INTERNATIONAL JOURNAL OF
AUTOMOTIVE SCIENCE AND TECHNOLOGY

2025, VOL. 9, NO:2, 269-275

www.ijastech.org

e-ISSN: 2587-0963

Nano Silicon Carbide Content on Functional Behaviour of Polypropylene Composites Featured With Basalt Fiber for Automotive Material

T. Vaitheeswaran[1*], J. Jayakumar[1], P. Periyasamy[1], R. Anandan[2], R. Ranjithkumar[1] and M. Nageswaran[3]

[1.] *Department of Mechanical Engineering, M.A.M School of Engineering, Trichy, Tamilnadu, India 621105.*

[2.] *Department of Mechanical Engineering, OASYS Institute of Technology, Trichy, Tamilnadu, India 621006*

[3.] *Department of Mechanical Engineering, Dhanalakshmi Srinivasan University, Trichy, Tamilnadu, India 62112*

Abstract

Polypropylene (PP) is commonly used for lightweight automotive cabinetry and panel applications due to its unique properties, including low density, chemical resistance, improved fatigue resistance, and good thermal insulation. However, the PP matrix typically exhibits lower strength and impact toughness. This research aims to enhance the mechanical properties of PP composites by incorporating 20 weight percent (wt%) of basalt fiber (3-5 mm) along with varying wt% of silicon carbide (SiC) nanoparticles, using the hot compression molding technique. To improve adhesive strength, an epoxy coupling agent is used, and a compression load of 100 MPa is applied. The effectiveness of the composite processing, the fiber-ceramic combination in surface morphology, and the effects of SiC nanoparticles on stress-strain behavior, impact strength, and microhardness of both pure PP and the PP/20 wt% basalt fiber composites are evaluated. The results are compared with the properties of the unreinforced PP matrix. Transmission electron microscope (TEM) analysis revealed a uniform distribution of fibers and ceramics with minimal spacing between the fibers, contributing to the enhanced mechanical properties of the composite. Notably, the PP composite with 20 wt% basalt fiber and 5 wt% silicon carbide demonstrated a tensile strength of 48 MPa, with a slight decrease in strain percentage to 10.5% due to the increased SiC content. It also exhibited a high impact toughness of 24 kJ/m² and improved microhardness of 39 HV. This PP/20 wt% chopped basalt fiber/5 wt% silicon carbide nanoparticle hybrid nanocomposite shows great potential for automotive cabinetry and panel applications.

Keywords: Basalt fiber; Hot pressing; Silicon carbide; Surface morphology; Tensile stress

Research Article

History
Received 13.04.2025
Revised 16.05.2025
Accepted 16.06.2025

Contact
* Corresponding author
T. Vaitheeswaran
vaitheemech1989@outlook.com
Address: Department of Mechanical Engineering, M.A.M School of Engineering, Trichy, Tamilnadu, India 621105.

Tel:+918056505005

To cite this paper: Vaitheeswaran, T., Jayakumar, J., Periyasamy, P., Anandan, R., Ranjithkumar, R., Nageswaran, M. Nano Silicon Carbide Content on F unctional Behaviour of Polypropylene Composites Featured With Basalt Fiber for Automotive Material. International Journal of Automotive Science and Technology. 2025; 9 (2): 269-275. https://doi.org/10.30939/ijastech..1674906

1. Introduction

Composite materials are becoming increasingly important in various engineering applications because they offer better performance compared to traditional monolithic materials [1–3]. In particular, their practical applications related to environmental and structural stability are crucial in determining the service life of these composites [4–5]. Additionally, incorporating hard ceramic particles into the matrix material enhances functional properties beyond those found in monolithic alloys [6–7]. Polymer matrix hybrid nanocomposites are familiar in the automotive panel, dash board, and roof frame applications due to their high strength-to-weight ratio, improved toughness, and better thermal and corrosion resistance behaviour [8]. Hand layup associated with the hot compression method was popular and utilized for polymer composite fabrications [9-10], which offered even compression pressure leading to better interface adhesive bonding between the reinforcements (fiber/ceramic particle) and matrix (polymer) [11]. It results in superior mechanical and thermal behaviour compared to a monolithic polymer matrix [12]. However, the choice of reinforcement (natural/synthetic fiber and nano ceramic particles), matrix, coupling agent, and its process decided the properties of the composite [13-14].

Polypropylene (PP) based composites were attracted in automotive applications due to their unique properties like enhanced strength, lightweight, improved toughness, and better wear resistance behavior than monolithic PP [15-16]. Kaya et al. [17] developed a polypropylene hybrid nanocomposite with different weight percentages of SiC nanoparticles and constant weight percentages of carbon fiber via the compression molding process and evaluated its surface morphology and mechanical/thermal behaviour of composites. It results show that the composite contained higher SiC was found to reduce tensile strength and improve thermal behaviour compared to the PP matrix. Rana et al. [18] investigated the surface morphological and mechanical behaviour of high-density polyethylene hybrid composite embedded with aluminium and silicon carbide nanoparticles via an extrusion process. The 40 % of aluminium and silicon carbide particles found enhanced tensile strength and flexural strength behaviour compared to the PP matrix [19]. Polypropylene hybrid composite was made with carbon hybrid and elium resin via compression molding technique and evaluated its impact toughness behaviour for bicycle helmet applications. The excellence of carbon hybrid and elium resin leads to better impact absorption energy behaviour [20]. The polypropylene composite was made with recycled fly ash particles and studied the mechanical and surface morphology behaviour of composites. The composite composed with 60:40 ratios of PP: fly ash showed the optimum tensile strength (21.4 MPa) and improved impact toughness (20.4 kJ/m^2) [21]. Moreover, the combinations of fiber-ceramic in a polymer matrix provided better mechanical and thermal behaviour compared to a monolithic polymer matrix [22]. Aruna et al. [23] utilized an advanced injection molding process to create an epoxy hybrid composite incorporating both flax and glass fibers. This composite demonstrated excellent tensile and flexural strength. Certain enhancements in properties were observed with the fiber/fiber/ceramic combination. Notably, the tensile performance of the composite was showed significant improvement [24]. Moreover, the addition of 10-15% glass fiber, along with increased carbon particles, contributed to enhanced mechanical properties [25]. Additionally, the hybrid composite that included silicon carbide (SiC) nanoparticles exhibited a marked improvement in both tensile and flexural strength. The presence of SiC is believed to enhance strength by restricting particle mobility and dislocation [26]. Furthermore, moisture absorption characteristics are crucial for composites in practical applications [27]. The synergy of fiber and ceramic reinforcements within a polymer matrix provides enhanced functional performance compared to the base matrix alone [28].

Current results closely related to past studies including reinforcement selection, processing, and its characteristics are elaborated above. Polypropylene has several advantages including light weight, improved chemical resistance, and good thermal stability. However, it has consequences on poor adhesive behaviour resulting in reduced mechanical behaviour including low strength and impact toughness. The present research objectives are enriching the adhesive bonding, tensile stress, and impact strength of polypropylene hybrid nanocomposite featured with 20 wt% of (3-5mm) of chopped basalt fiber and 1-5wt% of nano (50nm) silicon carbide particle (SiC) with epoxy coupling agent via hot pressing technique. Influences of processing and fiber-ceramic combinations of surface morphology and mechanical properties like tensile stress, impact toughness, and microhardness of composite are investigated and its optimum outcome is compared with past literature to highlight the novelty of present research.

2. Materials and Methods

2.1. Materials

In the current research, polypropylene (granules) is chosen as the primary matrix material and has unique properties like lightweight, better toughness, and increased chemical and thermal stability behaviour [15]. Its functional behaviour is enhanced by the additions of chopped basalt fiber (3-5mm length) and nano silicon carbide particles (50 nm). Based on the past literature reported by Krishnaraj et al. [15] and Das et al. [26] the basalt fiber and nano SiC are chosen as 20 wt% and 1-5wt% respectively. The nano-SiC particles possess a hexagonal crystal structure, with a density of 3.21 g/cm³, a hardness of 9.5 on the Mohs scale, a coefficient of thermal expansion of 4.2 × 10-6 K-1, and high thermal conductivity of 270 W/m·K. Before the process, the basalt fiber and nano SiC is preheated by 300 ºC for 5 min through muffle furnace, which reduce the moisture content and enhances the bonding strength [15]. Araldite epoxy/hardener (AW106/HV 953 IN) is used to enhance the adhesive behaviour [11]. Table 1 presents the composite preparation details.

Table 1. Compositions of PP and its hybrid nanocomposites

Composite identification	PP	Basalt fiber	Nano SiC
1	100	0	0
2	79	20	1
3	77	20	3
4	75	20	5

2.2. Fabrication

Figure 1 shows the actual flow process layout for PP composite fabrication via the hot pressing technique. With respect to Table 1, the composite sample 3 preparation detail is presented. The 77wt% of polypropylene granular, 20 wt% chopped basalt fiber, and 3 wt% of nano SiC are weighted via Aczet-made CG 2002L model electronic weighing machine.

Meantime, the 1:10 ratios of epoxy and hardener are mixed manually and the weighted PP and its reinforcements are added into it and involved in mechanical blending action under 100 rpm speed for 10 min, which leads to enhancing the particle-fiber dispersion [11 and 15]. After the blending action, the composite mixture is held at a compression mold die, which is made of titanium nitride-coated tool steel. The composite mixtures are evenly pressed via a compression plunger with 100 MPa under 200 ºC for 10 min resistance time. It helps to enhance the bonding strength and release the air bubbles resulting in enhanced mechanical behaviour of composite [16]. During the processing of composites, the temperature profile followed by 180-200 ºC for 5 min ensure the complete melting and flow of PP [20]. Ultimately, the die-self cured the composite when the hot plate's temperature was gradually lowered to room temperature. Ultimately, the composite section was carefully removed by opening the mold. Ultimately, the die-self cures the composite once the hot plate's temperature is gradually lowered to room temperature (24±1 ºC). After processing, the developed composites undergo post-processing, including an annealing treatment at 80–100 °C for 1 h to minimize residual stress formation. Finally, the composite samples are cleaned and subjected to characterization studies.

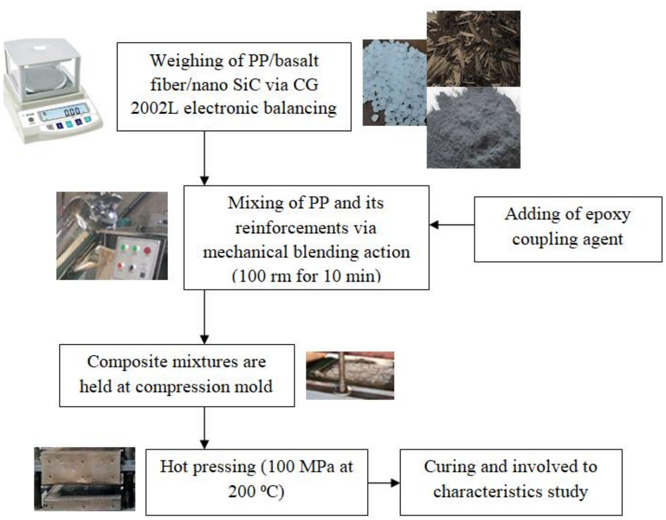

Figure 1. Flow process layout for PP and its composite fabrication

2.3. Characteristics

The microstructure of polypropylene (PP) and its composites is meticulously analyzed using a state-of-the-art transmission electron microscope (TEM) from JEOL, model JEM. Sample preparation involves crafting cubes measuring 3 mm³, each polished to a flawless, glassy finish. Furthermore, we rigorously assess the mechanical properties of PP and its composites, focusing on stress-strain behavior, impact toughness, and microhardness. These evaluations adhere to the highest industry standards, including ASTM D3039 (250 mm X 25 mm X 5 mm), ASTM D6110 (55 mm X 10 mm X 10 mm), and ASTM 2240 (6 mm thickness). The tensile strength of the composites is accurately measured using an Instron 58985 universal testing machine, with a precise crosshead speed of 5 mm/min. Charpy impact toughness is evaluated with an Instron 9050 impact tester, while the microhardness of each composite sample is expertly measured using a Zwick 30 Vickers hardness tester. To ensure reliability, three trials for each composite are conducted, and the average value is reported as the definitive measure of each composite's performance, all with a significance level of 5%. This thorough approach underscores our commitment to delivering accurate and meaningful insights into the mechanical behaviors of these advanced materials [23]. In compliance with the ASTM D570 standard, an investigation of the moisture absorption characteristics of polypropylene (PP) and its composite specimens was conducted. A test sample with dimensions of 76.2 mm x 25.4 mm x 3.2 mm was fabricated and subjected to immersion in distilled water at a temperature of 23±1 °C for a prolonged period of 14 days. The moisture absorption of the composite was quantitatively evaluated using the prescribed equation 1 [27].

$$Moisture\ absorption\ percentage = \left(\frac{W_t - W_o}{W_o}\right) X100 \qquad (1)$$

Where, W_t and W_O is the Wet weight after immersion at time (t) and initial dry weight in g.

3. Results and Discussions

3.1. Surface morphology

Figure 2 (a-d) dramatically showcases the findings from Transmission Electron Microscope (TEM) analysis of polypropylene (PP) and its innovative hybrid nanocomposites, which incorporate 20 wt% chopped basalt fiber and 1-5 wt% nano silicon carbide (SiC) particles. The application of precise hot pressing techniques has significantly elevated the quality of these composites [9]. As depicted in Figure 2 (a), the surface morphology of the PP matrix without reinforcement is pristine, exhibiting a clear structure devoid of major defects.

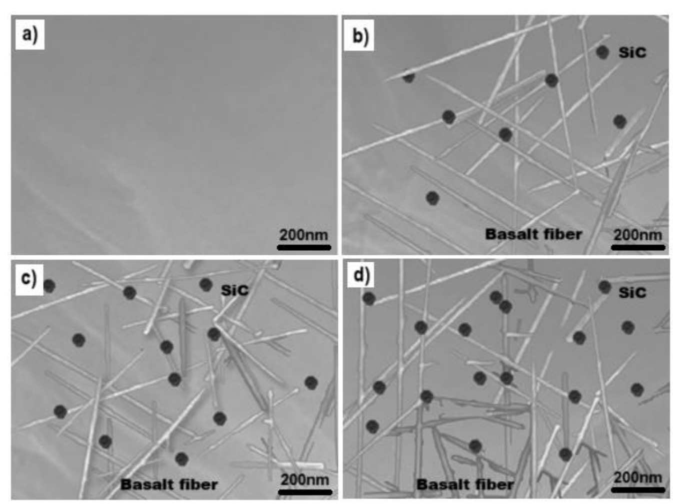

Figure 2. TEM micrograph of a) PP, b) PP/20wt% basalt fiber/1 wt% SiC, c) PP/20wt% basalt fiber/3 wt% SiC, and d) PP/20wt% basalt fiber/5 wt% SiC

Figures 2 (b-d) compellingly illustrate the remarkable uniformity of basalt fiber dispersion, which, when effectively bonded with nano SiC, creates an exceptional interface between the fiber-ceramic composite and the matrix. This combination not only enhances tensile strength but surpasses that of monolithic PP. The meticulous mechanical blending coupled with the applied compression has been critical in achieving superior distribution of fibers and particles throughout the PP matrix [15].Figure 2 (c) powerfully highlights the extensive dispersion of basalt fibers, with SiC nanoparticles strategically interspersed between them. This arrangement fosters an efficient interface with the PP matrix, resulting in impressive tensile strength, while the incorporation of nano SiC mitigates particle dislocation. Moreover, Figure 2 (d) illustrates the enhanced incorporation of nano SiC within the PP matrix, showcasing a seamless and uniform distribution of basalt fibers.

The synergistic effect of the epoxy coupling agent and optimized blending techniques is pivotal in achieving this uniform distribution of fiber and ceramic particles, leading to exceptional energy absorption capabilities. The robust anchoring of fiber-ceramic particles within the PP matrix results in superior absorption properties, outperforming those of the traditional monolithic PP matrix. This comprehensive analysis underscores the transformative potential of these hybrid nanocomposites in advancing material performance.

3.2. Stress-strain

Figure 3 compellingly highlights the stress-strain behavior of polypropylene (PP) and its innovative hybrid nanocomposites, which were engineered using a consistent 20 wt% of chopped basalt fiber alongside varying amounts of nano silicon carbide (SiC) particles, specifically between 1 and 5 wt%. The strategic combination of chopped basalt fiber and nano SiC dramatically enhances tensile strength while significantly reducing elongation percentages compared to the traditional monolithic PP matrix.

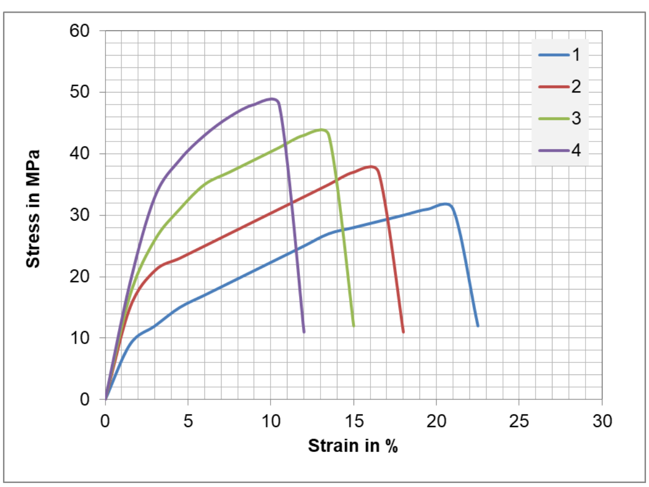

Figure 3. Stress-strain curve for prepared samples

In the baseline PP sample (sample 1), we observed a tensile strength of 31 MPa, accompanied by an elongation at break of 21%, reinforcing its established performance metrics [16]. The introduction of 1 wt% nano SiC in the hybrid nanocomposite (sample 2) resulted in a notable increase in tensile strength, achieving 37 MPa. Despite this strength enhancement, the elongation percentage decreased to 16.5%, a testament to the robust influence of SiC [17].

Sample 3, which included PP, 20 wt% basalt fiber, and 3 wt% nano SiC, exhibited an impressive tensile strength of 43 MPa. This remarkable improvement can be attributed to the efficient dispersion of fibers and ceramics, which together withstand maximum loads and significantly minimize particle dislocation. However, the elongation percentage decreased further to 13.5% due to the presence of the SiC hard phase, which effectively supports load-bearing capabilities while limiting dislocation. This research underscores the potential of these hybrid nanocomposites to transcend the limitations of traditional materials, showcasing their ability to deliver superior mechanical properties that could revolutionize applications in various industries.

3.3. Impact toughness- Charpy test

The impact toughness behavior of polypropylene (PP) and its innovative hybrid nanocomposites—featuring 20 wt% chopped basalt fiber and varying concentrations of nano silicon carbide (SiC) particles between 1-5 wt%—is clearly illustrated in Figure 4. The strategic combination of fiber and ceramic significantly enhances the composite's impact toughness, exceeding that of sample 1, which consists solely of PP without these advanced materials [20]. Importantly, sample 1 recorded an impact toughness of 17.1 kJ/m². With the addition of 20 wt% basalt fibers and just 1 wt% of nano SiC, the toughness improves to an impressive 18.5 kJ/m², showcasing a remarkable leap in performance.

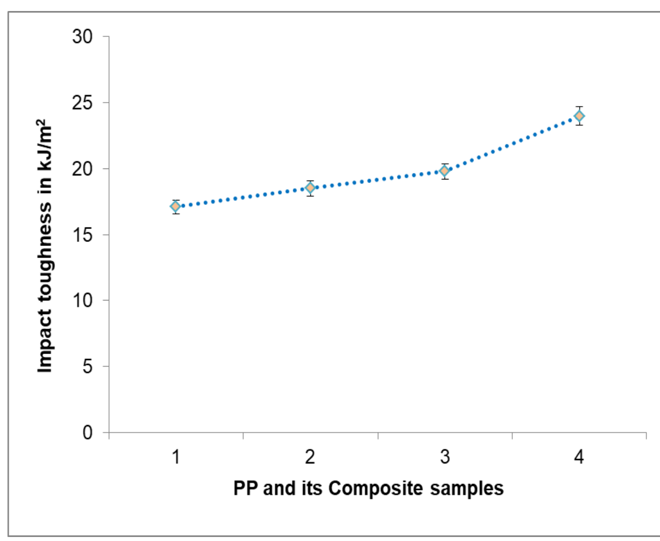

Figure 4. Impact toughness for prepared samples

This substantial enhancement in energy absorption behavior is attributed to the superior dispersion of basalt fibers and nano SiC within the PP matrix, which optimizes the material's structural integrity. Sample 3, incorporating PP with 20 wt% basalt fiber and 3 wt% nano SiC, achieved an impact toughness of 19.8 kJ/m², highlighting the effective pinning action of the fiber-ceramic combination that fortifies the PP matrix. Most strikingly, sample 4—comprising 20 wt% basalt fiber and 5 wt% nano SiC—reached a noteworthy impact toughness value of 24 kJ/m². This represents a remarkable 40% improvement over sample 1 (pure PP) and a 17.6% enhancement compared to a composite with a traditional 60:40 ratio of PP to fly ash [21]. These results clearly affirm the superior performance and potential of these hybrid composites in high-impact applications.

3.4. Microhardness

Figure 5 vividly demonstrates the remarkable microhardness behavior of polypropylene (PP) and its innovative hybrid nano-composite, which incorporates 20 wt% basalt fiber and varying concentrations of silicon carbide (SiC) nanoparticles at 1-5 wt%. The integration of SiC and basalt fiber into the PP matrix leads to a substantial enhancement in microhardness, significantly outperforming the traditional monolithic PP matrix. Specifically, the microhardness of the PP composite featuring 20 wt% basalt fiber and 1 wt% SiC nanoparticles registers an impressive 24 HV. With a strategic increase in SiC content to 3 wt% and 5 wt%, the microhardness escalates dramatically to 32 HV and 39 HV, respectively. This marked improvement can be attributed to the exceptional interfacial bonding between the PP matrix and the fiber/SiC nanoparticles, enabling the material to withstand indentation under applied loads effectively [26].

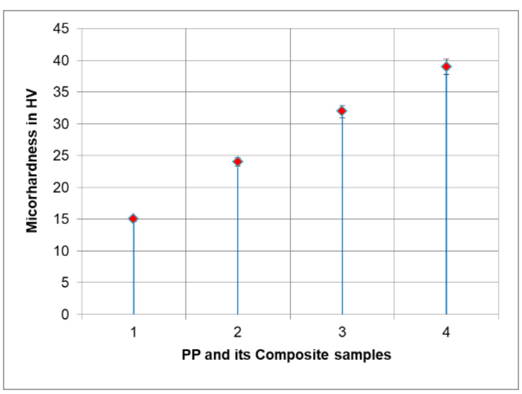

Figure 5. Microhardness for prepared samples

Notably, the microhardness of the PP/20 wt% basalt fiber/5 wt% SiC hybrid nanocomposite is an astounding 160% greater than that of the standard monolithic PP matrix.

3.5. Moisture absorption behaviour

The moisture absorption behavior of polymer composites is a critical factor in extending the service life of these materials in real-world applications. In the current study, we evaluated the moisture absorption of polypropylene (PP) and its composites over periods of 7 days and 14 days, with the results displayed in Figure 6.

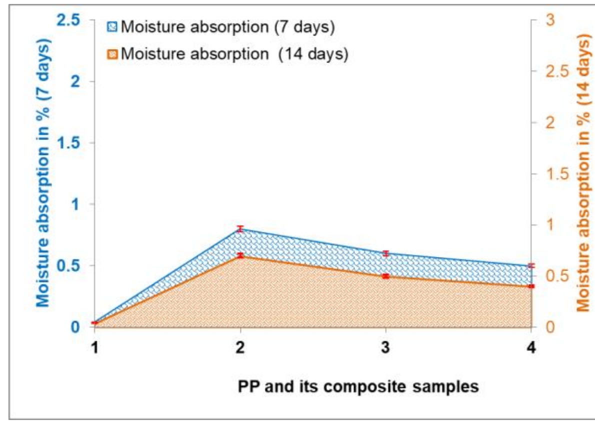

Figure 6. Moisture absorption behaviour

The composite lacking basalt fiber and silicon carbide (SiC) demonstrated minimal moisture absorption, measured at just 0.04% after both 7 and 14 days. Interestingly, the composites tested over 14 days exhibited lower moisture absorption compared to those tested over 7 days. This difference can be attributed to the improved fiber-ceramic interface, which helps limit moisture ingress. The moisture absorption values for samples 2, 3, and 4 were 0.7%, 0.5%, and 0.4%, respectively. The presence of nano SiC enhances surface hydrophobicity and effectively reduces micro-voids, thereby increasing the composite's resistance to moisture absorption [26].

Table 2. Comparison of current research to earlier research

Composite details	Tensile strength in MPa	Impact toughness	Applications	References
PP/10% lemon leaf/10% egg shell	18	-	Lightweight automotive cabin	19
Polypropylene/carbon hybrid and Eliumresin	-	101.1J	Bicycle helmet shells	20
Polypropylene/fly ash (60:40 ratios)	21.4	20.4 kJ/m^2	Automotive applications	21
Polypropylene/6 % SiC and 10 % hemp fiber	51.73	5.5 kJ/m^2	Automotive roof and seat frame	29
Polypropylene/13%Cellulose fiber/2%silica	38	-	Lightweight structural	30
Epoxy/20% bamboo fiber/4% SiC	42	21.5kJ/m^2	Lightweight automotive components	31
PP/20wt% Basalt fiber/ 5wt% nano SiC	48	24 kJ/m^2	Automotive cabinetry and panels	Current

These compelling findings underscore that the PP/20 wt% basalt fiber/5 wt% nano SiC hybrid nanocomposite not only exhibits superior microhardness but also offers optimal tensile strength and impact toughness compared to other composite samples. This research represents a significant advancement in the field, as detailed comparisons with previous literature studies further highlight its groundbreaking nature. More comprehensive insights are provided in Table 2. The tensile strength behaviour of PP/20 wt% basalt fiber/ 5 wt% nano SiC hybrid nanocomposite is found maximum value and shows 166 % , 124 % , 26.3 %, and 14.2 % better than PP/10% lemon leaf/10% eggshell composite [19], polypropylene/fly ash (60:40 ratios) composites [21], Polypropylene/13%Cellulose fiber/2%silica [30], and Epoxy/20% bamboo fiber/4% SiC [31]. Likewise, sample 4 (PP/20 wt% basalt fiber/ 5 wt% nano SiC hybrid nanocomposite) is found higher impact toughness value. It is 17.6 % better than the polypropylene/fly ash (60:40 ratios) composites [21].

3. Conclusions

This study presents an innovative approach to developing polypropylene (PP) and its hybrid nanocomposite, which features a remarkable combination of 20 wt% chopped basalt fiber and 1-5 wt% nano silicon carbide (SiC) particles, achieved through an advanced hot pressing technique. The integration of an epoxy coupling agent significantly enhances adhesive properties, resulting in a substantial increase in tensile strength and impact toughness of the composite. Below are the compelling findings from this investigation.

- The Transmission Electron Microscope (TEM) analysis provides striking insights into the surface morphology of PP and its composites. With precise composite processing, the distribution of fiber and ceramic particles is exceptionally uniform, and the incorporation of the epoxy coupling agent maximizes adhesion, leading to superior mechanical performance.
- Notably, composite sample 4—featuring 20 wt% basalt fiber and 5 wt% nano SiC particles—exhibits a remarkable tensile stress value that surpasses sample 1 (the PP matrix without the fiber-ceramic phase) by an impressive 55%.
- Furthermore, sample 4 stands out with exceptional impact toughness and microhardness properties, showing increases of 40% and 160%, respectively, compared to sample 1, which lacks the fiber-ceramic additive.
- The outstanding performance of the PP composite, composed of 20 wt% basalt fiber and 5 wt% nano SiC, highlights its strong potential for applications in automotive panel production. Future investigations will delve into wear behavior under varying loads, sliding speeds, and distances, while examining the impact of these parameters on wear rate and coefficient behavior. This research not only paves the way for enhanced material performance but also promises exciting possibilities for future applications. Furthermore, finite element analysis (FEA) was incorporated to optimize the composite sample design for structural and thermal stability studies, and the investigation of environmental durability is proposed for future research.

Conflict of Interest Statement

There is no conflict of interest in the study.

CRediT Author Statement

T.Vaitheeswaran: Writing-original draft, Validation, Supervision
J. Jayakumar: Conceptualization, Data collections,
P. Periasamy: Experimental work and data collections
R. Anandan: Validation, Conceptualization, support for testing
R. Ranjitkumar: Formal analysis and support for testing
M. Nageswaran: Data curation and Formal analysis

References

[1] Uygur I, Cicek A, Toklu E, KaraR, Saridemir S. Fatigue life predictions of metal matrix composites using artificial neural networks. Arch. Metall. Mater. 2014:59(1):97-103. https://doi.org/10.2478/amm-2014-0016

[2] Uygur I. Tensile behaviour of P/M processed (Al-Cu-Mg-Mn) / SiCp composites. Iranian J.Science & Techn. 2004:B28(B2): 239-48.

[3] Uygur I, Evans WJ, Bache M, ve Gulenc B. Fatigue behaviour of SiCp reinforced 2124 Aluminium matrix composites. Metallofiz. Nove. Tekhnol. 2004:26 (7): 927-39 .

[4] Uygur I. Notch behavior and fatigue life predictions of discontinuously reinforced MMCs. Arch. Metall. Mater. 2011:56(1):109-115. https://doi.org/10.2478/v10172-011-0012-1

[5] Uygur I. Influence of Particle Sizes and Volume Fractions on Fatigue Crack Growth Rates of Aerospace Al-Alloys Composites. Arch. Metall. Mater. 2024:69(1):337-41. https://doi.org/10.24425/amm.2024.147827

[6] Uygur I, Gerengi H. Investigation of Corrosion Fatigue Crack Growth in Aluminium Alloy-Based Metal Matrix Composites: A Comparative Study. Duzce University J. Sci. and Tech. 2025:13 (1):372-82. https://doi.org/10.29130/dubited.1562991

[7] Uygur I. Comparison of fatigue crack growth rates for particulate reinforcement composite and base alloy. In Properties of Materials, Edt, I.Uygur, Bıdge Pub, Ankara, Türkiye, 2023: pp. 77-87.

[8] Ravishankar B, Nayak SK, Kader MA. Hybrid composites for automotive applications – A review. J Reinf Plast Compos. 2019;38(18):835–45. http://dx.doi.org/10.1177/0731684419849708

[9] Kartik Shubham S, Pandey A, Purohit R. Development and characterization of biodegradable hybrid fiber-reinforced sandwich composites using hand lay-up and compression molding technique. J Mater Eng Perform. 2025. http://dx.doi.org/10.1007/s11665-025-10742-4

[10] Agma O, Basturk S. Synthetic, hybrid and natural composite fabrication processes. In: Structural Integrity and Monitoring for Composite Materials. Singapore: Springer Nature Singapore; 2023. p. 115–37. https://doi.org/10.1007/978-981-19-6282-0_7

[11] Velmurugan S, Janakiraman T, Nandhini S, Ganesha Rathinam M. Exploring the mechanical and morphological characteristics of hybrid-reinforced polymer composites. In: SAE Technical Paper Series. 400 Commonwealth Drive, Warrendale, PA, United States: SAE International; 2024. https://doi.org/10.4271/2023-01-5181

[12] Pandian A, Kaliappan S, Natrayan L, Reddy V. Analyzing the

moisture and chemical retention behavior of flax fiber–ceramic hybrid composites for automotive underbody shields. In: SAE Technical Paper Series. 400 Commonwealth Drive, Warrendale, PA, United States: SAE International; 2024. https://doi.org/10.4271/2024-01-5006

[13]Kaliappan S, Natrayan L, Mohammed Ali H, Kumar P. Thermal and mechanical properties of <italic>Abutilon indicum</italic> fiber-based polyester composites under alkali treatment for automotive sector. In: SAE Technical Paper Series. 400 Commonwealth Drive, Warrendale, PA, United States: SAE International; 2024. https://doi.org/10.4271/2024-01-5031

[14]Malkapuram D. Development of hybrid natural fiber reinforced composite material for automotive applications. In: SAE Technical Paper Series. 400 Commonwealth Drive, Warrendale, PA, United States: SAE International; 2023. https://doi.org/10.4271/2023-28-0131

[15]Krishnaraj, Sambandha T, Arun, Vaitheeswaran. Fabrication and wear characteristics basalt fiber reinforced polypropylene matrix composites. In: SAE Technical Paper Series. 400 Commonwealth Drive, Warrendale, PA, United States: SAE International; 2019. https://doi.org/10.4271/2019-28-2570

[16]Ramírez-Herrera CA, Tellez-Cruz MM, Pérez-González J, Solorza-Feria O, Flores-Vela A, Cabañas-Moreno JG. Enhanced mechanical properties and corrosion behavior of polypropylene/multi-walled carbon nanotubes/carbon nanofibers nanocomposites for application in bipolar plates of proton exchange membrane fuel cells. Int J Hydrogen Energy. 2021;46(51):26110–25. http://dx.doi.org/10.1016/j.ijhydene.2021.04.125

[17]Kaya N, Demiç Ş, Karaman M. Fabrication of carbon fiber/silicon carbide hybride polypropylene composites as thermal interface material. Polym Sci Ser A. 2025; http://dx.doi.org/10.1134/s0965545x2460128x

[18]Rana S, Hasan M, Sheikh MRK, Faruqui AN. Mechanical and morphological properties of high density polyethylene-Al-SiC hybrid composites. Adv Mater Process Technol. 2022;8(1):1135–46. http://dx.doi.org/10.1080/2374068x.2020.1853497

[19]Hayajneh MT, AL-Oqla FM, Al-Shrida MM. Hybrid green organic/inorganic filler polypropylene composites: Morphological study and mechanical performance investigations. E-polymers. 2021;21(1):710–21. http://dx.doi.org/10.1515/epoly-2021-0074

[20]Bhudolia SK, Gohel G, Subramanyam ESB, Leong KF, Gerard P. Enhanced impact energy absorption and failure characteristics of novel fully thermoplastic and hybrid composite bicycle helmet shells. Mater Des. 2021;209(110003):110003. http://dx.doi.org/10.1016/j.matdes.2021.110003

[21]Ajorloo M, Ghodrat M, Kang W-H. Incorporation of recycled polypropylene and fly ash in polypropylene-based composites for automotive applications. J Polym Environ. 2021;29(4):1298–309. http://dx.doi.org/10.1007/s10924-020-01961-y

[22]Ali NH, Shihab SK, Mohamed MT. Mechanical and physical characteristics of hybrid particles/fibers-polymer composites: A review. Mater Today. 2022;62:178–83. http://dx.doi.org/10.1016/j.matpr.2022.02.614

[23]Aruna M, Devanathan C, Chandramohan P, Manivannan S, Kumar MV, Kumar A, et al. Exposure of glass fiber on behaviour of epoxy/flax fiber hybrid composite made through injection mould route. J Inst Eng (India) Ser D. 2024; http://dx.doi.org/10.1007/s40033-024-00779-5

[24]Hangargi S, Swamy A, Raj RG, Aruna M, Venkatesh R, Madhu S, et al. Enhancement of Kevlar fiber-polypropylene composite by the inclusions of cotton stalk and granite particle: characteristics study. Biomass Convers Biorefin. 2024;14(23):30305–14. http://dx.doi.org/10.1007/s13399-023-04817-2

[25]Satish Kumar D, Sathish T, Mavinkere Rangappa S, Boonyasopon P, Siengchin S. Mechanical property analysis of nanocarbon particles/glass fiber reinforced hybrid epoxy composites using RSM. Compos Commun. 2022;32(101147):101147. http://dx.doi.org/10.1016/j.coco.2022.101147

[26]Das AD, Kamatchi RM, Kaliyaperumal G, Ajin M, Shanmugam R. Synthesis and functional behavior of sisal fiber-incorporated epoxy hybrid nanocomposite enriched by nano-SiC. J Inst Eng (India) Ser D. 2024; http://dx.doi.org/10.1007/s40033-024-00683-y

[27]Jagadeesh P, Puttegowda M, Boonyasopon P, Rangappa SM, Khan A, Siengchin S. Recent developments and challenges in natural fiber composites: A review. Poly. Composites. 2022:43(5):2545-61. https://doi.org/10.1002/pc.26619

[28]Dundar M, Ficici F, Ozen F, Unal H. Investigation of the Delamination Factor of Glass Sphere and Silicon Particle Reinforced (GS-SCR) Hybrid Composite Material. in Proceedings of the 6th International Congress & Exhibition on Advances in Applied Physics and Materials Science (APMAS 2016), 2017:131(3) 595–97. https://doi.org/10.12693/APhysPolA.131.595

[29]Venkatesh R. Influences of silicon carbide on mechanical performance of polypropylene/hemp fiber composite for automotive applications. Interactions. 2025:246:26. https://doi.org/10.1007/s10751-025-02251-6

[30]Iskakov, RM, Bukanova, AS, Obidin IM, Kuzin MS, Skvortsov IY. Eco-fricendly polypropylene composites reinforced with cellulose fibers and silica nanoparticles. Polymer. 2025:17(10):1290. https://doi.org/10.3390/polym17101290

[31]Tahir D, Karim MRA, Hu H. Analysis of mechanical and water absorption properties of hybrid composites reinforced with micron-size bamboo fibers and ceramic particles. Int. Polym. Proc. 2024:39(1):115-124. https://doi.org/10.1515/ipp-2023-4374