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Preparation & characterization of fiber reinforced with ceramic-based filler polymer matrix composites for high-temperature applications

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Abstract
The aim of this experimental study was to investigate the mechanical properties of epoxy polymer matrix composites reinforced with Synthetic fiber (S-glass) and ceramic filler, specifically Silicon Carbide (SiC), under different filler loading conditions. The combination of SiC as a secondary reinforcement with S-glass fiber was fabricated using the hand layup technique, incorporating filler loadings of 0%, 2.5%, 5%, and 7.5% by weight. Tensile testing was performed on samples prepared and cut according to ASTM standards at various temperature conditions. The results of the tests revealed that the addition of 7.5% SiC filler into the S-glass fiber reinforced epoxy composite significantly enhanced the tensile properties of the material, surpassing those of other composites under both normal and high temperature conditions. These findings suggest that as the SiC ceramic filler content increased in the composite, the mechanical properties exhibited proportional improvement, irrespective of the temperature conditions. This experimental research provides valuable insights into the characterization of mechanical properties in epoxy polymer matrix composites reinforced with Synthetic fiber (S-glass) and Silicon Carbide (SiC) ceramic filler. The study highlights the importance of filler loading in optimizing the performance of these composites, specifically in terms of tensile strength, across different temperature environments.

Keywords: S-glass Fiber, SiC Filler, Polymer, Temperature

1. Introduction

Composite materials, composed of a combination of two or more distinct materials, have gained significant attention and widespread use across various industries. These materials offer a unique combination of properties, such as high strength, lightweight nature, and excellent durability. However, when exposed to elevated temperatures, composite materials undergo various changes that can significantly impact their performance and structural integrity. Understanding the effects of elevated temperature on composites is essential for designing and utilizing them in applications where high temperatures are present. The impact of elevated temperature on composite materials, focusing on the changes in their mechanical properties, degradation mechanisms, and potential strategies to mitigate the negative effects of heat exposure [1].

Elevated temperature can have positive effects on composite materials, leading to enhanced properties and performance under specific conditions. While composite materials are known to experience certain challenges when exposed to high temperatures, such as degradation and loss of mechanical strength, there are instances where elevated temperature can be advantageous. This brief introduction explores some of the positive effects of elevated temperature on composite materials, highlighting how heat exposure can contribute to improved properties and expanded applications. Understanding these positive effects can aid in the development of composite materials tailored for high-temperature environments and specific industrial applications [2].

Fiber reinforced epoxy matrix composites are widely used in various industries due to their excellent mechanical properties, lightweight nature, and high strength-to-weight ratio. However, these composites are not immune to the detrimental effects of high temperatures. When exposed to elevated temperatures, the performance and integrity of fiber reinforced epoxy matrix composites can be significantly affected.

Understanding the effects of high temperature on these composites is crucial for designing and utilizing them in applications that involve elevated temperature environments. This explores the impact of high temperature on fiber reinforced epoxy matrix composites, highlighting the key changes in their mechanical properties and potential degradation mechanisms [3].

Filler-based fiber reinforced epoxy matrix composites are composite materials that incorporate fillers or additives, such as nanoparticles, fibers, or particulate reinforcements, to enhance their mechanical properties and performance. When these composites are exposed to elevated temperatures, several effects can be observed: Depending on the filler type and distribution, elevated temperature exposure can induce positive effects on the mechanical properties of the composite. Fillers such as carbon fibers or whiskers can reinforce the matrix and improve the composite's tensile, flexural, or impact strength at elevated temperatures, making it suitable for demanding applications that require both strength and thermal resistance. Effects of elevated temperature on filler-based fiber reinforced epoxy matrix composites depend on factors such as filler type, concentration, dispersion, and the compatibility between the filler and the epoxy matrix [4].

Ceramic fillers, such as ceramic fibers or particles, can significantly enhance the strength and stiffness of the composite. At high temperatures, these fillers maintain their mechanical properties and act as reinforcements, providing additional load-bearing capacity to the composite. The ceramic fillers help distribute and transfer mechanical loads, reducing the strain on the epoxy matrix and preventing premature failure. ceramic fillers contribute to the high-temperature resistance of fiber reinforced epoxy composites by providing thermal stability, reducing CTE mismatch, enhancing strength and stiffness, improving creep resistance, increasing thermal conductivity, and offering fire-resistant properties. The incorporation of ceramic fillers into the composite matrix enables the material to withstand mechanical loading at elevated temperatures, expanding its suitability for demanding applications in industries such as aerospace, automotive, and energy [5].

Conducting a literature review on the mechanical abilities of ceramic-based fillers in glass fiber reinforced epoxy polymer matrix composites is crucial for gaining knowledge, identifying gaps, evaluating filler effectiveness, exploring processing techniques, validating research findings, and understanding practical applications. It serves as a foundation for further research, enabling researchers to make informed decisions and contribute to the advancement of composite materials with improved mechanical properties.

The literature review allows researchers to explore the different processing techniques and parameters employed by various studies to incorporate ceramic-based fillers into glass fiber reinforced epoxy composites. Understanding the effects of filler dispersion, concentration, and manufacturing processes on the resulting mechanical properties is crucial for developing optimized composite materials. Lessons learned from previous research can help researchers make informed decisions about processing techniques to achieve desired mechanical improvements. Raj, *et al.* studied the incorporation of SiC particles improves the composite's mechanical properties, such as tensile strength, flexural strength, and impact resistance. Additionally, the SiC particles enhance the thermal stability and wear resistance of the composite, making it suitable for applications requiring high mechanical strength, thermal resistance, and wear performance [6].

Vera, *et al.* revealed that, the moisture absorption leads to dimensional changes, reduced tensile and flexural strength, and increased interfacial debonding in the composites. Understanding these moisture-induced effects is crucial for designing and utilizing Kolon/epoxy composites in applications where moisture exposure is a concern, allowing for appropriate mitigation strategies to be employed [7]. Mohan, *et al.* investigated the incorporation of SiC fillers enhances the wear resistance and mechanical properties of the composites, such as improved hardness and reduced friction coefficient. Furthermore, at elevated temperatures, the SiC fillers contribute to increased thermal stability and provide enhanced tribological performance, making the composites suitable for high-temperature applications requiring wear resistance [8].

Gaurav, *et al.* demonstrated that, the addition of SiC fillers enhances the thermal conductivity, dimensional stability, and mechanical strength of the composites. The synergistic combination of SiC fillers and chopped glass fibers results in composites with improved resistance to thermal expansion, higher thermal conductivity, and enhanced mechanical properties, making them suitable for applications requiring thermal stability and mechanical strength [9]. Arpitha, *et al.* reported the effect of hybridization of sisal and glass fibers in the composite leads to improved mechanical properties, including enhanced tensile strength, flexural strength, and impact resistance. Additionally, the incorporation of fillers further enhances the composite's performance by improving properties such as thermal stability and wear resistance, making these hybrid composites suitable for various structural applications [10]. Basavarajappa, *et al.* have examined the dry sliding wear characteristics of glass-epoxy composite filled with silicon carbide (SiC) and graphite particles. The study reveals that the addition of SiC and graphite fillers enhances the wear resistance of the composite, reducing the coefficient of friction and minimizing material loss. The combined effect of SiC and graphite particles improves the tribological performance of the glass-epoxy composite, making it suitable for applications requiring enhanced wear resistance under dry sliding conditions [11].

Biswas, *et al.* demonstrates that the incorporation of SiC fillers enhances the erosion resistance of the composites, reducing material loss and erosion rate. The combined reinforcement of glass and bamboo fibers further improves the erosion wear performance, making these composites suitable for applications where resistance to erosion wear is crucial [12]. John, *et al.* incorporation of SiC fibers enhances the mechanical properties of the composites, resulting in improved strength and toughness. The combination of SiC fibers and glass-ceramic matrix offers a synergistic effect, making these composites highly suitable for applications requiring both high strength and toughness [13]. Dong, *et al.* the addition of nanoparticles improves the interfacial bonding between the glass fibers and epoxy matrix, resulting in enhanced mechanical properties. Furthermore, the nanoparticles mitigate the degradation effects of thermal aging, maintaining the composite's performance and stability over time [14].

Hui, *et al.* stated in their work that, by increasing impact energy leads to greater damage and reduced mechanical properties in the composites, including reduced residual strength and increased delamination. Understanding this relationship is essential for designing C/SiC composites with improved impact resistance and maintaining structural integrity in impact-prone applications [15]. Gregory, *et al.* revealed the presence of carbon and boron nitride interphases improves the high-temperature performance of the composites, enhancing their resistance to stress rupture. The interphases act as barriers, reducing oxidation and preventing crack propagation, resulting in improved mechanical stability and prolonged service life of SiCf/SiCm mini-composites under elevated temperature conditions [16].

Patnaik, *et al.* studied the incorporation of SiC fillers improves the mechanical properties, such as hardness and tensile strength, of the composites. Furthermore, the composites exhibit enhanced resistance to erosion wear, making them suitable for applications requiring wear-resistant materials in harsh environments [17]. Tapan, *et al.* study demonstrates that the addition of SiC reinforcement enhances the mechanical properties, including tensile strength and impact resistance, of the composites. The thermo-mechanical characterizations reveal improved thermal stability and dimensional stability, making these composites promising for applications requiring both mechanical strength and thermal performance [18]. Prewo had incorporated the SiC fibers enhances the mechanical properties of the composites, resulting in improved tension and flexural strength. The combination of SiC fibers and glass ceramics offers a synergistic effect, making these composites highly suitable for applications where high strength and reliability are required [19].

Rajesh, *et al.* studied the incorporation of Al2O3 and SiC reinforcements improves the mechanical properties of the composites, including increased tensile strength, flexural strength, and impact resistance. The combination of glass fibers and ceramic reinforcements results in composites with enhanced strength and toughness, making them suitable for various structural applications [20]. Sudheer, *et al.* the addition of PTW and graphite fillers improves the mechanical properties, such as tensile strength and flexural strength, of the composites. Furthermore, the hybrid fillers enhance the wear esistance of the composites, reducing material loss and improving the tribological performance [21]. Teja, *et al.* demonstrated that the incorporation of SiC fillers enhances the mechanical properties, including tensile strength and flexural strength, of the composites. Additionally, the SiC filler material improves the thermal stability of the sisal fiber reinforced composites, making them suitable for applications requiring both mechanical strength and thermal resistance [22]. Amal, *et al.* incorporated of fine SiC particles enhances the thermal stability and mechanical properties, such as tensile strength and flexural strength, of the composites. The combination of SiC and carbon fiber reinforcements offers a synergistic effect, making these composites suitable for applications where high strength and thermal performance are desired [23].

The understanding from the above literature survey is that, the incorporation of SiC particles improves the mechanical properties, thermal stability, and wear resistance of various composites, including glass-epoxy, glass-ceramic, and jute-epoxy composites. SiC fillers enhance the strength, toughness, and tribological performance of the composites, making them suitable for high-stress, high-temperature, and wear-prone applications.

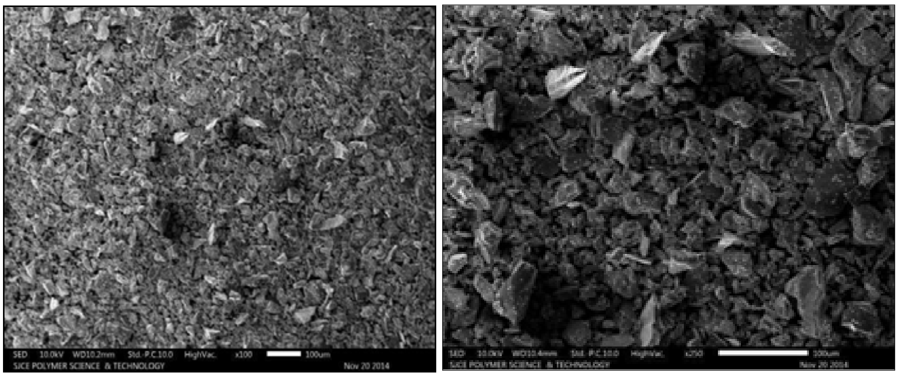
The addition of other reinforcements like PTW, graphite, and carbon fibers further enhances the mechanical and wear properties of the composites, while interphases such as carbon and boron nitride improve high-temperature performance and stress rupture resistance. Understanding these effects is essential for designing composite materials with tailored properties for specific applications. Understanding of the interaction and optimization of multiple reinforcement materials in composite systems.

Further investigation is needed to explore the synergistic effects, optimal combinations, and processing parameters of different reinforcement materials to achieve desired mechanical, thermal, and wear properties. Additionally, there is a need for more comprehensive studies on the long-term durability and reliability of these composites under different environmental conditions, such as exposure to moisture, elevated temperatures, and cyclic loading.

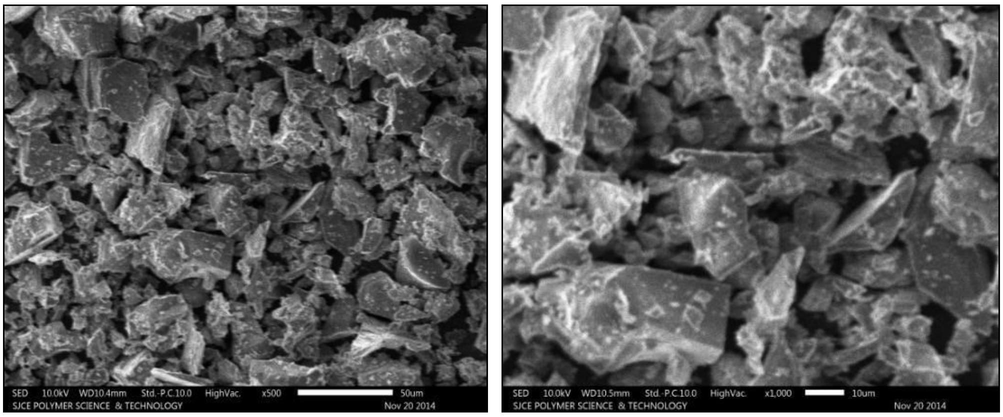
2. Materials & Methods

2.1 Materials used for Composite M

The composite materials were fabricated using different combinations, incorporating Silicon Carbide (SiC) filler with varying weight percentages (0%, 2.5%, 5%, and 7.5%). The SiC filler, with a particle size of 45 microns, was added to an s-glass fiber reinforced with an epoxy polymer matrix (Lapox L-12) and a suitable hardener (K-6) in a specified ratio. The quality of the SiC filler was ensured through SEM and XRD analysis indicated in the figure 1, which revealed irregular sizes and shapes of the fillers. From the figure 2, EDAX analysis confirmed the purity of the SiC filler, with predominantly silica content and trace amounts of oxygen and carbon.



(a) 100x **(b) 250x**



(c) 500x **(d) 1000x**

Fig 1: SEM Pictures of SiC Filler

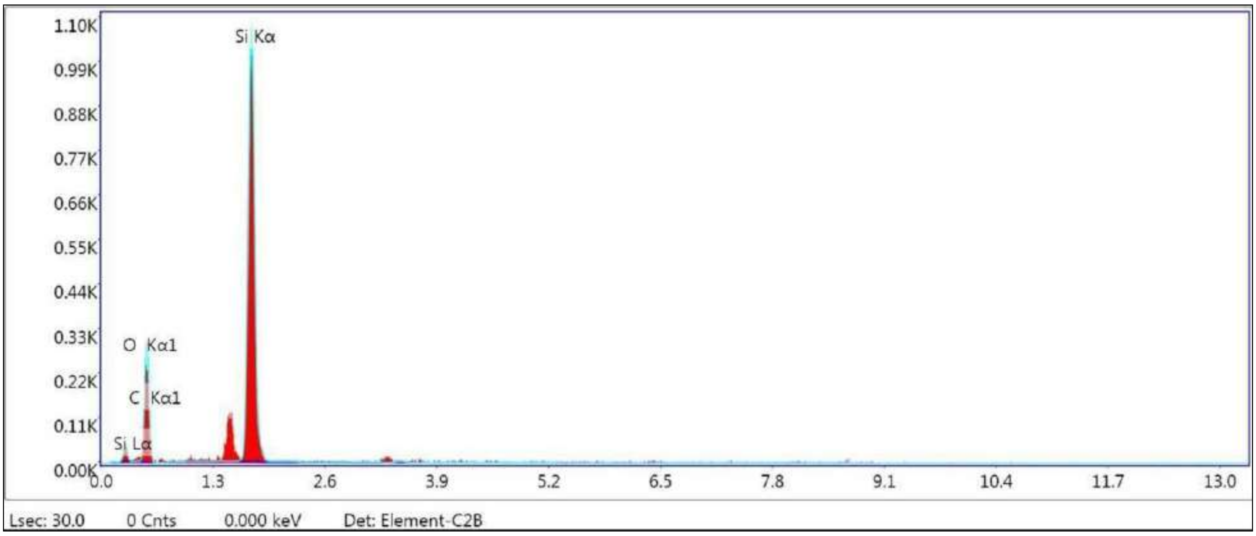


Fig 2: EDAX – SiC Particles

2.2 Method of Manufacturing Composite Materials

The composite laminates were fabricated using the hand layup technique to meet the specific testing requirements. Figure 3 illustrates the step-by-step process of the hand layup technique employed to produce the required specimens. Table 1 provides the details of the different compositions of the composite laminates manufactured according to the specified criteria. The samples were then cut following ASTM guidelines using abrasive water jet machining (AWJM) and subsequently dried in an oven at an appropriate temperature, as depicted in Figure 4.

Fig 3: Machining of laminate & specimens as per standards

Fig 4: Hand Layup Method

Table 1: Configurations of composite materials prepared

Sample Code.	Composite Prepared	Reinforcement (wt. %)	Matrix (wt. %)	Filler (wt. %)
S1	S-G-E	55% S-Glass Fiber	45% Epoxy Resin	0% SiC Filler
S2	S-G-E-F-SiC-2.5%	52.5% S-Glass Fiber	45% Epoxy Resin	2.5wt.% SiC Filler
S3	S-G-E-F-SiC-5%	50% S-Glass Fiber	45% Epoxy Resin	5 wt.% SiC Filler
S4	S-G-E-F-SiC-7.5%	47.5% S-Glass Fiber	45% Epoxy Resin	7.5 wt.% SiC Filler

2.3 Tensile Testing of Composite Materials

Mechanical assessment namely the tensile ability of the prepared material was done according to ASTM D638, in normal room temperature and at high temperature of 100 ^{0}C. ASTM D638 is a widely recognized standard test method used to determine the tensile properties of plastics, including their ultimate tensile strength, yield strength, elongation at break, and modulus of elasticity. The test involves subjecting a standardized dog bone-shaped specimen to a uniaxial tensile force until it breaks, while measuring the corresponding load and elongation.

This standard provides a consistent and reliable approach for evaluating the mechanical performance and tensile behavior of various plastic materials, allowing for material comparison, quality control, and design considerations in industries such as automotive, aerospace, and manufacturing [24].

3. Results & Discussion

3.1 Tensile Features of Composites Produced

The tensile properties of S-glass fiber/epoxy composites with varying weight percentages (0%, 2.5%, 5%, and 7.5%) of SiC filler were evaluated according to ASTM D638 [24] using a computerized universal testing machine (UTM) maintaining the span length of 57 mm at a cross speed loading of 5 mm/min both at normal room temperature and high temperature of 100 ^{o}C.

3.2 Tensile Test Results of Composites at Room Temperature, $T_R = 29\ ^0C$

The results for samples that were tested at room temperature as follows, that includes ultimate tensile strength, Young's modulus, peak load, and maximum displacement, are presented in Table 2. The findings indicate that the tensile strength is significantly influenced by the filler content. The composite with 7.5% SiC filler exhibited an ultimate tensile strength of 429.7 MPa and a Young's modulus of 16.07 GPa. However, beyond 7.5 wt. % SiC content, the tensile strength initially increased and then decreased with further increases in filler content.

The observed results is likely the reinforcing effect of the SiC filler in the composite. SiC particles have high strength and stiffness, which can enhance the mechanical properties of the composite. At lower filler content, the SiC particles contribute to increased bonding and load transfer between the fibers and the matrix, resulting in improved tensile strength. However, as the filler content exceeds a certain threshold (7.5 wt.% in this case), the excessive amount of SiC particles can lead to agglomeration or poor dispersion, causing stress concentrations and weakening the composite's overall strength. This could explain the decrease in tensile strength observed at higher filler contents.

Table 2: Tensile Features of composite materials at room temperature, $T_R = 29$ °C

Sample. Code	Composite Prepared	UTS (MPa)	E (GPa)	Peak Load (N)	Maxi. Displacement (mm)
S1	S-E-C	294.8	11.36	8604.4	5.2
S2	S-2.5% SiC-E	333.7	12.43	15767.1	6
S3	S-5% SiC-E	408.7	17.69	15343.5	6
S4	S-7.5% SiC-E	429.7	16.07	16127.2	6.4

3.3 Tensile Examination Outcomes of Composites at High Temperature, $T_H = 100$ ⁰C

The experimental results obtained from testing the samples at elevated temperatures are presented in Table 3, including parameters such as ultimate tensile strength, Young's modulus, peak load, and maximum displacement. The data indicates a significant influence of the filler content on the tensile strength of the composite. Specifically, the composite with 7.5% SiC filler exhibited an ultimate tensile strength of 287.7 MPa and a Young's modulus of 6.92 GPa. However, beyond a filler content of 7.5 wt. %, the tensile strength initially increased and then decreased as the filler content further increased. This behavior can be attributed to the thermal stability and mechanical properties of the SiC-filled composite. The excellent thermal conductivity of SiC particles enhances the composite's ability to withstand high temperatures. At lower filler content, the SiC particles contribute to improved bonding and load transfer, leading to an increase in tensile strength. However, excessive filler content can result in agglomeration or hinder the matrix's deformation capability, creating stress concentrations and reducing the tensile strength. Additionally, the mismatch in thermal expansion between the SiC particles and the matrix introduces internal stresses, further compromising the overall strength of the composite at elevated temperatures.

Table 3: Tensile features of composite materials at high temperature, $T_R = 100$ °C

Sample Code	Composite Prepared	UTS (MPa)	E (GPa)	Peak Load (N)	Maxi. Displacement (mm)
S1	S-E-C	181.5	4.79	6055.2	5.0
S2	S-2.5% SiC-E	228.4	6.95	10774.2	6.4
S3	S-5% SiC-E	268.2	5.33	10538.2	6.8
S4	S-7.5% SiC-E	287.1	6.92	10695.2	6.7

3.4 Comparison-tensile properties at diverse temperature conditions

Figure 5 indicates the comparison of composites tensile tested at varying temperatures. Overall, the technical reason behind comparing these contents is to understand the influence of SiC filler content on the mechanical properties of the composites at different temperatures. It highlights the reinforcing effect of SiC, the effects of filler agglomeration, dispersion, and thermal expansion mismatch, all of which contribute to variations in tensile strength.

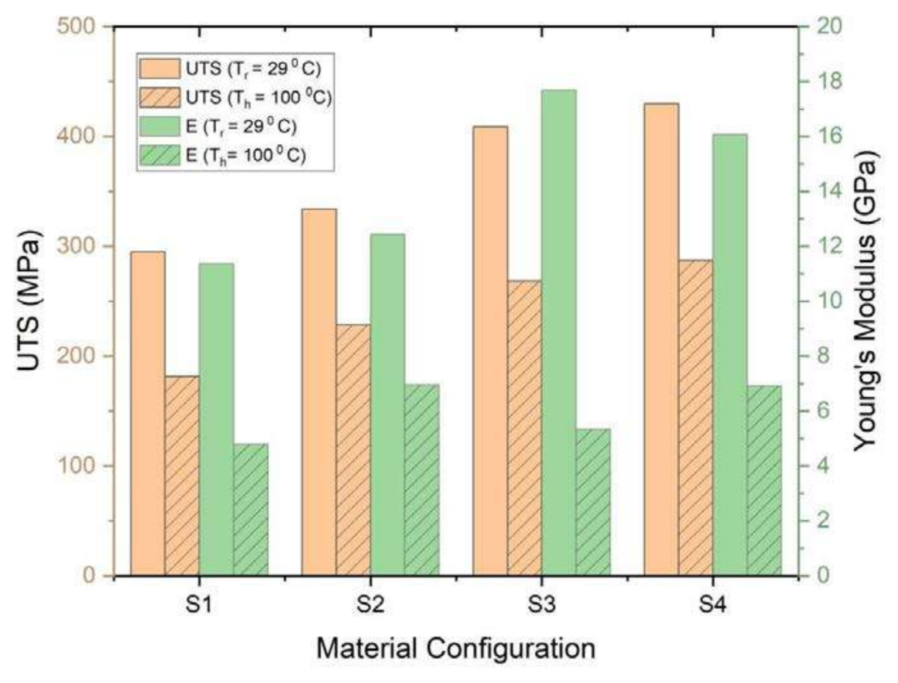


Fig 5: Tensile properties of composite at varying temperature conditions

4. Conclusion

In conclusion, the research findings demonstrate the significant influence of SiC filler content on the mechanical properties of the composite at both room temperature and elevated temperatures. At room temperature, the composite with 7.5% SiC filler exhibited the highest ultimate tensile strength and Young's modulus, indicating the reinforcing effect of SiC particles. The presence of SiC particles contributes to increased bonding and load transfer, enhancing the tensile strength of the composite.

However, beyond a certain threshold (7.5 wt. %), the excessive filler content can lead to agglomeration and poor dispersion, resulting in stress concentrations and a decrease in tensile strength. At elevated temperatures, the composite with 7.5% SiC filler still showed improved tensile strength compared to other compositions. The excellent thermal conductivity of SiC particles enables the composite to withstand high temperatures. The SiC particles contribute to enhanced bonding and load transfer at lower filler content, leading to increased tensile strength. However, excessive filler content can cause agglomeration, hinder the matrix's deformation capability, and introduce internal stresses due to thermal expansion mismatch, thereby reducing the tensile strength of the composite.

Overall, this research emphasizes the importance of optimizing the SiC filler content in composite materials to achieve the desired mechanical properties, considering both room temperature and elevated temperature conditions. These findings provide valuable insights for designing and engineering composites with improved tensile strength and thermal stability for various applications.

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6. Conflict of Interest: Nil.

7. Funding: Nil.

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