UDK 54-311:677.521:52-334.6 ISSN 1580-2949
Original scientific article/Izvirni znanstveni članek Mater. Tehnol.

THE EFFECT OF SILICON-CARBIDE ADDITIONS ON THE MECHANICAL AND THERMAL CONDUCTIVITY PROPERTIES OF FIBER-REINFORCED EPOXY COMPOSITES

VPLIV DODATKA SILICIJEVEGA KARBIDA NA MEHANSKE LASTNOSTI IN TOPLOTNO PREVODNOST EPOKSIDNIH KOMPOZITOV OJAČANIH Z VLAKNI

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Prejem rokopisa – received: 2024-09-12; sprejem za objavo – accepted for publication: 2024-10-17

doi:10.17222/mit.2024.1276

This study investigates the impact of adding silicon carbide (SiC) filler with various weight percentages on the mechanical and thermal properties of carbon- and glass-fiber-reinforced epoxy composites. Alterations in the filler content were analyzed to observe the composite material's response to loading, assessing mechanical properties such as hardness, impact resistance, tensile strength, flexural strength and thermal conductivity. The investigation focuses on composite materials comprising carbon fibers and glass fibers to enhance the binder material (epoxy resin). Accordingly, four different groups of samples were prepared for experimentation. The first group consisted solely of epoxy resin, while the second group of samples contained epoxy resin reinforced with 15 *w*/% SiC. The third and fourth groups of samples included three layers of glass fibers, with and without 15 *w*/% SiC reinforcement, respectively. In the fifth and sixth groups of samples there were three layers: one upper layer of glass fibers, one layer of carbon fiber in the middle, and one layer of glass fiber at the bottom, with and without 15 *w*/% SiC reinforcement, respectively. The experimental findings revealed that the sixth group of samples exhibited lower heat conductivity (with an overall reduction of 10.9 % compared to samples from other groups), while demonstrating the highest tensile strength, hardness, flexural strength values and impact resistance (showing improvements of 20 %, 50 %, 19.5 %, and 11 % respectively, compared to samples from other groups).

Keywords: mechanical properties, SiC, glass fiber, epoxy, thermal conductivity, carbon fiber

V članku avtorji opisujejo študijo učinka dodajanja polnila iz silicijevega karbida (SiC) v različnih masnih deležih na mehanske in toplotne lastnosti z ogljikovimi in/ali steklenimi vlakni ojačanih epoksidnih kompozitov. Analizirali so vpliv spremembe deleža dodanega SiC na mehanske in termične lastnosti kompozitov (trdoto, udarno žilavost, natezno in upogibno trdnost ter toplotno prvodnost). Avtorji so se v raziskavi osredotočili na analize kompozitnih materialov z epoksidno matrico in različno vsebnostjo steklenih ali ogljikovih vlaken. Za preizkuse so uporabili šest različnih skupin preizkušancev. V prvi skupini je bila samo oksidna matrica. V drugi skupini vzorcev je bila epoksidna matrica ojačana s 15-timi *w*/% SiC. V tretji in četrti skupini so preizkušanci vsebovali še plasti steklenih vlaken brez in z dodatkom 15 *w*/% SiC. Peta in šesta skupina preizkušancev sta vsebovali po tri plasti: zgornjo plast steklenih vlaken, srednjo plast ogljikovih vlaken in spodaj še plast steklenih vlaken ter brez in z dodatkom 15 mas.% SiC. Ugotovitve na podlagi preizkusov so pokazale, da ima šesta skupina preizkušancev za približno 10,9 % nižjo toplotno prevodnost kot preostale skupine preizkušancev. Med tem, ko je le-ta skupina imela za 20 % višjo natezno trdnost in za 50 % višjo upogibno trdnost, za 19,5 %, večjo trdoto in za 11 % večjo udarno žilavost, glede na ostale skupine preizkušancev.

Ključne besede: mehanske lastnosti, SiC, steklena in ogljikova vlakna, epoksi, toplotna prevodnost

1 INTRODUCTION

Numerous modern industrial technologies and applications require materials with superior characteristics, which cannot be met by the typical monolithic materials, like ceramics, polymers and metal alloys. Due to their heterogeneous nature, composite materials have numerous benefits compared with conventional engineering materials, making them an attractive option for a wide range of industrial applications.[1] The characteristics of the composites have been obtained as a function of their constituent materials, their distributions, and the interactions among them, in addition to the potential unusual combinations of the material characteristics. The composite materials are known for improved mechanical characteristics, like high specific strength, high specific stiffness, good impact characteristics and high fatigue strength.[2] The fiber-reinforced composites attracted a great deal of attention from such a wide family of composites due to their good mechanical characteristics. Those composites discovered many different application areas. As a result of their anisotropic nature, the direction dependence of their characteristics leads to much better flexibility of the design, which cannot be obtained from particle-reinforced composites or monolithic materials.[3]

Typically, achieving the desired blend of properties in composite materials is tailored to specific applications.[4]

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Defining composite materials with a single, straightforward definition proves challenging due to the diverse range of materials falling under this category and the varied uses they serve.[5] However, a practical standard definition often entails identifying materials with a matrix that binds the components together, reinforcing strength and stiffness. The balance of structural properties in composite material is better compared with the material alone.[6]

In such regard, composite materials only represent a giant step towards an ever-constant attempt to optimize the materials. In the strict sense of the word, the concept of composite materials is not new. The most common example where the use of composite materials is nature.[7] In the 1930s, modern composites were utilized in the case where glass fibers were reinforced with resin. The boats and aircraft were built by these glass composites, typically referred to as fiber glass. Since the 1970s, advances in composite systems incorporating metal and ceramic matrices, as well as new fibers such as carbon, aramids, and boron, have expanded the range of applications for composite materials.[8] In manufacturing recently, underground fiber-reinforced plastic (FRP) pipes have been deployed in a wide range of applications, like the water mains, sewer lines, culverts, gas lines, oil lines, etc. There is now the potential to use engineering sciences to design underground pipes with a level of precision similar to that achieved in the design of bridges and buildings.[9]

In general, the fiber-reinforced plastic (FRP) is lighter, thinner, and harder than the available concrete or steel pipe lines, and it has been considered good in strength/stiffness per weight unit. These characteristics of FRP are suitable for construction when buried underground and may decrease the materials' failure risks. Notably, as there are thick, soft grounds, there is a wide variety of large-scale residential development sites with poor soil conditions, where high embankment sections and greater burial depths are common. These conditions can lead to deformations in the isotropic materials of the structural members.[10] It is crucial to investigate how variations in temperature affect the changes on the characteristics of fiber-reinforced epoxy composites, as temperature fluctuations can lead to changes in strength and ductility[11]. According to Nielsen and Landel (1994), an increase in temperature typically reduces the strength and ductility, while a decrease in temperature tends to increase the ductility and strength.[12] In efforts to enhance the mechanical properties of composites, silicon carbide (SiC) filler particles have been introduced into fiber-reinforced epoxy. Studies by Imanaka et al. and Yamamoto et al.[13] have highlighted the significance of shape, particle size and percentage content in influencing the mechanical properties of fiber-reinforced polymer composites. Research findings, such as those by Nakamura et al.,[14] indicate that the structure and shape of silica particles play significant roles in properties like fatigue resistance, tensile strength, and fracture properties.[15] Despite numerous studies on various natural materials, there remains much to explore.[16] In contrast to prior studies that primarily focused on either glass- or carbon-fiber composites, or solely on mechanical properties, this work provides a holistic assessment of both the mechanical and thermal properties in a hybrid system. The novelty of this study lies in its comprehensive investigation of the synergistic effects of silicon carbide (SiC) filler on the mechanical and thermal properties of hybrid carbon- and glass-fiber-reinforced epoxy composites. This study is distinctive in its approach by combining both glass and carbon fibers, along with varying SiC filler content, to optimize the performance of the epoxy matrix. The findings reveal a novel composite architecture that offers superior mechanical performance with reduced thermal conductivity, advancing our understanding of hybrid composite systems and their potential for advanced engineering applications. Thus, this study delves into the effects of incorporating glass and carbon fiber with silicon carbide (SiC) reinforcement. Five tests were conducted on each sample group to assess the influence of material configuration on the mechanical properties. These tests included measurements of the hardness, tensile strength, impact resistance, flexural strength and thermal conductivity. The results allowed for conclusive observations.

2 EXPERIMENTAL PART

2.1 Materials used

In this study, Sikadur-52 epoxy resin was employed as the polymer matrix. The resin was combined with the hardener in a weight and volume ratio of 2:1 (A). At normal room temperature, Sikadur-52 epoxy resin manifests as a clear and thick liquid. Glass fibers and carbon fibers were obtained from a woven mat. The properties of these materials, including glass fibers, carbon fibers, and epoxy resin, as provided by the manufacturer, are summarized in **Table 1**.

Table 1: Mechanical and physical properties of fibers epoxy resin and silicon carbide (SiC)

Fiber's type	Density (g/cm^3)	Young's Modulus (GPa)	Tensile strength (MPa)	Elongation at break (%)	Poisson's ratio
Glass fiber	2.54	72.4	3445	4.8	0.21
Carbon fiber	1.8	135	3900	2.1	0.2
Epoxy resin	1.1	1.8	37	8	0.3
Silicon carbide (SiC)	3.1–3.2	450	300	0.1	0.14–0.17

Table 2: Provides the manufacturing details for samples in each group, including the types and quantities of fiber layers used and their configurations.

Sample	Number of layers			Layers arrangement
	Glass fibers	carbon fibers	Silicon carbide (SiC) %	
First group	–		–	Consisted solely of epoxy resin
Second group	–	–	15	Included samples of epoxy resin reinforced with 15 *w*/% SiC
Third group	3	–	–	Samples contained three layers of glass fibers
Fourth group	3	–	15	Consisted of three layers of glass fibers reinforced with 15 *w*/% SiC.
Sixth group	2	1	–	Comprised three layers: one upper layer of glass fibers, one layer of carbon fiber in the middle, and one layer of glass fiber at the bottom
Sixth group	2	2	15	Comprised three layers: one upper layer of glass fibers, one layer of carbon fiber in the middle, and one layer of glass fiber at the bottom with 15 *w*/% SiC reinforcement

2.2. Experimental work

The sample was arranged according to the stacking sequence depicted. Six separate sets of samples were prepared for the testing. The specimens in the first group consisted solely of epoxy resin. The second group included samples of epoxy resin reinforced with 15 *w*/% SiC. In the third group, the samples contained three layers of glass fibers. The fourth group consisted of three layers of glass fibers reinforced with 15 *w*/% SiC. The fifth and sixth groups of samples comprised three layers: one upper layer of glass fibers, upper and lower layers were reinforced by glass-fiber, while the mid one was reinforced by carbon-fiber, with and without 15 *w*/% SiC reinforcement, respectively. The reinforcing material constituted a volumetric fraction of 40 % in all samples. **Table 2** provides the manufacturing details for samples in each group, including the types and quantities of fiber layers used and their configurations. To create the composites, layers of fibers were stacked within a mold measuring (130 × 130 × 5) mm. The glass fibers were intricately arranged to achieve the described layer configuration (**Figure 1**). A designated area within the mold was allocated for pouring the epoxy binder, which was then applied until it thoroughly covered the intertwined fibers. Subsequently, appropriate pressure was exerted on the mixture, and the entire assembly was pressed.[17]

All samples were fabricated at a temperature of 25 °C and left in the mold for 24 h to ensure the solidification process was complete. Following the protocols outlined in a recent study by Agayev, S.,[18] the materials were then

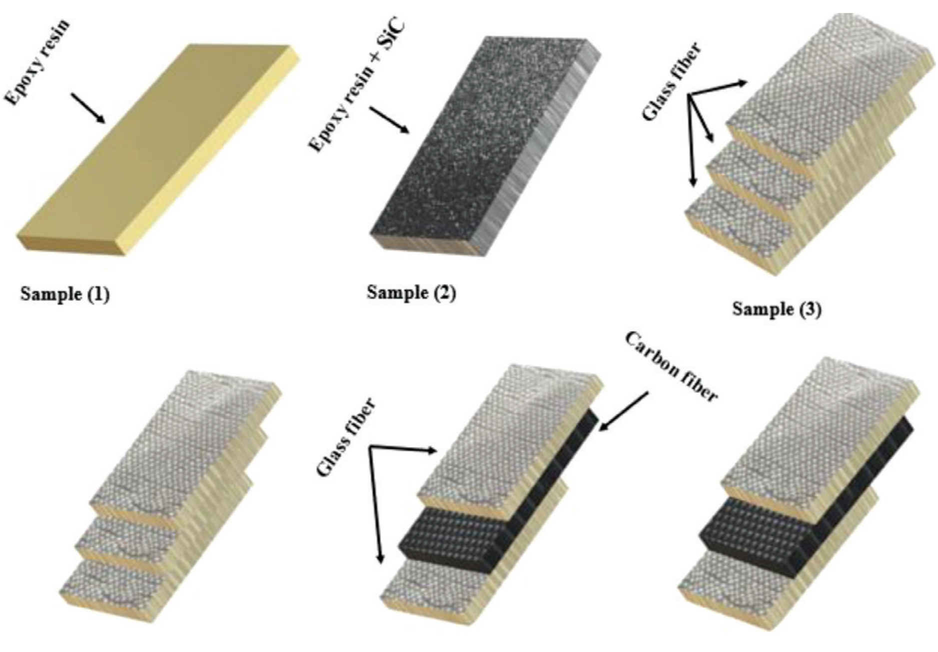

Figure 1: Arrangement of glass and carbon fibers within the fabricated specimens

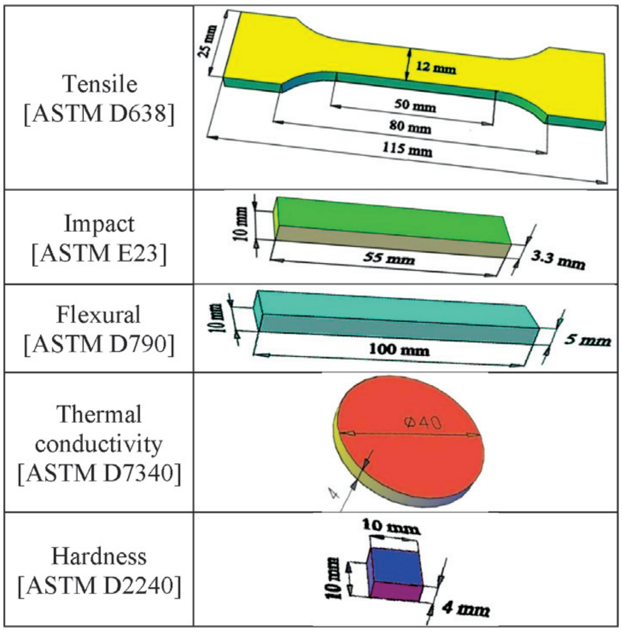

Figure 2: Dimensions of samples for tensile, flexural, impact, hardness testing and thermal conductivity[16]

subjected to four hours of drying at 60 °C in a furnace. Specimens for mechanical characterization are subsequently cut using a CNC router machine, adhering to the dimensions specified in **Figure 2**. The hardness of the composite polymer mixture is determined using the ASTM D2240 hardness test (Shore D type), while the tensile properties of the samples are measured using (Lloyds, capacity 1–50 KN). Testing is conducted at room temperature with a testing speed of 5 mm/min. The dimensions of the samples conform to the ASTM D638 Type 1 standard, measuring (115 × 25 × 3.5) mm. The Charpy impact test is performed in accordance with the ASTM E23 standard, with impact test samples sized at (55 × 10 × 3.3) mm. Additionally, the flexural strength of the samples is evaluated according to ASTM D790, with specimens measuring (100 × 10 × 5) mm. Thermal conductivity samples are implemented following ASTM D7340 using Lee's Disc apparatus.[18,19] The samples have a disc shape, featuring a diameter of 40 mm and a thickness of 4 mm, as depicted in the sequence shown in **Figure 2**.

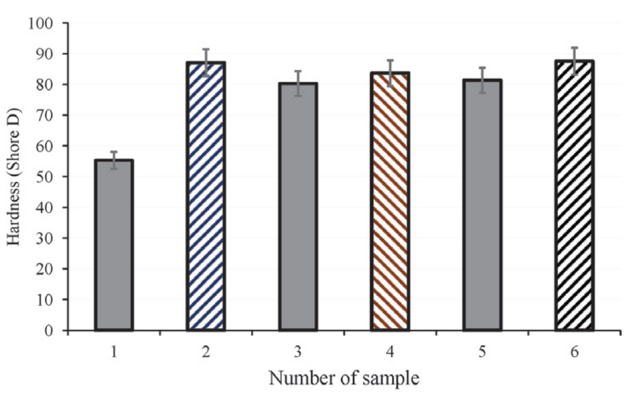

Figure 3: Effect of fiber layers and silicon carbide on hardness values

3 RESULTS AND DISCUSSION

The characteristics of a material, both physical and mechanical, elucidate its performance across practical applications. Hardness is a mechanical test. Because it is a reaction of materials to an applied force, while mechanical properties gauge its response to diverse loads. Experiments were conducted to examine how incorporating the SiC filler influences these properties, and to determine the ideal loading levels of glass- and carbon-fiber reinforcements.

3.1 Hardness (Shore D)

Hardness, as a surface characteristic, serves as an indicator of wear resistance on the composite's surface. **Figure 3** illustrates the measured hardness values for all the weight percentages of SiC reinforcement. The data reveals a consistent increase in hardness with rising SiC content, following a linear trend from 0 *w*/% SiC to 15 *w*/% SiC. The increase in hardness after adding SiC is due to the pinning of chain sliding or the hindrance of chain movement under applied loads by SiC particles. A slight uptick in hardness values was noted in samples incorporating glass and carbon fibers. This increase is attributed to the higher density resulting from filler particles positioned between the fiber and the matrix, leading to decreased compressibility and enhanced hardness. Conversely, the decrease in hardness can be explained by the increase in voids and mismatches when using two types of reinforcement with larger weight fractions. The introduction of a modest volume fraction of SiC can enhance the composite's hardness and wear resistance. As the SiC filler content increases, the filler particles occupy the voids between the fiber and matrix, forming a denser structure and consequently the improving hardness.[20]

3.2 Tensile strength

Figure 4 illustrates the tensile strength plotted against epoxy, epoxy with glass-fibers reinforcement, and epoxy with glass-fibers and carbon-fibers reinforcement. Tensile strength exhibits an increment from 0 *w*/% to 15 *w*/% SiC content. The unique structure of the glass and carbon fiber samples demonstrates superior tensile behavior, surpassing the glass fiber group by 76 %. When subjected to tensile forces, the carbon and glass fibers within the composite matrix mutually reinforce each other. This synergy delays and prevents material cracking, attributed to the uniform fiber distribution in the fourth group of samples comprising alternating layers of glass and carbon fibers.[8] Consequently, the fibers boost the composite material, mitigating the likelihood of plastic deformation. Specifically, the inclusion of carbon-fiber layers in the sixth group of samples, arranged be-

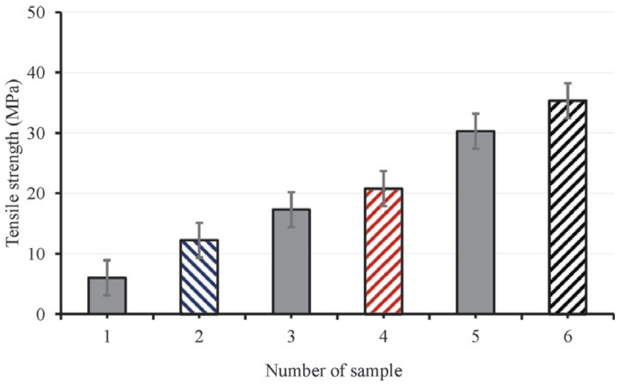

Figure 4: Tensile strengths for different fiber layers

tween layers of glass fibers, enhances the tensile strength. This arrangement effectively distributes the applied loads across the fibers, thus improving the load distribution and subsequently enhancing the tensile strength. These findings align with conclusions drawn from previous studies.[21]

3.3 Impact properties

The ability of a composite materials to withstand impact loads without failure is crucial for design engineers assessing components for industrial or structural applications. This study found that during impact resistance testing, the sixth group of samples demonstrated superior performance (**Figure 5**). This superiority is attributed to the organized distribution of carbon fibers within the sample's core, which facilitates uniform load dispersion and increases the energy required to fracture the composite, as the carbon fibers bear the primary force. In contrast, the impact strength of samples from the sixth group increased due to the positioning of carbon fibers amidst layers of glass fibers, which enhanced the shock resistance of these samples. The inclusion of SiC particles in the carbon fiber matrix further enhances the composite's capacity to absorb and dissipate energy upon impact, resulting in increased toughness. This improvement is primarily due to the SiC particles acting as barriers that hinder crack propagation, preventing sudden fractures. Additionally, the SiC particles improve load transfer between the carbon fibers and the epoxy matrix, contributing to a stronger bond. This combination of improved energy absorption and increased bonding efficiency leads to a more durable material capable of withstanding higher impact forces.[22]

3.4 Flexural properties

Flexural strength determines the highest stress that a composite material can endure under bending conditions, a crucial aspect for various applications. Figure 6 illustrates that incorporating carbon fiber between glass-fiber layers enhances the flexural properties of composite materials. The fiber arrangement in the sixth group of samples effectively distributes applied loads, reducing stress concentration and consequently leading to higher flexural strength. Additionally, research by Yahaya et al.[23] highlights the influence of the layering sequence on the mechanical properties of hybrid polymeric composites, particularly on flexural behavior. Similarly, in this study, the various stacking sequences resulted in the sixth group of samples exhibiting 16.4 % higher flexural strength compared to the second group of samples and 10.7 % higher than the third group samples. The presence of reinforcing fibers or fillers can effectively distribute the applied loads, reducing the likelihood of crack initiation and propagation. Additionally, a well-designed composite structure can better withstand the bending forces, leading to higher overall flexural strength. These enhancements collectively contribute to the material's improved performance in structural applications. Moreover, upon examining the fracture area, it was evident that the failure in the fourth set of samples occurred abruptly (brittle fracture), indicating higher resistance to the applied stresses compared to the other groups.[24] The sequence of failure in glass and carbon fibers begins with crack propagation, followed by debonding, and culminating in fracture. These interfacial cracks hinder the effective transfer of force, leading to matrix debonding and fiber pull-out, indicating a partially plastic fracture mechanism. The sixth set of samples, containing carbon

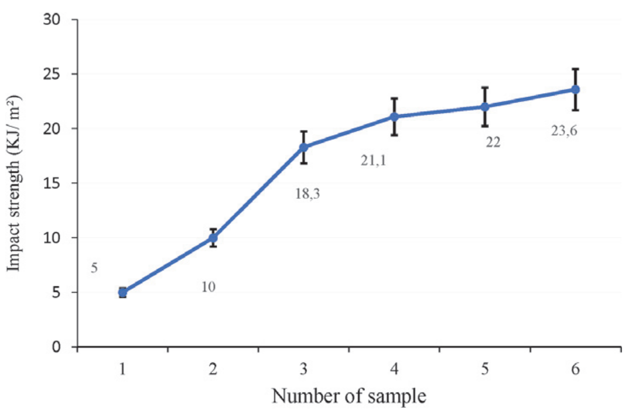

Figure 5: Impact strengths for different fiber layers

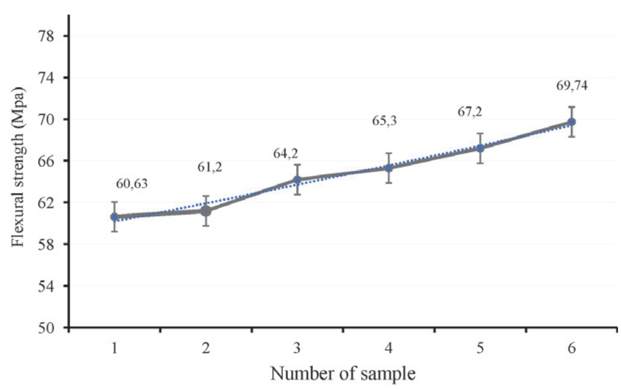

Figure 6: Impact of the arrangement and type of fiber layers on flexural strength

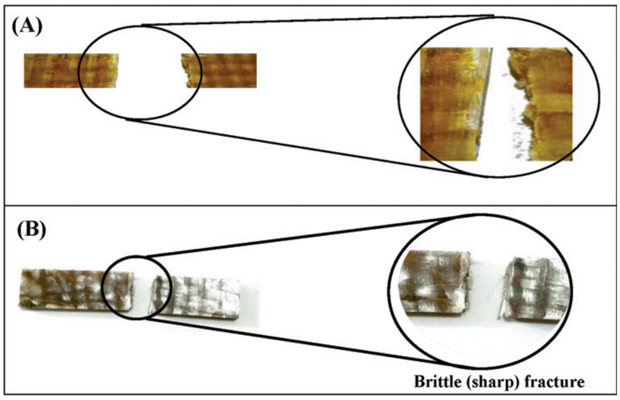

Figure 7: Fractured specimens impact strength after testing (a) fifth group, (b) sixth group

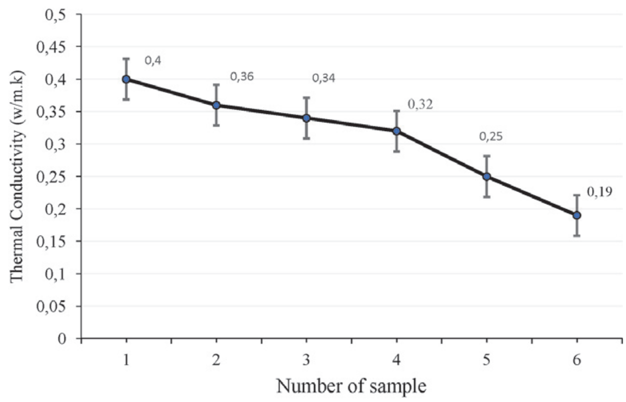

Figure 8: Thermal conductivities for different fiber layers

fiber, exhibited better shock resistance compared to earlier groups, as the carbon fibers acted as stress-concentration sites, which sped up the fracture process. Additionally, an analysis of the fracture surface (**Figure 7**) revealed a sharp, brittle fracture in the sixth set, indicating greater resistance to applied stress than the other samples.

3.5 Thermal conductivity

Regarding thermal conductivity, the sixth group samples displayed the poorest performance (**Figure 7**). This is attributed to the presence of alternating layers of carbon and glass fibers in these samples, rendering them more effective thermal insulators compared to the other specimens. These layers are arranged sequentially, starting with glass fibers, followed by carbon fibers, and glass fibers in the third layer. As a result, this particular configuration, characterized by the diversity of additives (fiber layers), contributed to a decrease in thermal conductivity.[25] The interaction between the carbon fibers and SiC particles also contributes to a more uniform thermal distribution, reducing the localized hotspots. Consequently, this composite exhibited improved thermal management properties, making it suitable for applications requiring effective heat dissipation.

4 CONCLUSIONS

The current study involved testing various hybrid composite materials, where the reinforcing material constitutes a volumetric fraction of 40 % in all the samples comprising carbon fibers and glass fibers. The following conclusions can be drawn from the test results.

As the SiC filler content increases up to 15 *w*/%, mechanical properties such as hardness, tensile strength, interlaminar shear strength, flexural strength, and impact strength also increase.

The sixth group of samples, which included a single layer of carbon fiber sandwiched between two layers of glass fiber at the top and bottom, demonstrated superior performance in terms of tensile strength, hardness, and bending strength. This superiority is due to the cohesion and interlocking of carbon fibers, enabling them to bear greater applied loads during the tests.

This research also advocates for the use of glass and carbon fibers as reinforcement agents in polymeric compounds, highlighting their potential for advantages across diverse industries.

Acknowledgment

The researchers wishes to express heartfelt appreciation to the personnel at the Baquba Technical Institute, Middle Technical University (MTU) in Iraq, as well as to the Materials Engineering Department at the University of Technology, Iraq.

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