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Study of Ablation Characteristics Carbon Fiber Reinforced Plastic with Silicon Carbide Pores

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Abstract

Significant thermal stress is placed on spacecraft during atmospheric re-entry, primarily due to aerodynamic heating. This intense heat can cause severe material damage threatening the spacecraft's structural integrity. To address this challenge, efforts are focused on improving the ablation resistence of spacecraft components. In this work, carbon fiber reinforced plastic (CFRP) composites containing silicon carbide (SiC) holes are explored as a potential solution for enhancing thermal protection system. Four different composite versions were developed using compression molding: CF100% (pure carbon fiber), CF30% and SiC70%, CF40% and SiC60%, and CF50% and SiC50%. The composites were thoroughly evaluated in terms of their thermal conductivity, thermal expansion, and flammability according to ASTM standards. Among the tested composites, the CF50% and SiC50% composite exhibited the highest thermal conductivity, demonstrating the best heat transfer performance. This indicates its potential to efficiently manage heat during re-entry. On the other hand, the composite of CF40% and SiC60% showed balanced performance with improved flammability resistance, a slower rate of thermal expansion, and moderate thermal conductivity. According to these results, the CF40% and SiC60% composite provides a well-rounded option for high-temperature aerospace applications by fusing structural stability and safety against thermal stress with efficient thermal management. By developing composite materials for harsh environmental settings, this study advances aerospace vehicle durability and safety.

Keywords: Ablation resistance, thermal protection, high-temperature composites, thermal conductivity, compression moulding

INTRODUCTION

As humanity extends its reach beyond Earth, the engineering challenges associated with re-entering the Earth's atmosphere become increasingly significant [1]. Aerodynamic heating during re-entry can cause extreme temperatures that severely degrade and damage spacecraft structures [2, 3]. This is due to the combination of high velocity and friction [4]. Between the atmospheric gases and the vehicle's surface, resulting in thermal stress that can compromise structural integrity [5, 6]. Traditionally, materials such as reinforced carbon-carbon composites [7, 8] have been used to shield spacecraft from these harsh conditions [9]. However, the quest for materials with better performance and durability under extreme thermal stress continues [10]. Silicon carbide, a ceramic compound with exceptional thermal conductivity and abrasion resistance, has emerged as a promising material for aerospace applications [11]. When integrated into polymeric composites [12].

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Silicon carbide enhances the material's thermal stability and ablation resistance [13]. That makes it usable in high a temperature which is something like [14]. This research is a study on the fabrication of silicon carbide-polymer matrix composite tiles [15]. Designed to offer superior protection against the intense heat and pressures of atmospheric re-entry [16]. This study aims to address the gaps in current thermal protection technologies by exploring the ablation characteristics of these innovative composite materials [17]. Through a detailed examination of their performance under simulated re-entry conditions. This research seeks to contribute to safer and more efficient thermal protection systems, thereby advancing our capabilities in space exploration and travel [18].

MATERIALS AND METHODS

Material Selection

The material has been selected based on the application of high thermal Resistance and for the study ablative characters. The materials used are: Chopped (or) forged carbon fiber, Silicon carbide (SiC) and Phenol-formaldehyde (or) phenolic resin PFR110.The composite is fabricated with a square mold of 3 mmthickness using a compression molding.

Fabrication Process

A mould frame made of MS (Mild Steel) flat, with a thickness of 3mm, is utilized. The frame configuration includes one side fixed with an MS sheet and the other side with a removable MS sheet. The fixed and removable MS sheets have thicknesses of 1.5mm. Dimensions for the frame are 320 mm × 320 mm × 3 mm, and for the MS sheets, 400 mm × 400 mm × 1.5 mm respectively, as illustrated in Figure 1.To facilitate the release of the final product, the frame and MS sheets are covered with high-temperature heat-resistant Teflon tape, serving as a release film. To be more specific, this tape not only keeps from sticking but also does not fail at high temperatures which are used in this process.

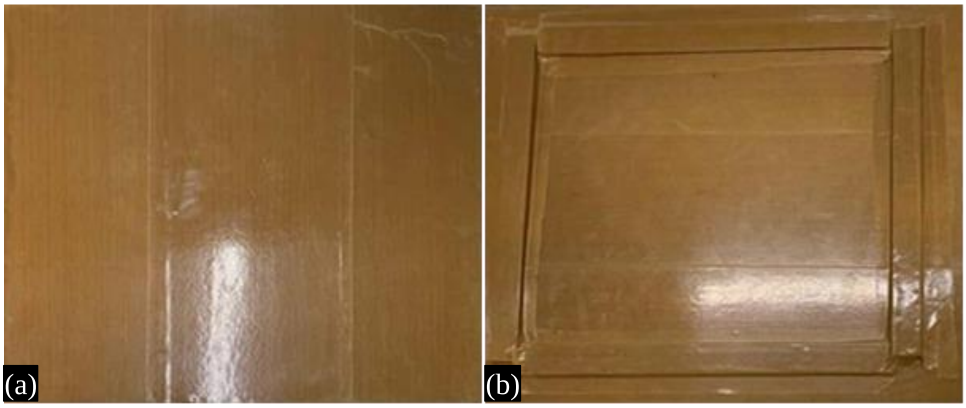

Figure 1. MS Sheet Mould, (a) MS Sheet Fixed, (b) MS Sheet Removable.

Sample Preparation

Ratio 1: For only carbon fiber specimen, a mass of 537.6 g is mixed with 806 g of phenolic resin and poured into the mould and placed inside the compression moulding, as illustrated in the Figure 2a. Ratio 2: For 30% carbon fiber and 70% silicon carbide, a mass of 161.28g of carbon fiber and 690.12g of silicon carbide is used. Silicon carbide is mixed with 700g of phenolic resin as a paste. 40% of that Silicon carbide and resin mixture is poured into the mould (Figure 2b) and the carbon fiber is placed over it (Figure 2c). The remaining 60% of that mixture is poured above the fiber (Figure 2d). Finally mould has been closed and placed inside the compression moulding (Figure 2e). Ratio 3 & 4: The mixture of carbon fiber and silicon carbide for the ratio 3 & 4 are 215.04g of CF & 591.66g of SiC, 268.8g of CF & 493.056g of SiC respectively. The mass of phenolic resin used for these ratios are 600g and 550g respectively. The remaining procedure for mixing and making the sample is same as Ratio 2.

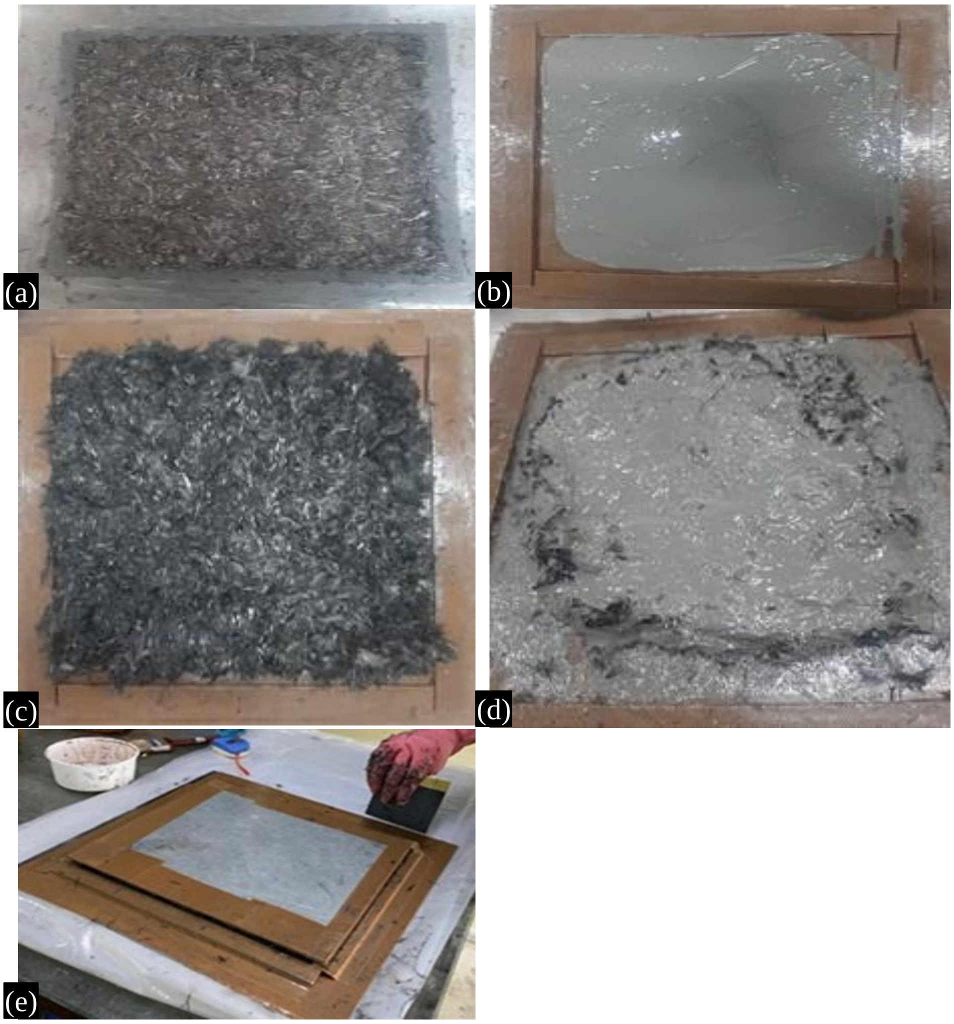

Figure 2. Mixture process. (a) Carbon fiber and phenolic resin mixture, (b) 40% of SiC and Phenolic resin mixture, (c) Carbon fiber placed over the mixture, (d) 60% of SiC-phenolic resin mixture, (e) Mould covered.

Fabrication Using Compression Moulding

This method is commonly used to manufacture sheet moulding or bulk moulding. Compression moulding machine uses a male and female dies or platens in order to shape the mould. The reinforcement combined with resin is then placed in the mould and then the application of high pressure is applied through hydraulic press by closing the mould halves. After the material is cured, the pressure is released and the part is removed from the mould. Exterior body panels for structural members such as automobile bumpers are widely manufactured using this method. Wax has been applied to the top and bottom die of the compression moulding for easy removable of mould. Mould with composite mixture has been placed inside the compression moulding and the values are set. The values for fabricating the tile are kept at 170°C (curing temperature of resin) for 4 hours in a loading condition of 10 bar. After 4 hours the mould is removed from the machine and the specimen is taken out. The specimen is trimmed to the size of 300 mmx 300 mmx 3 mm. These specimens from each composition are taken for several thermal tests.

Experimental Setup and Test Procedures

The specimens from 4 different composites were subjected to several thermal tests including thermal conductivity, thermal expansion and flammability. The size of the specimens and the test procedure were conducted based on the recommended procedures of the American Society for Testing and Materials (ASTM).

Figure 3. Compression Moulding, (a) Mould placed inside the compression moulding, (b) Mould pressed against fixed plate

Thermal Conductivity

Thermal conductivity is a measure which determines the degree to which a given material can transfer heat. In customary notation, it goes by ”κ” or ”λ”. Thermal conductance is the ability of a material to transfer heat and low thermal conductance material transfer heat at a slower rate than high thermal conductance material. For instance the metals are good conductors of heat and in many circumstances have a high coefficient of thermal conduction, while materials such as Styrofoam are insulators. Consequently thermal insulating materials have low thermal conductivity and are used for thermal insulation and high thermal conductivity are widely used in heat sink. Thermal resistivity is the thermal conductivity of material Thermal conductivity formula is $q = \kappa T$, whereby q is heat flux, κ is the thermal conductivity and T is temperature gradient. Fourier’s Law deals with heat conduction. Two slab guarded hot plate: The guarded hot plate method is a steady state measuring method that determines a material’s thermal conductivity and utilizes electrical power output of hot plate with directed heat conduction.

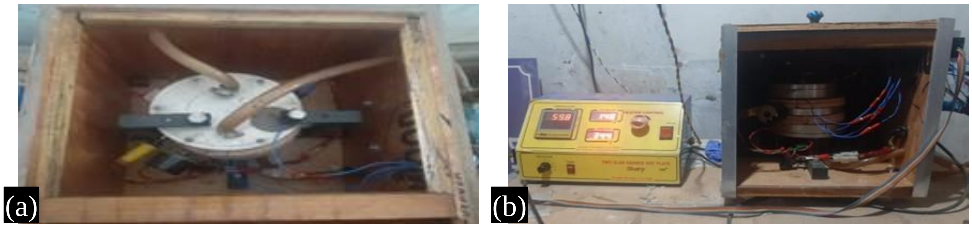

Figure 4. Experimentation, (a) Top view of the two slab guarded hot plate, (b) Front view of the two slab guarded hot plate

An electrically heated plate warms up the sample from one of its surfaces. This plate is set inside a guard, a metal plate that has been heated to the same temperature as the plate independently. A cooled plate regulates the temperature of the sample’s opposite side as well. This is how the one-plate approach is set up; Figure 4 shows this. The heated plate is positioned between two identically sized samples in the two-plate arrangement. The hot plate is inserted into the guard once more. These might have a square or round form. The electric heater produces a flow of heat at a set pace. Heat flow that is unidirectional is therefore produced. The temperature hold of the heating and cooling plates is constant as soon as equilibrium is reached. The resultant temperature differential throughout the sample is then measured by the thermocouples.

Figure 5. Thermal conductivity specimen as per ASTM E1530, (a) Carbon fiber alone, (b) 30% carbon fiber with 70% silicon carbide, (c) 40% carbon fiber with 60% silicon carbide, (d) 50% carbon fiber with 50% silicon carbide

The ASTM E1530 specification calls for a specimen with a 50 mmdiameter disc and a temperature range of 50 to 150 degrees Celsius. The Figure 5 depicts the specimens used in the thermal conductivity measurement.

Thermal Expansion

The ability of matter, mostly not inclusive of change of phase, to change its volume, density, shape and area with a change in temperature is referred to as thermal expansion. An object's size varies in response to temperature changes, and this phenomenon is described by the coefficient of thermal expansion. lesser coefficients indicate a lesser tendency for size change. More precisely, it assesses the fractional change in size under constant pressure for every degree of temperature variation. Three types of coefficients have been developed: volumetric, linear, and area. The specific application and the dimensions deemed significant determine the coefficient to be used. When it comes to solids, the change may only matter across a certain length or area. Assuming that pressure has little impact, we could write: $\alpha L = \frac{1}{dL/dT}$

Where, dL/dT is the rate at which that linear dimension is affected for every increment of change in temperature and L is a linear measurement. One can estimate the shift in the linear dimension as follows: $\Delta L = \alpha \Delta T\ L/L$

Figure 6. Dilatometer for thermal expansion.

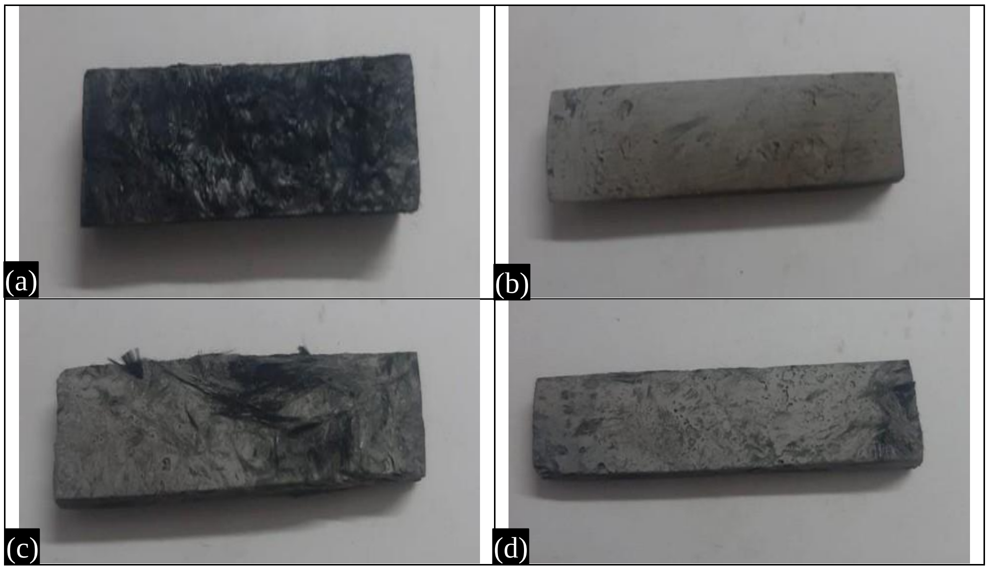

Figure 7. Thermal expansion of specimen as per ASTM E831, (a) Carbon fiber, (b) 30% carbon fiber with 70% silicon carbide, (c) 40% carbon fiber with 60% silicon carbide, (d) 50% carbon fiber with 50% silicon carbide

As long as the fractional change in length $\Delta L \ll 1$ is minimal and the linear-expansion coefficient does not fluctuate much with temperature changes ΔT, this estimation is effective. The precise differential equation (using dL) has to be integrated if any of these requirements are not met. Dilatometry is the analytical technique used to measure the change of dimensions of a material with respect to temperature. In a dilatometry experiment, a sample is placed in a sample holder and one end of the sample is touched to a push rod. After that, the sample and holder are sealed within a furnace and the sample is heated, cooled, or exposed to isothermal conditions as per the specified temperature program. A very precise displacement sensing device measures the sample's linear dimensional change (expansion or contraction) during the experiment. Figure 6 shows an illustration of the dilatometer. Metals, glass, ceramics, and other materials may all be tested with dilatometry. Numerous parameters are measured, such as the glass transition temperature, softening point, coefficient of thermal expansion, and linear thermal expansion. As per the standards, the specimen size for ASTM E831 is 40 mmx 10 mmx 5 mm and the temperature ranges from 50°C to 500°C. The Figure 7 represents those specimens.

Flammability

Testing for flammability establishes how quickly a substance or final product will burn or ignitewhen it comes into contact with heat or fire. In addition to posing a serious danger to public safety, noncompliance with flammability testing regulations can limit market access and resultin regulatory bodies taking enforcement action. The flammability test measures how quickly self-supporting polymers burn in comparison to other materials. The main applications of this test are material comparisons, production control, and quality control. It is not applicable as fire danger criteria. The flammability or combustibility of the material in air depends mainly on the volatility of the material and the temperature sensitive composition specific vapor pressure. Thus, more of the material will evaporate, perhaps in the form of a mist, or dust. To compare the burn rates and burn resistance of the fabrics especially those used in automotive interiors, a horizontal tester, as shown in Figure 8 is used. The draft-free stainless steel cabinet of the horizontal flammability tester, which includes adoor-mounted burner, sample holder, and viewing glass, is safe and simple to use. A solenoidcontrol gas valve, an automated ignition timer, and controls are all part of the automatic gas andtiming control system.Test protocol: The different flammability tests all follow a similar protocol, which consistsof orienting a test sample either vertically or horizontally and placing it in the test chamber, applying a flame from a Bunsen burner for a predetermined amount of time, and measuring how long the flame propagates. As per the standards, the specimen size for ASTM D635 is 125 mmx 12.5 mmx 5 mmand the temperature ranges from 500°C to 1300°C.

Figure 8. Horizontal Flammability Tester.

Theory and Calculation

Four specimens were fabricated using compression moulding. In that three specimens will be reinforced with silicon carbide and another one will be carbon fiber alone. Reinforced tiles willhave three different ratios of silicon carbide as 50%, 60% and 70% respectively. The ratios forthe specimen are taken as follows:

Ratio 1: Carbon fiber alone.
Ratio 2: Carbon fiber 30% and silicon carbide 70%.
Ratio 3: Carbon fiber 40% and silicon carbide 60%.
Ratio 4: Carbon fiber 50% and silicon carbide 50%.

Note: The ratios of each specimen is taken with respect to mass and phenolic resin is taken 1.5times of Silicon Carbide. Calculations for determining the mass of components based on theirdensities and the mold

Volume: The density of chopped carbon fiber, d_{CF}, typically ranges from 1.75 to 1.93 g/cm^3. For calculations, we use the lower bound:

d_{CF} = 1.75 g/cm3

The density of Silicon carbide, d_{SiC} is given as:

d_{SiC} = 3.21 g/cm^3

The volume of the mold, V, is calculated as:
V = 32 × 32 × 0.3 = 307.2 cm3

Using the density-mass-volume relationship:
Mass = Density × Volume

Therefore,
Mass of CF = d_{CF} × V = 1.75 × 307.2 = 537.6 g
Mass of SiC = d_{SiC} × V = 3.21 × 307.2 = 986.112 g

RESULTS AND DISCUSSIONS

Test specimens are shown in Figure 9.Test standard: ASTM D635; Temperature 500°C to 1300°C.

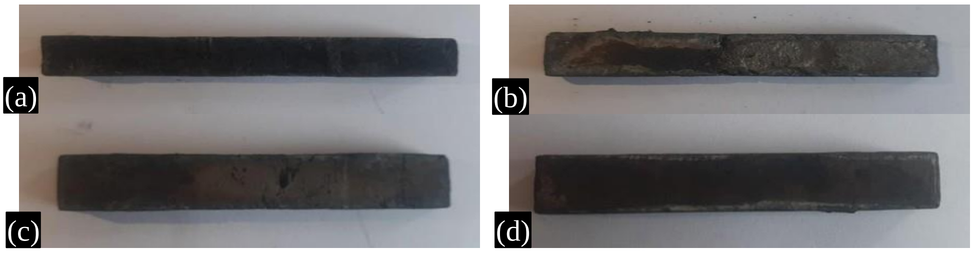

Figure 9. Horizontal flammability test specimens, (a) Carbon fiber, (b) 50% carbon fiber with 50% silicon carbide, (c) 40% carbon fiber with 60% silicon carbide, (d) 30% carbon fiber with 70% silicon carbide

Thermal conductivity for four different samples are tested, and the test results and graphs are given below:
q = V × A
ΔX = 5 mm
D = 160 mm

Where q, ΔX, and D are common for all four specimens.

Table 1. Thermal conductivity for the composition of CF100%.

Temp (°c)	V	A	Temp (K)				q (W)	(T1+T3)/2 (K)	(T2+T4)/2 (K)	K (W/mK)
			T1	***T2***	***T3***	***T4***				
50	150	0.32	307	306.7	306	307	46.8	306.5	306.85	0.016634
75	150	0.335	307.5	310.2	310.2	308.3	48.9	308.85	309.25	0.015208
100	150	0.35	313.5	313.5	308.3	311	49.35	310.9	312.25	0.004548
125	150	0.334	321.5	320.9	310.2	315.7	50.55	315.85	318.3	0.002567
150	150	0.338	333.3	330.8	309.7	321.3	50.85	321.5	326.05	0.00139

The thermal conductivity data for a composite consisting solely of carbon fiber (CF100%) are shown in Table 1. Temperatures between 50°C and 150°C are included in the data, together with the associated values for thermal conductivity (κ), temperature gradients (ΔT), and heatflux (q). The findings show how well the material transfers heat at different temperatures.

The thermal conductivity of a composite of 30% carbon fiber and 70% silicon carbide (SiC) is shown in Table 2. The measurements contain identical parameters (q, ΔT, κ) and span the same temperature range (50°C to 150°C). This information facilitates comparing this composite's thermal performance to that of other composites with various compositions.

Table 2. Thermal conductivity for the composition of CF30% and SiC70%.

Temp (°c)	V	A	Temp (K)				q (W)	(T1+T3)/2 (K)	(T2+T4)/2 (K)	K (W/mK)
			T1	***T2***	***T3***	***T4***				
50	150	0.32	307.5	307.7	308.5	308.1	48	308	307.9	0.059713
75	150	0.335	309.7	310.3	310.3	307.8	50.25	310	309.05	0.006580
100	150	0.35	315.3	314.2	314.2	307.8	52.5	314.75	311	0.001742
125	150	0.334	325.6	323.3	322.4	309.8	50.1	324	316.55	0.000837
150	150	0.338	339.2	336.3	331.3	309.6	50.7	335.25	322.95	-0.00051

Table 3. Thermal conductivity for the composition of CF40% and SiC60%.

Temp (°c)	V	A	Temp (K)				q (W)	(T1+T3)/2 (K)	(T2+T4)/2 (K)	K (W/mK)
			T1	***T2***	***T3***	***T4***				
50	150	0.312	307	306.7	306	307	46.8	306.5	306.85	0.016634
75	150	0.326	307.5	310.2	310.2	308.3	48.9	308.85	309.25	0.015208
100	150	0.329	313.5	313.5	308.3	311	49.35	310.9	312.25	0.004548
125	150	0.337	321.5	320.9	310.2	315.7	50.55	315.85	318.3	0.002567
150	150	0.339	333.3	330.8	309.7	321.3	50.85	321.5	326.05	0.00139

The thermal conductivity of a composite consisting of 60% silicon carbide and 40% carbon fiber is displayed in Table 3. It contains temperature-specific measurements of thermal conductivity, temperature gradients, and heat flow, much as the preceding tables. The information is utilized to assess how well this particular composite conducts heat.

Table 4. Thermal conductivity for the composition of CF50% and SiC50%.

Temp (°c)	V	A	Temp (K)				q (W)	(T1+T3)/2 (K)	(T2+T4)/2 (K)	K (W/mK)
			T1	***T2***	***T3***	***T4***				
50	150	0.338	307.2	307.2	306.9	307.1	50.7	307.05	307.15	0.063072
75	150	0.342	309.5	307.9	308.7	308.7	51.3	309.1	308.3	0.007977
100	150	0.338	313.8	313.8	308.7	311.3	50.7	311.25	312.55	0.004852
125	150	0.331	322.4	321.4	309.4	316.3	49.65	315.9	318.85	0.002094
150	150	0.329	340.8	334.7	309.2	326.4	49.35	325	330.55	0.001106

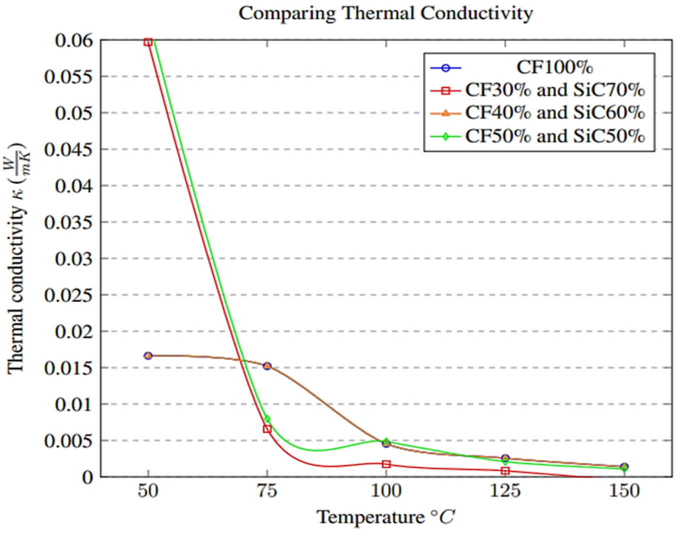

Figure 10. Comparative thermal conductivity of different materials across temperature.

The thermal conductivity values for a composite including equal amounts of silicon carbide and carbon fiber (50% SiC and 50% CF) are shown in Table 4. The experiments are conducted across the usual temperature range, providing the essential information to evaluate the heat conduction performance of this composition in comparison to other ratios.

In comparison to pure carbon fiber, the silicon carbide addition enhances the composite materials' thermal conductivity, as seen in Figure 10. CF50% and SiC50%, on the other hand, appear to be the ideal composition for thermal conductivity since they retain greater conductivity across a wider temperature range. At higher temperatures, the conductivity of composites with larger silicon carbide content (70%) significantly decreases, indicating possible problems with material durability.

CONCLUSION

In this study, the compression molding process was effectively used to manufacture composites of carbon fiber reinforced plastic with silicon carbide pores. The carbon fiber (CF100%), the carbon fiber with 70% silicon carbide (CF30% and SiC70%), the 40% carbon fiber with 60% silicon carbide (CF40% and SiC60%), and the 50% carbon fiber with 50% silicon carbide (CF50% and SiC50%) were the four compositions that were examined. The thermal conductivity, thermal expansion, and flammability of the composites were tested. The primary conclusions drawn from the experimental results are as follows:

- *Thermal Conductivity:* Using the ”Two slab guarded hot plate” apparatus, testing carried out in accordance with ASTM E1530 revealed that the composite containing 50% carbon fiber and 50% silicon carbide (CF50% and SiC50%) showed the maximum thermal conductivity over the temperature range. On the other hand, the composite containing 40% carbon fiber and 60% silicon carbide (CF40% and SiC60%) also performed admirably, indicating that it would be a good choice for high-temperature applications.
- *Thermal Expansion:* The specimens were evaluated using a dilatometer with temperatures ranging from 30°C to 500°C in accordance with ASTM E831. In comparison to other specimens, the composite containing 40% carbon fiber and 60% silicon carbide (CF40% and SiC60%) showed a slower rate of sinkage, suggesting improved dimensional stability under heat stress.
- *Flammability Test:* All of the materials underwent ASTM D635 testing. When compared to other specimens, the composite containing 40% carbon fiber and 60% silicon carbide (CF40% and SiC60%) performed better at withstanding high temperatures.

According to the overall findings, the CF40% and SiC60% composite shows a balanced performance across thermal conductivity, thermal expansion, and flammability resistance, while the CF50% and SiC50% composite exhibits the greatest thermal conductivity. Consequently, the composite material composed of CF40% and SiC60% may be regarded as a versatile option for applications that necessitate a blend of high thermal stability and resistance to thermal stress.

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