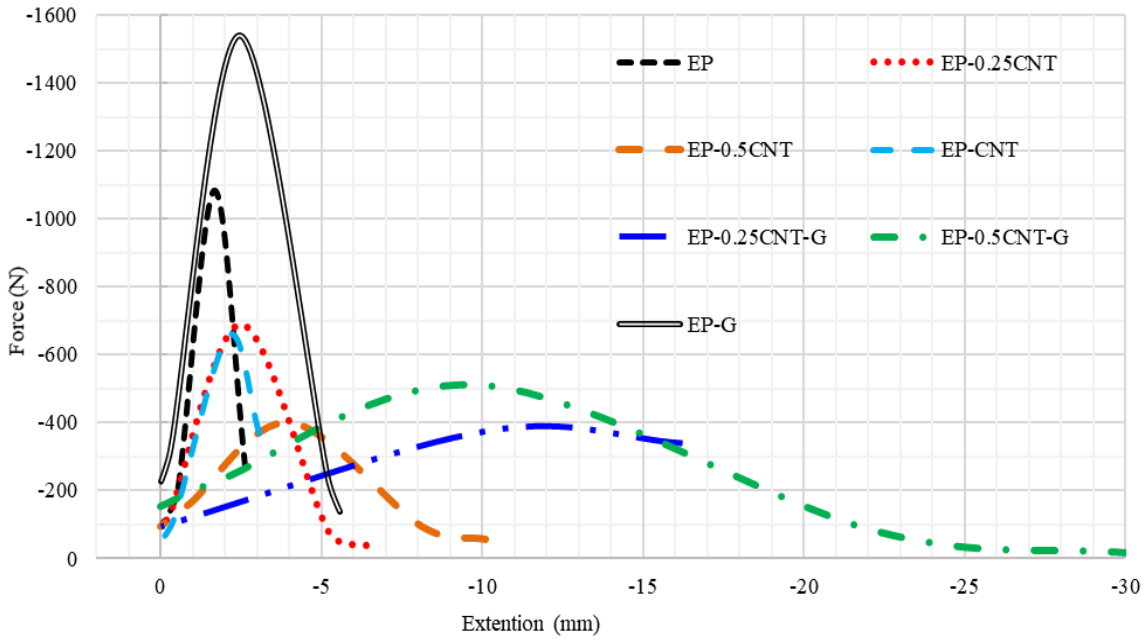


Fig. 2 Bending diagram of composite samples

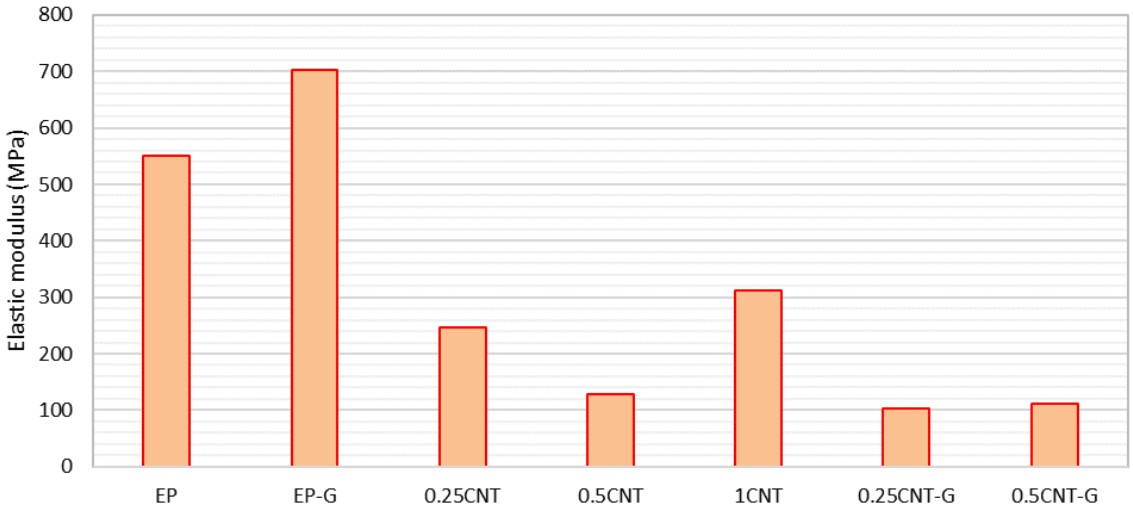


Fig. 3 Experimental Elasticity obtained from epoxy composite samples

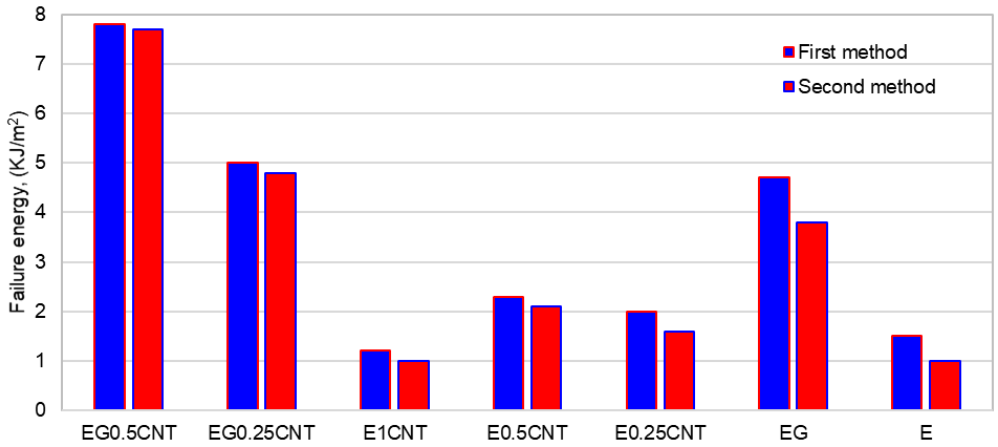


Fig. 4 Comparison of fracture energy calculated by two methods, the first method: according to the area under the graphs, and the second method, based on mathematical presented equations

not only paves the way for broader applications in physical education equipment but promises advancements in durability, performance, and overall material integrity. These findings propel continued exploration and utilization of nanocomposites across diverse applications, emphasizing their significance in advancing practical uses for advanced materials.

References

Agasti, N., Gautam, V., Priyanka, Manju, Pandey, N., Genwa, M., Meena, P.L., Tandon, S. and Samantaray, R. (2022), "Carbon nanotube based magnetic composites for decontamination of organic chemical pollutants in water: A review", *Appl. Surf. Sci. Adv.*, **10**, 100270. https://doi.org/10.1016/j.apsadv.2022.100270.

Aguilar-Ferrer, D., Szewczyk, J. and Coy, E. (2022), "Recent developments in polydopamine-based photocatalytic nanocomposites for energy production: Physico-chemical properties and perspectives", *Catal. Today*, **397-399**, 316-349. https://doi.org/10.1016/j.cattod.2021.08.016.

Ajayan, P.M. and Zhou, O.Z. (2001), *Applications of Carbon Nanotubes*, Springer Berlin Heidelberg, Berlin, Heidelberg.

Ashfaq, A., Khursheed, N., Fatima, S., Anjum, Z. and Younis, K. (2022), "Application of nanotechnology in food packaging: Pros and Cons", *J. Agric. Food Res.*, **7**, 100270. https://doi.org/10.1016/j.jafr.2022.100270.

Azimi, M., Mirjavadi, S.S., Shafiei, N. and Hamouda, A.M.S. (2016), "Thermo-mechanical vibration of rotating axially functionally graded nonlocal Timoshenko beam", *Appl. Phys. A.*, **123**(1), 104. https://doi.org/10.1007/s00339-016-0712-5.

Cao, C., Wang, J., Kwok, D., Cui, F., Zhang, Z., Zhao, D., Li, M.J. and Zou, Q. (2022), "webTWAS: A resource for disease candidate susceptibility genes identified by transcriptome-wide association study", *Nucl. Acids Res.*, **50**(D1), D1123-D1130. https://doi.org/10.1093/nar/gkab957.

Cao, Y., Niu, B., Wang, H. and Zhao, X. (2024), "Event-based adaptive resilient control for networked nonlinear systems against unknown deception attacks and actuator saturation", *Int. J. Robust Nonlinear Control.*, Research Article. https://doi.org/10.1002/rnc.7231.

Cheng, Q., Ali, H.E. and Albaijan, I. (2023), "Optimization of the cross-section regarding the stability of nanostructures according to the dynamic analysis", *Adv. Concr. Constr.*, **15**(4), 215-228. https://doi.org/10.12989/acc.2023.15.4.215.

Cui, R., Jiang, K., Yuan, M., Cao, J., Li, L., Tang, Z. and Qin, Y. (2020), "Antimicrobial film based on polylactic acid and carbon nanotube for controlled cinnamaldehyde release", *J. Mater. Res. Technol.*, **9**(5), 10130-10138. https://doi.org/10.1016/j.jmrt.2020.07.016.

Dai, H. (2002), "Carbon nanotubes: Opportunities and challenges", *Surf. Sci.*, **500**(1), 218-241. https://doi.org/10.1016/S0039-6028(01)01558-8.

Dai, Y., Jiang, Z., Chen, K.Y., Zuo, D., Ali, H.E. and Albaijan, I. (2023), "Geometry impact on the stability behavior of cylindrical microstructures: Computer modeling and application for small-scale sport structures", *Steel Compos. Struct.*, **48**(4), 443. https://doi.org/10.12989/scs.2023.48.4.443.

Dresselhaus, M.S., Dresselhaus, G. and Saito, R. (1995), "Physics of carbon nanotubes", *Carbon*, **33**(7), 883-891. https://doi.org/10.1016/0008-6223(95)00017-8.

Dzenis, Y. (2008), "Structural nanocomposites", *Science*, **319**(5862), 419-420. https://doi.org/10.1126/science.1151434.

Ebbesen, T.W. (1994), "Carbon nanotubes", *Ann. Rev. Mater. Sci.*, **24**(1), 235-264. https://doi.org/10.1146/annurev.ms.24.080194.001315.

Ebrahimi, F., Shafiei, N., Kazemi, M. and Mousavi Abdollahi, S.M. (2017), "Thermo-mechanical vibration analysis of rotating nonlocal nanoplates applying generalized differential quadrature method", *Mech. Adv. Mater. Struct.*, **24**(15), 1257-1273. https://doi.org/10.1080/15376494.2016.1227499.

Ehyaei, J., Akbarshahi, A. and Shafiei, N. (2017), "Influence of porosity and axial preload on vibration behavior of rotating FG nanobeam", *Adv. Nano Res.*, **5**(2), 141. https://doi.org/10.12989/anr.2017.5.2.141.

Fan, W., Zhang, Q. and Wang, Y. (2013), "Semiconductor-based nanocomposites for photocatalytic H2 production and CO2 conversion", *Phys. Chem. Chem. Phys.*, **15**(8), 2632-2649. https://doi.org/10.1039/C2CP43524A.

Fan, X., Wei, G., Lin, X., Wang, X., Si, Z., Zhang, X., Shao, Q., Mangin, S., Fullerton, E., Jiang, L. and Zhao, W. (2020), "Reversible switching of interlayer exchange coupling through atomically thin VO2 via electronic state modulation", *Matter*. **2**(6), 1582-1593. https://doi.org/10.1016/j.matt.2020.04.001.

Feng, S., Du, X., Luo, J., Zhuang, Y., Wang, J. and Wan, Y. (2023), "A review on facilitated transport membranes based on π-complexation for carbon dioxide separation", *Sep. Purif. Technol.*, **309** 122972. https://doi.org/10.1016/j.seppur.2022.122972.

Fito, J., Kefeni, K.K. and Nkambule, T.T.I. (2022), "The potential of biochar-photocatalytic nanocomposites for removal of organic micropollutants from wastewater", *Sci. Total Environ.*, **829**, 154648. https://doi.org/10.1016/j.scitotenv.2022.154648.

Fu, L., Li, J., Yang, J., Liu, Y., He, C. and Chen, Y. (2023), "Purification process and reduction of heavy metals from industrial wastewater via synthesized nanoparticle for water supply in swimming/water sport", *Adv. Nano Res.*, **15**(5), 441-449. https://doi.org/10.12989/anr.2023.15.5.441.

Gan, J., Li, F., Li, K., Li, E. and Li, B. (2023), "Dynamic failure of 3D printed negative-stiffness meta-sandwich structures under repeated impact loadings", *Compos. Sci. Technol.*, **234**, 109928. https://doi.org/10.1016/j.compscitech.2023.109928.

Ghadiri, M., Hosseini, S.H.S. and Shafiei, N. (2016a), "A power series for vibration of a rotating nanobeam with considering thermal effect", *Mech. Adv. Mater. Struct.*, **23**(12), 1414-1420. https://doi.org/10.1080/15376494.2015.1091527.

Ghadiri, M., Shafiei, N. and Alavi, H. (2017a), "Thermo-mechanical vibration of orthotropic cantilever and propped cantilever nanoplate using generalized differential quadrature method", *Mech. Adv. Mater. Struct.*, **24**(8), 636-646. https://doi.org/10.1080/15376494.2016.1196770.

Ghadiri, M., Shafiei, N. and Alireza Mousavi, S. (2016b), "Vibration analysis of a rotating functionally graded tapered microbeam based on the modified couple stress theory by DQEM", *Appl. Phys. A*, **122**(9), 837. https://doi.org/10.1007/s00339-016-0364-5.

Ghadiri, M., Shafiei, N. and Babaei, R. (2017b), "Vibration of a rotary FG plate with consideration of thermal and Coriolis effects", *Steel Compos. Struct.*, **25**(2), 197-207. https://doi.org/10.12989/scs.2017.25.2.197.

Ghadiri, M., Shafiei, N. and Hossein Alavi, S. (2017c), "Vibration analysis of a rotating nanoplate using nonlocal elasticity theory", *J. Solid Mech.*, **9**(2), 319-337.

Ghadiri, M., Shafiei, N., Salekdeh, S.H., Mottaghi, P. and Mirzaie, T. (2016c), "Investigation of the dental implant geometry effect on stress distribution at dental implant–bone interface", *J. Brazil. Soc. Mech. Sci. Eng.*, **38**(2), 335-343. https://doi.org/10.1007/s40430-015-0472-8.

Guan, S. (2023), "Systematic test on the effectiveness of MEMS nano-sensing technology in monitoring heart rate of Wushu exercise", *Adv. Nano Res.*, **15**(2), 155-163. https://doi.org/10.12989/anr.2023.15.2.155.

Haddon, R.C. (2002), "Carbon nanotubes", *Accounts Chem. Res.*,

35(12), 997-997. https://doi.org/10.1021/ar020259h.

He, L. and Deng, Q. (2023), "Construction of sports engineering structures with high resistance to improve the quality of sports training", *Struct. Eng. Mech.*, **86**(2), 211-220. https://doi.org/10.12989/sem.2023.86.2.211.

Hua, Y., Li, F., Hu, N. and Fu, S.Y. (2022), "Frictional characteristics of graphene oxide-modified continuous glass fiber reinforced epoxy composite", *Compos. Sci. Technol.*, **223**, 109446. https://doi.org/10.1016/j.compscitech.2022.109446.

Huang, S., Zong, G., Zhao, N., Zhao, X. and Ahmad, A.M. (2024), "Performance recovery-based fuzzy robust control of networked nonlinear systems against actuator fault: A deferred actuator-switching method", *Fuzzy Sets Syst.*, **480**, 108858. https://doi.org/10.1016/j.fss.2024.108858.

Iijima, S. (2002), "Carbon nanotubes: Past, present, and future", *Physica B*, **323**(1), 1-5. https://doi.org/10.1016/S0921-4526(02)00869-4.

Jia, S., Niu, X., Jia, F. and Mahmoudi, T. (2023), "Advantages and disadvantages of renewable energy-oil-environmental pollution-from the point of view of nanoscience", *Adv. Concr. Constr.*, **16**(1), 69-78. https://doi.org/10.12989/acc.2023.16.1.069.

Jiang, H., Xie, Y., Zhu, R., Luo, Y., Sheng, X., Xie, D. and Mei, Y. (2023), "Construction of polyphosphazene-functionalized Ti3C2TX with high efficient flame retardancy for epoxy and its synergetic mechanisms", *Chem. Eng. J.*, **456**, 141049. https://doi.org/10.1016/j.cej.2022.141049.

Jin, H., Zhang, B. and Duan, X. (2023), "Impact of nanocomposite material to counter injury in physical sport in the tennis racket", *Adv. Nano Res.*, **14**(5), 435-442. https://doi.org/10.12989/anr.2023.14.5.435.

Komarneni, S. (1992), "Feature article, Nanocomposites", *J. Mater. Chem.*, **2**(12), 1219-1230. https://doi.org/10.1039/JM9920201219.

Kong, H., Luo, X., Zhang, P., Feng, J., Li, P., Hu, W., Wang, X. and Liu, X. (2023), *Self-Healing, Solvent-Free, Anti-Corrosion Coating Based on Skin-like Polyurethane/Carbon Nanotubes Composites with Real-Time Damage Monitoring*,

Krysko, A.V., Awrejcewicz, J., Bodyagina, K.S., Zhigalov, M.V. and Krysko, V.A. (2021a), "Mathematical modeling of physically nonlinear 3D beams and plates made of multimodulus materials", *Acta Mechanica*, **232**(9), 3441-3469. https://doi.org/10.1007/s00707-021-03010-8.

Krysko, A.V., Awrejcewicz, J., Pavlov, S.P., Bodyagina, K.S. and Krysko, V.A. (2019), "Topological optimization of thermoelastic composites with maximized stiffness and heat transfer", *Compos. Part B Eng.*, **158**, 319-327. https://doi.org/10.1016/j.compositesb.2018.09.047.

Krysko, A.V., Awrejcewicz, J., Zhigalov, M.V., Bodyagina, K.S. and Krysko, V.A. (2021b), "On 3D and 1D mathematical modeling of physically nonlinear beams", *In. J. Non-Linear Mech.*, **134** 103734. https://doi.org/10.1016/j.ijnonlinmec.2021.103734.

Krysko, A.V., Awrejcewicz, J., Zhigalov, M.V., Pavlov, S.P. and Krysko, V.A. (2017), "Nonlinear behaviour of different flexible size-dependent beams models based on the modified couple stress theory. Part 1: Governing equations and static analysis of flexible beams", *Int. J. Non-Linear Mech.*, **93**, 96-105. https://doi.org/10.1016/j.ijnonlinmec.2017.03.005.

Krysko, A.V., Kalutsky, L.A. and Krysko, V.A. (2024), "Stress-strain state of a porous flexible rectangular FGM size-dependent plate subjected to different types of transverse loading: Analysis and numerical solution using several alternative methods", *Thin Wall. Struct.*, **196**, 111512. https://doi.org/10.1016/j.tws.2023.111512.

Lau, J.S. and Li, Z. (2023), "Human functions in innovation and sustainable marketing", *Adv. Concr. Constr.*, **16**(2), 97. https://doi.org/10.12989/acc.2023.16.2.097.

Lee, S.H., Pumprueg, S., Moudgil, B. and Sigmund, W. (2005), "Inactivation of bacterial endospores by photocatalytic nanocomposites", *Colloid Surfaces B Biointerf.*, **40**(2), 93-98. https://doi.org/10.1016/j.colsurfb.2004.05.005.

Li, F., Gan, J., Zhang, L., Tan, H., Li, E. and Li, B. (2024), "Enhancing impact resistance of hybrid structures designed with triply periodic minimal surfaces", *Compos. Sci. Technol.*, **245**, 110365. https://doi.org/10.1016/j.compscitech.2023.110365.

Li, J., Bin, N., Guo, F., Gao, X., Chen, R., Yao, H. and Zhou, C. (2023a), "Analysis on the influence of sports equipment of fiber reinforced composite material on social sports development", *Adv. Nano Res.*, **15**(1), 49-57. https://doi.org/10.12989/anr.2023.15.1.049.

Li, Q., Hu, X., Perkins, P. and Ren, T. (2023b), "Antimicrobial film based on poly(lactic acid) and natural halloysite nanotubes for controlled cinnamaldehyde release", *Int. J. Biol. Macromol.*, **224**, 848-857. https://doi.org/10.1016/j.ijbiomac.2022.10.171.

Li, X., Ali, H.E. and Albaijan, I. (2023c), "TiO 2-containing nanocomposite structure: Application and investigation in shoes sports medical soles in physical activities", *Adv. Nano Res.*, **15**(4), 329-337. https://doi.org/10.12989/anr.2023.15.4.329.

Li, Y., Li, M., Kong, X., Baniasadi, A., Shaker, A.H. and Ali, H.E. (2023d), "Psychological capital to foster employee creativity in nanotechnology companies: the mediating role of JS and CSR", *Adv. Nano Res.*, **15**(3), 277-283. https://doi.org/10.12989/anr.2023.15.3.277.

Li, Z. (2023), "Resistance of concrete made of fibers in weight lifting slabs against impact in sports training", *Struct. Eng. Mech.*, **86**(3), 325-336. https://doi.org/10.12989/sem.2023.86.3.325.

Li, Z., Peng, S. and Chen, G. (2023e), "Research on safety assessment and application effect of nanomedical products in physical education", *Adv. Nano Res.*, **15**(3), 253-261. https://doi.org/10.12989/anr.2023.15.3.253.

Lin, Y., Taylor, S., Li, H., Fernando, K.A.S., Qu, L., Wang, W., Gu, L., Zhou, B. and Sun, Y.P. (2004), "Advances toward bioapplications of carbon nanotubes", *J. Mater. Chem.*, **14**(4), 527-541. https://doi.org/10.1039/B314481J.

Liu, J., Zhou, Y., Lu, J., Cai, R., Zhao, T., Chen, Y., Zhang, M., Lu, X. and Chen, Y. (2023), "Injectable, tough and adhesive zwitterionic hydrogels for 3D-printed wearable strain sensors", *Chem. Eng. J.*, **475**, 146340. https://doi.org/10.1016/j.cej.2023.146340.

Lu, Z.Q., Liu, W.H., Ding, H. and Chen, L.Q. (2022), "Energy transfer of an axially loaded beam with a parallel-coupled nonlinear vibration isolator", *J. Vib. Acoust.*, **144**(5). https://doi.org/10.1115/1.4054324.

Ma, Z., Qi, J., Xun, W. and Li, Y. (2023), "Sports injury treatment and sports rehabilitation employing the Nanoparticles containing zinc oxide", *Adv. Nano Res.*, **15**(1), 67-74. https://doi.org/10.12989/anr.2023.15.1.067.

Melinte, V., Stroea, L. and Chibac-Scutaru, A.L. (2019), "Polymer nanocomposites for photocatalytic applications", *Catalysts*, **9**(12), 986. https://doi.org/10.3390/catal9120986

Moniruzzaman, M. and Winey, K.I. (2006), "Polymer nano-composites containing carbon nanotubes", *Macromolecules*, **39**(16), 5194-5205. https://doi.org/10.1021/ma060733p.

Mousavi, S.M., Shafiei, N. and Dadvand, A. (2017), "Numerical simulation of subsonic turbulent flow over NACA0012 airfoil: Evaluation of turbulence models", *Sigma J. Eng. Natural Sci.*, **35**(1), 133-155.

Omidi, S., Oskooee, M.B. and Shafiei, N. (2013), "Finite element analysis of an ultra-fine grained Titanium dental implant covered by different thicknesses of hydroxyapatite layer", *Indian J. Dent.*, **4**(1), 1-4. https://doi.org/10.1016/j.ijd.2012.10.002.

Paul, D.R. and Robeson, L.M. (2008), "Polymer nanotechnology:

Nanocomposites", *Polymer*, **49**(15), 3187-3204. https://doi.org/10.1016/j.polymer.2008.04.017.

Petousis, M., Ninikas, K., Vidakis, N., Mountakis, N. and Kechagias, J.D. (2023), "Multifunctional PLA/CNTs nano-composites hybrid 3D printing integrating material extrusion and CO2 laser cutting", *J. Manuf. Proc.*, **86**, 237-252. https://doi.org/10.1016/j.jmapro.2022.12.060.

Petronella, F., Truppi, A., Ingrosso, C., Placido, T., Striccoli, M., Curri, M.L., Agostiano, A. and Comparelli, R. (2017), "Nanocomposite materials for photocatalytic degradation of pollutants", *Catalysis Today*, **281**, 85-100. https://doi.org/10.1016/j.cattod.2016.05.048.

Popov, V.N. (2004), "Carbon nanotubes: properties and application", *Mater. Sci. Eng. Rep.*, **43**(3), 61-102. https://doi.org/10.1016/j.mser.2003.10.001.

Shafiei, N., Ghadiri, M., Makvandi, H. and Hosseini, S.A. (2017), "Vibration analysis of Nano-Rotor's Blade applying Eringen nonlocal elasticity and generalized differential quadrature method", *Appl. Math. Modell.*, **43**, 191-206. https://doi.org/10.1016/j.apm.2016.10.061.

Shafiei, N., Hamisi, M. and Ghadiri, M. (2020), "Vibration analysis of rotary tapered axially functionally graded Timoshenko nanobeam in thermal environment", *J. Solid Mech.*, **12**(1), 16-32. https://doi.org/10.22034/jsm.2019.563759.1273.

Shafiei, N., Kazemi, M. and Ghadiri, M. (2016), "Nonlinear vibration behavior of a rotating nanobeam under thermal stress using Eringen's nonlocal elasticity and DQM", *Appl. Phys. A*, **122**(8), 728. https://doi.org/10.1007/s00339-016-0245-y.

Shahabinejad, E., Shafiei, N. and Ghadiri, M. (2018), "Influence of Temperature Change on Modal Analysis of Rotary Functionally Graded Nano-beam in Thermal Environment", *J. Solid Mech.*, **10**(4), 779-803.

Sheng, C., He, G., Hu, Z., Chou, C., Shi, J., Li, J., Meng, Q., Ning, X., Wang, L. and Ning, F. (2021), "Yarn on yarn abrasion failure mechanism of ultrahigh molecular weight polyethylene fiber", *J. Eng. Fibers Fabrics*, **16**, 15589250211052766. https://doi.org/10.1177/15589250211052766.

Shivanian, E., Ghadiri, M. and Shafiei, N. (2017), "Influence of size effect on flapwise vibration behavior of rotary microbeam and its analysis through spectral meshless radial point interpolation", *Appl. Phys. A*, **123**(5), 329. https://doi.org/10.1007/s00339-017-0955-9.

So, H.H., Cho, J.W. and Sahoo, N.G. (2007), "Effect of carbon nanotubes on mechanical and electrical properties of polyimide/ carbon nanotubes nanocomposites", *Eur. Polym. J.*, **43**(9), 3750-3756. https://doi.org/10.1016/j.eurpolymj.2007.06.025.

Song, S., Zhang, T. and Zhui, Z. (2023), "Dynamic analysis of nanotube-based nanodevices for drug delivery in sports-induced varied conditions applying the modified theories", *Steel Compos. Struct.*, **49**(5), 487. https://doi.org/10.12989/scs.2023.49.5.487.

Su, Z., Meng, J. and Su, Y. (2023), "Application of SiO_2 nanocomposite ferroelectric material in preparation of trampoline net for physical exercise", *Adv. Nano Res.*, **14**(4), 355-362. https://doi.org/10.12989/anr.2023.14.4.355.

Sun, Z., Wan, Z. and Sachs, S.G. (2023), "Compatibility of carbon nanotubes in concrete with air entrainer and superplasticizer", *Constr. Build. Mater.*, **364**, 129944. https://doi.org/10.1016/j.conbuildmat.2022.129944.

Thostenson, E.T., Li, C. and Chou, T.W. (2005), "Nanocomposites in context", *Compos. Sci. Technol.*, **65**(3), 491-516. https://doi.org/10.1016/j.compscitech.2004.11.003.

Vaia, R.A. and Wagner, H.D. (2004), "Framework for nanocomposites", *Mater. Today*, **7**(11), 32-37. https://doi.org/10.1016/S1369-7021(04)00506-1.

Vijayan, B.K., Dimitrijevic, N.M., Finkelstein-Shapiro, D., Wu, J. and Gray, K.A. (2012), "Coupling titania nanotubes and carbon nanotubes to create photocatalytic nanocomposites", *ACS Catal.*, **2**(2), 223-229. https://doi.org/10.1021/cs200541a.

Wang, C., Guo, L., Xia, Y., Zhang, C., Sang, X., Xu, C., Zhu, G., Ji, H., Zhao, P., Fang, H., Peng, Z. and Zhang, X. (2024), "Flexural performance and damage evolution of multiple fiberglass-reinforced UV-CIPP composite materials-- A view from mechanics and energy release", *J. Mater. Res. Technol.*, **29**, 3317-3339. https://doi.org/10.1016/j.jmrt.2024.02.051.

Wang, G., Peng, K., Zhou, H., Liu, G., Lou, Z. and Pan, F. (2023a), "Nanocomposite reinforced structures to deal with injury in physical sports", *Adv. Nano Res.*, **14**(6), 541-555. https://doi.org/10.12989/anr.2023.14.6.541.

Wang, H., Huang, Z., Zeng, X., Li, J., Zhang, Y. and Hu, Q. (2023b), "Enhanced anticarbonization and electrical performance of epoxy resin via densified spherical boron nitride networks", *ACS Appl. Electr. Mater.*, **5**(7), 3726-3732. https://doi.org/10.1021/acsaelm.3c00451.

Wang, P., Gao, Z., Pan, F., Moradi, Z., Mahmoudi, T. and Khadimallah, M.A. (2022), "A couple of GDQM and iteration techniques for the linear and nonlinear buckling of bi-directional functionally graded nanotubes based on the nonlocal strain gradient theory and high-order beam theory", *Eng. Anal. Bound. Elem.*, **143**, 124-136. https://doi.org/10.1016/j.enganabound.2022.06.007.

Wei, J., Sun, L., Han, J. and Huang, W. (2022), "MWCNTs/CB waterborne conductive smart coating for damage monitoring of composites: Design, fabrication, characterization, and verification", *Prog. Organ. Coatings*, **172**, 107136. https://doi.org/10.1016/j.porgcoat.2022.107136.

Wu, C.-S. and Liao, H.T. (2007), "Study on the preparation and characterization of biodegradable polylactide/multi-walled carbon nanotubes nanocomposites", *Polymer*, **48**(15), 4449-4458. https://doi.org/10.1016/j.polymer.2007.06.004.

Wu, W., Zhang, L., Wu, Y. and Zhao, H. (2024a), "Adaptive saturated two-bit-triggered bipartite consensus control for networked MASs with periodic disturbances: A low-computation method", *IMA J. Math. Control Inform.*, dnae002. https://doi.org/10.1093/imamci/dnae002.

Wu, Y., Lu, S., Zhang, C., Wang, C. and Fang, H. (2024b), "Unveiling the three-dimensional network and deformation mechanism of foamed polyurethane by coarse-grained and graph theory", *J. Mater. Res. Technol.*, **29**, 4650-4661. https://doi.org/10.1016/j.jmrt.2024.02.156.

Xiao, N., Yang, K., Yin, X., Zhang, F., Wu, Y., Zhang, H., Xiong, B., Zhu, Y., Duan, M. and Zhang, C. (2022), "Analysis of mechanical properties and tribological optimization of Ti-16 wt%Ni alloys with MgAl–Al2O3-graphene microchannels", *Wear*, **510-511** 204515. https://doi.org/10.1016/j.wear.2022.204515.

Yan, C., Zhang, T., Zheng, T. and Mahmoudi, T. (2024), "Stability characteristic of bi-directional FG nano cylindrical imperfect composite: Improving the performance of sports bikes using carbon nanotubes", *Steel Compos. Struct.*, **50**(4), 459-474. https://doi.org/10.12989/scs.2024.50.4.459.

Yang, K., Zhang, F., Chen, Y., Zhang, H., Xiong, B. and Chen, H. (2022a), "Recent progress on carbon-based composites in multidimensional applications", *Compos. Part A Appl. Sci. Manuf.*, **157**, 106906. https://doi.org/10.1016/j.compositesa.2022.106906.

Yang, S., Huang, Z., Hu, Q., Zhang, Y., Wang, F., Wang, H. and Shu, Y. (2022b), "Proportional optimization model of multiscale spherical bn for enhancing thermal conductivity", *ACS Appl. Electr. Mater.*, **4**(9), 4659-4667. https://doi.org/10.1021/acsaelm.2c00878.

Yang, Y. and Mao, Y. (2023), "Effect of cross-section geometry on the stability performance of functionally graded cylindrical

imperfect composite structures used in stadium construction", *Geomech. Eng.*, **35**(2), 181-194. https://doi.org/10.12989/gae.2023.35.2.181.

Yang, Y., Zhu, H., Xu, X., Bao, L., Wang, Y., Lin, H. and Zheng, C. (2021), "Construction of a novel lanthanum carbonate-grafted ZSM-5 zeolite for effective highly selective phosphate removal from wastewater", *Micropor. Mesopor. Mater.*, **324**, 111289. https://doi.org/10.1016/j.micromeso.2021.111289.

Ye, M., HangKong, O., Lin, Y., Ynag, Q., Xu, Q., Chen, T., Sun, L. and Ma, L. (2023), "Electron transport properties of Y-type zigzag branched carbon nanotubes", *Adv. Nano Res.*, **15**(3), 263-275. https://doi.org/10.12989/.2023.15.3.263.

Zhang, C., Liu, D., Zhang, X., Spencer, C., Tang, M., Zeng, J., Jiang, S., Jolivet, M. and Kong, X. (2020), "Hafnium isotopic disequilibrium during sediment melting and assimilation", *Geochem. Perspect. Lett.*, **12**, 34-39.

Zhang, C., Zhu, D., Luo, Q., Liu, L., Liu, D., Yan, L. and Zhang, Y. (2017), "Major factors controlling fracture development in the Middle Permian Lucaogou Formation tight oil reservoir, Junggar Basin, NW China", *J. Asian Earth Sci.*, **146**, 279-295. https://doi.org/10.1016/j.jseaes.2017.04.032.

Zhang, C., Liu, D.D., Jiang, Z.X., Song, Y., Luo, Q. and Wang, X. (2022a), "Mechanism for the formation of natural fractures and their effects on shale oil accumulation in Junggar Basin, NW China", *Int. J. Coal Geol.*, **254**, 103973. https://doi.org/10.1016/j.coal.2022.103973.

Zhang, H., Zou, Q., Ju, Y., Song, C. and Chen, D. (2022b), "Distance-based Support Vector Machine to Predict DNA N6-methyladenine Modification", *Curr. Bioinform.*, **17**(5), 473-482. https://doi.org/10.2174/1574893617666220404145517.

Zhang, L. and Huang, Y. (2023), "Investigating the role of nano in preserving the environment with new energy and preventing oil pollution", *Adv. Nano Res.*, **15**(6), 541-550. https://doi.org/10.12989/anr.2023.15.6.541.

Zhang, C., Khorshidi, H., Najafi, E. and Ghasemi, M. (2023a), "Fresh, mechanical and microstructural properties of alkali-activated composites incorporating nanomaterials: A comprehensive review", *J. Clean. Prod.*, **384**, 135390. https://doi.org/10.1016/j.jclepro.2022.135390.

Zhang, P., Song, J. and Mahmoudi, T. (2023b), "Simulation and modeling for stability analysis of functionally graded non-uniform pipes with porosity-dependent properties", *Steel Compos. Struct.*, **48**(2), 235-250. https://doi.org/10.12989/scs.2023.48.2.235.

Zhang, X., Li, J., Cui, Y., Habibi, M., Ali, H.E., Albaijan, I. and Mahmoudi, T. (2023c), "Static analysis of 2D-FG nonlocal porous tube using gradient strain theory and based on the first and higher-order beam theory", *Steel Compos. Struct.*, **49**(3), 293-306. https://doi.org/10.12989/scs.2023.49.3.293.

Zhang, Z., Du, J. and Mahmoudi, T. (2023d), "Green synthesis of silver nanoparticles to the microbiological corrosion deterrence of oil and gas pipelines buried in the soil", *Adv. Nano Res.*, **15**(4), 355-366. https://doi.org/10.12989/anr.2023.15.4.355.

Zhao, S., Liang, W., Wang, K., Ren, L., Qian, Z., Chen, G., Lu, X., Zhao, D., Wang, X. and Ren, L. (2023), "A multiaxial bionic ankle based on series elastic actuation with a parallel spring", *IEEE T Ind. Electr.*, 1-13. https://doi.org/10.1109/TIE.2023.3310041.