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Experimental investigation of tensile strength and thermal conductivity of nanoparticle reinforcement composite materials

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Abstract

In this study, different nanoparticles were added to composite materials made of polymers, which are frequently used in industrial, at different concentration ratios. By adding nanoparticles to the matrices, it is aimed to analyze the thermal conductivity and tensile strength of the material. These resins, which were mixed homogeneously with a magnetic stirrer, were applied to the carbon fiber fabric and placed in the mold in layers by hand laying method. The samples in the mold were kept at room temperature (25 °C) for 48 hours and their production has completed. The prepared samples were mixed for 20 minutes by adding 100% resin + carbon fiber, 2% and 5% TiO_2, 2% and 5% SiO_2, 2% TiO_2 + SiO_2 and 5% TiO_2 + SiO_2 hybrid nanoparticles by mass concentration. Tensile strength and thermal conductivity values of the completed samples were measured. Among the samples obtained, it was determined that the composite material without nanoparticles had a maximum tensile strength value of 774.43 MPa. For the thermal conductivity value, it was determined that the thermal conductivity value of the reinforced sample with 5% TiO_2 nanoparticles increased by 15.74% compared to the composite material without nanoparticles.

Keywords: Nanoparticle, TiO_2, SiO_2, thermal conductivity, carbon fiber.

1. Introduction

Since the 1940s, the demand for composite materials has increased due to the rapid growth in population and technological advancement, rising production demands, and a progressive decline in the supply of sustainable raw resources. When spacecraft production commenced, scientists started looking for more mechanically sound materials that would meet both the demands of the time and the current material qualities. The idea of creating high-strength and lighter materials has been proposed since metal materials and alloys can match the requirements for strength and cost but not for low weight. At this stage, composite materials came into play. The coatings of Unmanned Aerial Vehicles (UAV), warplanes, propeller blades and spacecraft, airframes, avoiding the icing of aircraft wings, solar panel equipment used in satellites, and optical platforms of space vehicles have all increasingly used carbon fiber reinforced composite materials. due to the enhanced strength, dimensional stability, corrosion resistance, thermal expansion, and thermal conductivity qualities of carbon

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fiber-reinforced composite materials. Thermal conductivity is a key material characteristic, particularly in the aviation industry. To ensure that heat is transferred to the environment rather than being retained in systems with significant heat generation and output, carbon fiber is used in rocket engines as an example. Additionally, it is now a popular method to utilize nanoparticles to improve a material's heat conductivity. Nanofluids, which are generally used in the base fluid in cooling systems, are used to increase the cooling load. Experimental and numerical studies on the electrical and thermal behavior of carbon fiber (Kf) reinforced composite polymers (CFRP) were conducted by Ergün et al. in 2017 [1].

Chandra et al. 2015 Al_2O_3 (Aluminum Oxide) nanoparticles were added in epoxy at 3.27%, 7.75%, 13.4%, and 26.8% volumetric concentration ratios in his study on the thermal conductivity of composites in their studies. They discovered that the heat conductivity improved by 47.3 percent, 123 percent, 211 percent, and 1067 percent, respectively, as the nanoparticle concentration increased [2]. The thermal conductivity of pure epoxy was initially measured as 0.22 W/m.K., and the thermal conductivity measured as a result of the production of Al2O3, hBN, and epoxy reinforced composite material was 1.72 W/m.K. Anderson et al. (2015) investigated Al2O3 and hBN (Boron Nitride) hybrids reinforced epoxy composites in their studies. E increased, it was found [3]. Van-Dung Mai and others The thermal conductivity of an Al_2O_3 and epoxy-containing composite in 2019 was 2.77 W/m.K at a concentration ratio of 72.5 percent, and it increased to 3.35 W/m.K at a concentration ratio of 76.5 percent [4].

Ouyang et al. 2020, In their study, they showed that the thermal conductivity of the nanoparticle-added composite material rose by 1800% when compared to the thermal conductivity of the resin when the Al_2O_3 nanoparticle was added at a rate of 75% by weight to the n-Al_2O_3 and PR (Polypropylene) composite [5]. In a study by Hongkun Li and colleagues published in 2020, they assessed the heat conductivity of a composite made using the packaging approach and an epoxy and Al_2O_3 mixture. When 79 percent Al_2O_3 nanoparticles by mass were added, the thermal conductivity of 100 percent epoxy increased from 0.28 W/m.K at the beginning to 6.7 W/m.K. The value of heat conductivity was found to have increased by 23 times [6]. The influence of nanoparticle size on thermal conductivity was studied by Majeed et al. in 2019. In this study, it was found that the composite's thermal conductivity was increased by including titanium dioxide (TiO_2) into epoxy at concentration ratios of 0%, 2%, 4%, 6%, 8%, 10%, and 12%, with the maximum concentration occurring at 20 °C. Increased by 93 [7] Shihang Wang et all. 2020. In the study, it was measured that the thermal conductivity value of the samples with 0.1%, 0.5%, 1%, 3%, 5% by volume concentrations of TiO_2 nanoparticle in the epoxy resin was 0.28 W/m.K with a maximum increase of 8% [8]. Altstadt et al. In 2019, created carbon fiber prepreg laminates by adding graphite nanoparticles up to 20% of the volume into the composite material. It was observed that as the volumetric concentration of the added nanoparticle in the epoxy increased, the thermal conductivity increased up to 4 times [9]. Moldoveanu et all. 2018, added Al_2O_3 and SiO_2 nanoparticles using liquid water into the base. Researchers looked into the thermal conductivity of nanofluids with volumetric concentration ratios of 1%, 1%, 1.5%, 2%, and 3%. They observed that when the concentration increased, the conductivity increased up to 14% [10]. Hajar Alias et all. 2017, They observed that the mass concentrations of TiO_2 nanoparticles in nanofluids containing 0.25 percent, 0.50 percent, 0.75 percent, and 1.00 percent increased the thermal conductivity by 5 percent [11].

In this study, different nanoparticles were used in addition to one specific type of nanoparticle to examine the mechanical and thermophysical characteristics of the composite material. By mass-adding 2 and 5 percent, TiO_2, 2 and 5 percent SiO_2, 2 and 5 percent TiO_2 + SiO_2 hybrid nanoparticles to the carbon fiber reinforced composite materials, the thermal conductivity and tensile strength values of 7 different materials were experimentally investigated.

2. Materials and Methods

In this study, nanoparticles were added to the epoxy resin chosen as the matrix at the ratios of 2% TiO_2, 5% TiO_2, 2% SiO_2, 5% SiO_2, hybrid 2% TiO_2 + SiO_2, and 5% TiO_2 + SiO_2 by mass. The manual lay-up technique was used to create carbon fiber-reinforced composite materials that were both nanoparticle-reinforced and nanoparticle free. In Table 1, the materials and nanoparticle amounts used in each sample prepared are given.

Table 1. Sample composition and mass % ratios

Sample	Carbon Fiber	Epoxy	Hardener	TiO_2	SiO_2	Total Mass (g)
1	33.13%	47.73%	19.13%	0	0	27.13
2	32.71%	46.90%	18.41%	2%	0	27.16
3	33.00%	44.27%	17.73%	5%	0	26.97
4	34.44%	45.40%	21.32%	0	2%	25.87
5	37.19%	40.83%	16.98%	0	5%	23.88
6	34.58%	45.27%	18.14%	1%	1%	25.76
7	34.49%	43.18%	17.34%	2.5%	2.5%	25.77

2.1. Materials

Carbon fiber fabric produced from Tenax-E HTA 40 3k yarn was used in plain weaving type. Plain carbon fiber fabric has a more durable structure when compared to twill fabric types. Using a sponge, the mold release agent was applied to the mold's surface. The mold release agent protects both the product and the mold by forming a film that is resistant to polyester on the mold. As a matrix material, lamination epoxy resin L285 was used. The resin has a viscosity of 600-900 mPa.s. and a density of 1.18-1.23 g/cm^3. Epoxy and H285 hardener were combined. This hardener's density ranges from 0.94 to 0.97 g/cm^3, and its viscosity ranges from 50 to 100 mPa.s. Table 2 lists the characteristics of the nanoparticles that were added to the composite material.

Table 2. Nanoparticle Properties [12]

Nanoparticle	Density (g/cm^3)	Purity	Average Size (nm)	Color	Geometry	Thermal Conductivity (W/m.K)
TiO_2	3.9	>%99.5	10-25	White	Spherical	10
SiO_2	2.4	>%99.5	15-20	White	Spherical	1.3

2.2. Material Preparation Techniques

Before beginning the experimental studies, a number of preliminary experiments were conducted in order to obtain the sample with the most suitable geometry, wetting the carbon fiber of the resin, and homogeneous dispersion of the nanoparticles in the matrix. A 3k plain carbon fiber fabric with dimensions of 1200 mm x 800 mm was cut into 120 mm x 35 mm pieces with tensile test geometry in mind. A 4 mm thick sample made of 15 layers of carbon fiber was prepared to meet the thickness requirements for the tensile test standards and to measure thermal conductivity. Epoxy and hardener have a mass ratio of 100:40. With the help of a brush, this mixture was mixed for 10 minutes at room temperature (25 °C) to produce the sample, and for 20 minutes to create nanoparticle samples with 2-5% TiO_2, 2-5% SiO_2, hybrid 2% TiO_2 + SiO_2, and 5% TiO_2 + SiO_2 ratios [7]. The surface of the mirror, which served as the mold, was cleaned, and a mold release agent was applied before manual lay-up production could begin. On the mold release was placed the first layer of carbon fiber, and using a brush, the resin that had been previously prepared was applied to the fabric's surface. In order to spread the resin evenly across the fabric and remove any air that was still present in the resin in the produced layers, the sample's surface was flattened with a cylindrical object. The remaining 14 layers underwent the same procedures. A weight suitable for the part's dimensions was set on the sample at the end of the procedure to make sure the surface was smooth. After 48 hours at room temperature (25 °C), the composite material reached a sufficient thickness, and the production was completed [13]. 7 carbon fiber and nanoparticle-reinforced composite samples were created at the conclusion of the study.

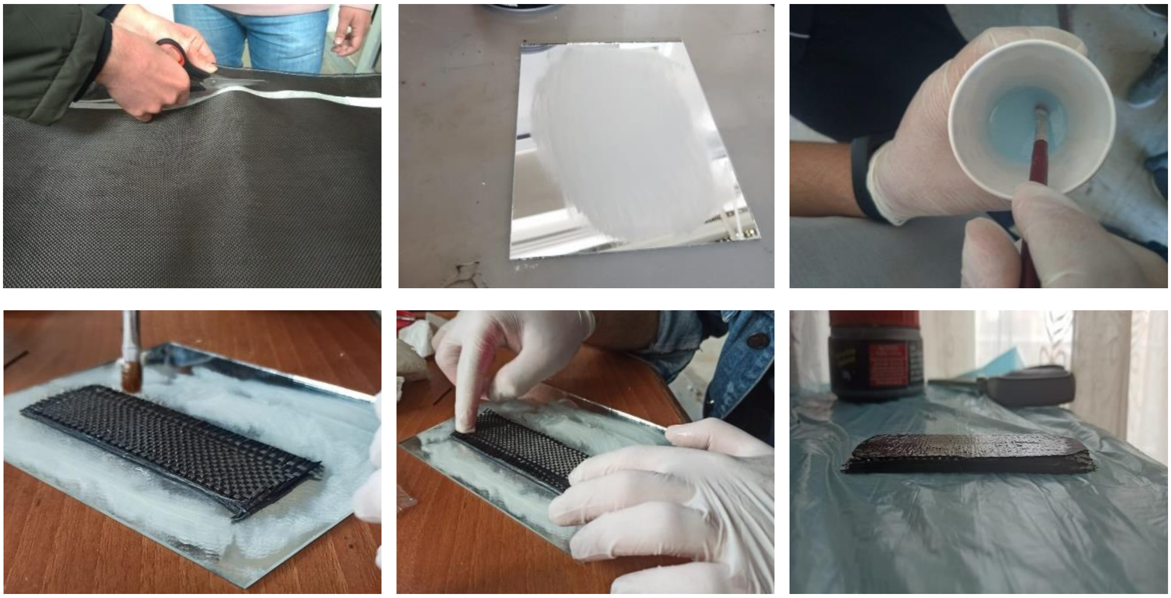


Fig. 1. Carbon fiber and nanoparticle reinforced composite material preparation steps

2.2. Test of materials

Thermal conductivity and tensile tests were carried out for 7 different samples, which were completed in Figure 1.

2.2.1. Thermal Conductivity Test

Thermal conductivity is a measure of the rate of heat flow through the material exposed to heat. The thermal conductivity coefficient affects the flow rate. A material's low thermal conductivity coefficient suggests that it will be insulating. The rate of heat transfer along unit length per unit area at unit temperature difference is the definition of a material's thermal conductivity [14, 15]. Figure 2 shows that holes of the right size for the probes of the thermal conductivity test device were drilled on the sample. By inserting the probes into the holes on the KD2-Decagon thermal conductivity measuring instrument, the thermal conductivity values of the samples were calculated.

2.2.2. Tensile Test

Uniaxial load is applied to a sample until it ruptures in this destructive testing technique. This test can be used to determine a material's yield/tensile strength, unit elongation, elastic modulus, and Poisson's ratio, among other mechanical characteristics. In accordance with the standards, a tensile sample from the material to be tested must be prepared for the tensile test. Between the test device's jaws is put the tensile sample. A certain speed of tension is applied to the sample until it breaks uniaxially. With the aid of the apparatus, the elongation (L) of the material against it and the force F applied during tensile is measured and recorded. The force (F) and elongation (L) values obtained as a result of the experiment are used to obtain the stress (σ) and unit elongation (ΔL) values by using the area and final length values. And the stress-strain (σ –ΔL) diagram is created. This diagram is called a tensile diagram [16]. In Figures 3 and 4, the dimensions of the samples to be prepared for the tensile tests and the samples obtained are shown.

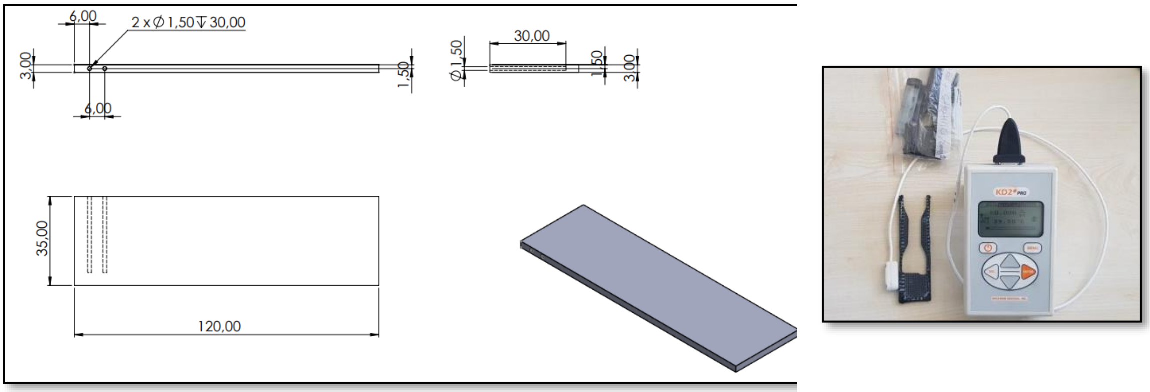


Fig. 2. Preparation of samples for thermal conductivity and measuring device

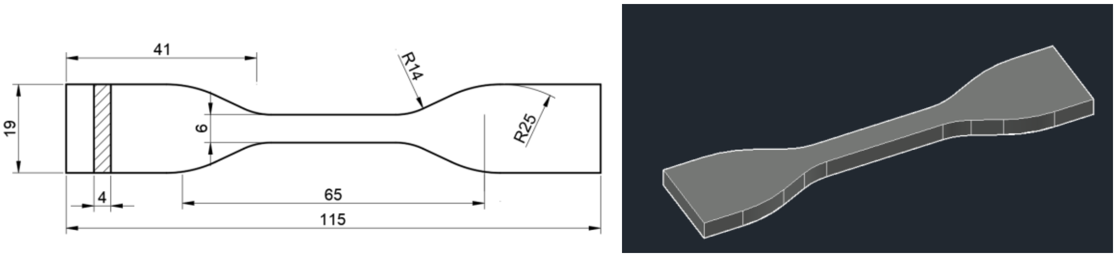
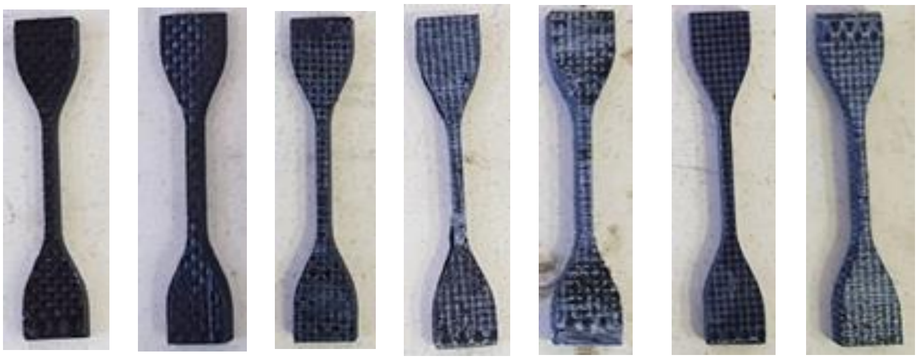


Fig. 3. Dimensions of Tensile Sample (ASTM D608-10).



%100 E+Cf	%2 SiO_2 +E+Cf	%5 SiO_2 +E+Cf	%2 TiO_2 +E+Cf	%5 TiO_2 +E+Cf	%2 SiO_2 +TiO_2 +E+Cf	%5 SiO_2 +TiO_2 +E+Cf

*E: epoxy, Cf: Carbon fiber,

Fig. 4. Prepared tensile samples.

3. Results And Discussions

3.1. Tensile Test Findings

The tensile strength results of carbon fiber reinforced composites with 2%, 5%, 5%, 2%, and 5% hybrid TiO_2 + SiO_2 nanoparticles in the mass ratio are shown in Figure 6. Because the composite materials with 2% TiO_2 + SiO_2 and 5% TiO_2 were damaged before the tensile test, the tensile tests could not be completed. The longitudinal elongation value was measured as 2.56% and the maximum stress value as 774.43 MPa when the sample without nanoparticles was examined. The highest measured stress value is this one. The sample reinforced with 2% SiO_2 had a longitudinal elongation of 2.37% and a maximum tensile stress value of 670.95 MPa. The sample with 2% TiO_2 reinforcement had a longitudinal elongation of 2.29% and a maximum stress value of 583.41 MPa. The sample reinforced with 5% SiO_2 had a longitudinal elongation of 2.86% and maximum tensile stress of 758 MPa. The 5% TiO_2 + SiO_2 hybrid sample's longitudinal elongation was 2.28%, and its maximum tensile stress was 644.38 MPa. Examining Figures 5 and 6, it can be seen that while the tensile strength of the composite material with nanoparticle reinforcement is higher, it increases as the concentration ratio increases for the composite material without nanoparticle reinforcement.

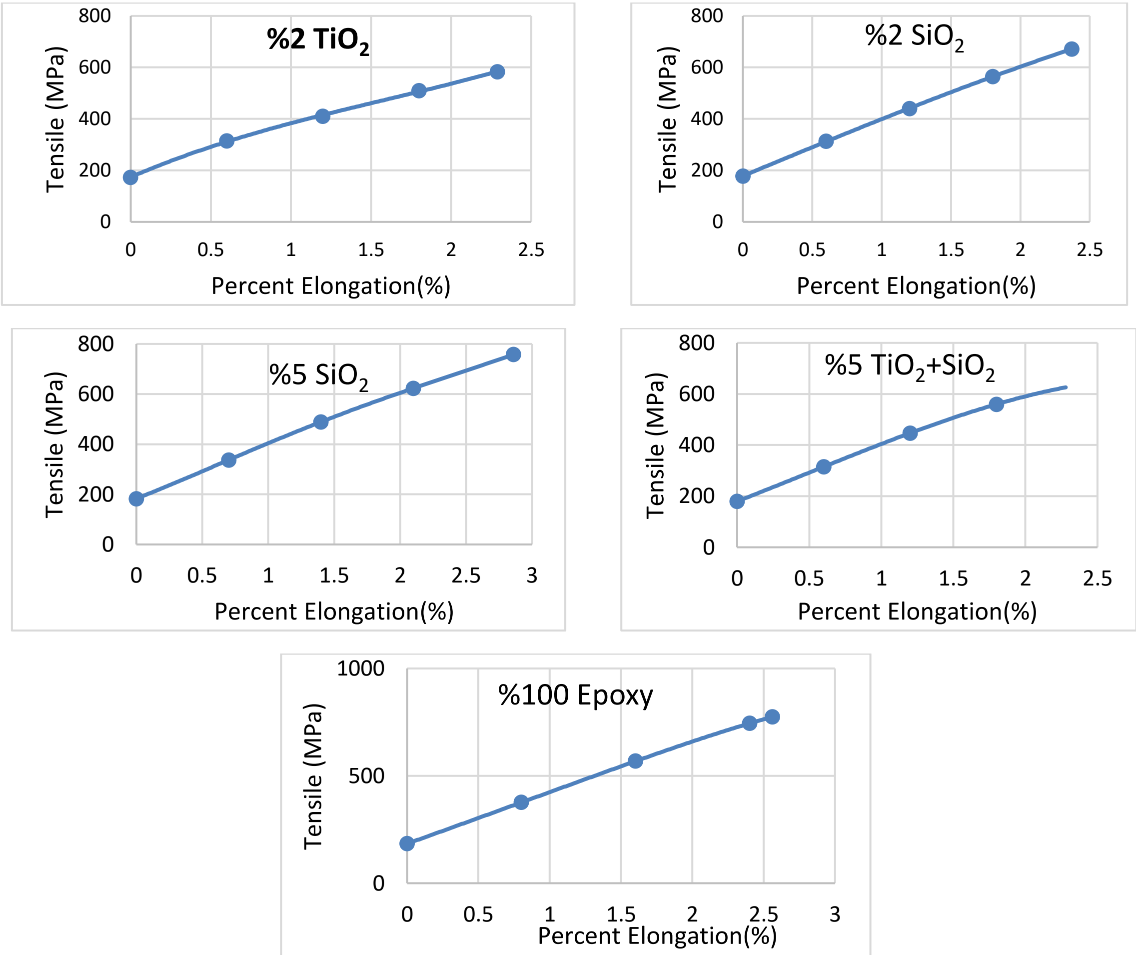


Fig. 5. Obtained tensile test results.

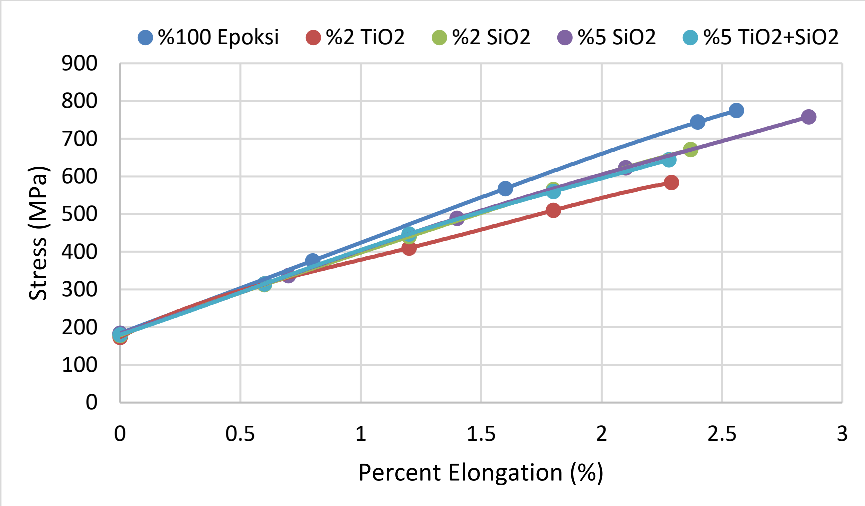


Fig. 6. Comparison of the obtained tensile test results.

3.2. Thermal Conductivity Coefficient Findings

Thermal conductivity values of 7 different samples with 100% epoxy+carbon fiber, 2% SiO_2, 2% TiO_2, 5% SiO_2, 5% TiO_2, and 2% SiO_2+TiO_2 at room temperature with KD2-Decagon Table 3 includes the results of the thermal conductivity device measurement. The highest measured thermal conductivity value, 0.216 W/m.K, is found in Table 3 and is associated with the composite material that has 5% TiO_2 added. The lowest measured thermal conductivity value was found to be 0.182 W/m.K for a 100% epoxy+carbon fiber composite material. The thermal conductivity value increased up to 15.74% more than the base material. This demonstrates that it can meet needs in environments where high cooling performance is desired.

Table 3. Measured thermal conductivity values

Sample	%100 Epoxy+Cf	%2 TiO_2	%2 SiO_2	%2 SiO_2+TiO_2	%5 SiO_2	%5 TiO_2	%5 SiO_2+TiO_2
Thermal Conductivity (W/m.K)	0.182	0.208	0.196	0.200	0.206	0.216	0.209
% Increase	-	12.50	7.14	9.00	11.65	15.74	12.92

4. Conclusions

With the findings, it was found that adding nanoparticles to carbon fiber + epoxy composite materials at various concentration ratios decreases the tensile strength of the material, but increases the cooling load in terms of the thermophysical *property* of the material, i.e., thermal conductivity, as the concentration ratio rises. The composite materials with the highest tensile strength were made with 100% epoxy and carbon fiber, 5% SiO_2, 2% SiO_2, 2% TiO_2, and 5% SiO_2+TiO_2, respectively. In comparison to TiO_2, this demonstrates that SiO_2 nanoparticle-doped composite materials have a higher tensile strength than those with TiO_2. The composite materials reinforced with 100% epoxy and carbon fiber had the highest thermal conductivity values, followed by those with 5% TiO_2, 5% SiO_2+ TiO_2, 2% TiO_2, 5% SiO_2, 2% SiO_2, and 5% SiO_2, respectively. Here, it has been found that TiO2-added composite materials have better thermal conductivity than SiO_2-added composite materials.

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