Influences of Nano Silicon Carbide Particles on Microstructural and Mechanical Properties of Polypropylene Composites

E Vadivel1,a), R Venkatesh1,b)

1 Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha Institute

*of Medical and Technical Sciences, SIMATS, Chennai, 602105, Tamil Nadu, India.*

Corresponding author: a)[*iamevadivel@gmail.com*](mailto:iamevadivel@gmail.com)*, b)*[*venkidsec@gmail.com*](mailto:venkidsec@gmail.com)

Abstract: Polymer composites present compelling advantages that make them invaluable across various industries. With a unique properties like strength-to-weight ratio, enhanced impact toughness, superior thermal stability, increased stiffness, and excellent corrosion resistance, these materials are ideal for applications in the automotive, aviation, and sports sectors. This research focuses on the preparation and enhancing the functional properties of polypropylene (PP) nanocomposites integrated with nano silicon carbide (SiC) particles using an epoxy coupling agent through hand layup followed by hot compression molding, applying a compression force of 100 MPa. The study examines how the inclusion of nano SiC particles and epoxy affects the mechanical performance of the resulting composites. Microstructure of developed samples is examined through transmission electron microscopy (TEM), which shows the homogenous particle dispersion resulting enhanced mechanical properties of composites. The findings reveal significant enhancements in impact resistance, microhardness, and tensile strength, surpassing those of conventional unreinforced PP. Notably, the PP/5 wt% nano SiC composite showed impressive improvements of 37.5% in impact toughness, 121% in hardness, and 24% in tensile strength over the unreinforced monolithic PP matrix. These outstanding properties position the PP/5 wt% nano SiC composite as an excellent choice for automotive cabinetry, promising durability and performance that can't be overlooked.

# Introduction

Reduction of weight and enhancement of specific strength is the prime goal for the automotive industry, and polymer-based composites fill their finding by combining multi-reinforcement via an advanced manufacturing process [1-2]. Polypropylene-based composites are better choices for automotive components due to their lower specific weight and enhanced mechanical and high chemical resistance behaviour [3]. Besides, the natural fiber-embedded PP composite finding a challenge for higher moisture absorption leads to limits the properties of composites [4], which is overcome by the fiber treated with sodium hydroxide (NaOH) chemical [5]. However, composite laminate is prepared by hand layup technique, which is the common route and economic operation [6]. However, the adhesive behaviour of the composite may decided by the choice of coupling agent and its compression action [7]. Hand layup associated with compression (hot) action found better bonding strength between matrix to fiber and favours enhancing the functional behaviour of composites [8].

Different weight percentages of multiwall carbon nanotube featured PP composite by compression moulding process and evaluated its mechanical and thermal behaviour of composites. The higher content of nanofiller favours superior impact & tensile strength and enhanced thermal stability behaviour [9]. The polyester composite is made with SiC nanoparticles and Kevlar fiber via the compression mould technique. The impact of SiC action on the functional behaviour of polymer composites is evaluated, and the composite fabricated by2.5wt% of SiC and 15wt% of Kevlar fiber exhibited optimum impact strength, better hardness, and improved tensile strength behaviour of composites [10-14]. The effect of nanographene filler on the mechanical and thermal behaviour of polypropylene composites is studied, and the composite fabricated by a higher content of graphene nanoplatelets is exposed to superior tensile strength, improved toughness, and optimum thermal stability behaviour compared to monolithic PP matrix [15-19]. Polymer hybrid nanocomposite is synthesized with different weight percentages of graphene nanoplatelets and alumina nanoparticles via hand layup associated with the compression mould route. The improved content of alumina exposed increased hardness, better yield, tensile strength, and higher flexural strength behaviour [20-23]. Varied weight percentages of sisal fiber integrated polypropylene composites are made via hand layup technique and evaluated its tensile, flexural, and impact strength of composite with ASTM standards. Loading of higher sisal fibre shows better enhancement in tensile/flexural and impact toughness properties, which are superior to monolithic PP matrix [24-29]. Moreover, the natural fiber is processed with 5% NaOH solution and incorporated with a polypropylene matrix via a compression moulding route. The improved content of banana natural fiber influences good tensile strength, better fiber distribution, and enhanced flexural strength behaviour [30-32]. However, polymer composite behaviour is enhanced by the addition of multiple reinforcements via advanced processing techniques, including compression (hot), injection, and vacuum bag route [33-35].

The polypropylene composite closely related to past studies is discussed above. The polymer composite made with natural fiber composite was found to improve moisture absorption, resulting in decreased mechanical properties of the composite and limiting the composite life. There are no specific reports available on SiC-reinforced polymer composite. This research investigation of polypropylene (PP) composites are fabricated with 0, 1, 3, and 5wt% of nano SiC with epoxy coupling agent via hand layup route associated with hot compression mould route. Impacts of SiC and epoxy coupling agents on microstructure, impact toughness, microhardness, and tensile strength behaviour of PP composites are evaluated. Its results are compared with the PP matrix developed without reinforcements.

# Materials and Fabrication

## Selection of base and filler material

With the benefits including lower specific weight, improved strength, and better toughness reasons [9], polypropylene (PP) is taken as a base matrix, whose functional properties are enhanced by the integration of 1, 3, and 5wt% of nano silicon carbide particles. The SiC nanoparticle has superior elastic modulus, higher hardness, and improved thermal stability at higher processing temperatures [10, 36-38]. The basic properties of PP and nano SiC are highlighted in Table 1.

Table 1 Physical properties of PP and nano SiC

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Behaviour/Material | Density in g/cc | Tensile strength in MPa | Size | Nature | Melting temperature in ⁰C |
| PP-Base matrix | 0.94 | 45 | 300 mm X 300 mm | Polymer | 170 |
| Nano SiC-Reinforcements | 3.21 | - | 50nm | Ceramic | 2730 |
| Epoxy resin-coupling agent | 1.2 | 35-90 | - | Thermosetting polymer | 300 |

Epoxy (LY556) Araldite and trimethylene tetra amine (HY951) are taken as epoxy resin and hardener phase, which is mixed by 10:1 ratio. It is considered a coupling agent between the PP-SiC-PP matrix.

## Fabrication of PP and its nanocomposites with nano SiC

The composite fabrication details, along with their composition, are presented in Table 2. Based on this, the PP and its composites are fabricated. Presently, the composite sample 3 fabricating details are elaborated.

The 300 mm X 300mm X 0.5 mm PP lamina is prepared and kept in the table. The coupling agent of epoxy resin: hardener: nano SiC is blended as ratios of 10:1:3 via mechanical stirrer with 50rpm for 5 min favours to uniform particle dispersion [6, 39], and the mixing solution is applied over the PP matrix by hand roller featured with soft roller brush. The next layer of PP is fixed over the solution. A similar procedure was repeated for 10mm thickness and covered with a Teflon sheet. The composite layers are kept in a hot compression press, which is shown in Figure 1. The 100 MPa pressure is applied with a processing temperature of 200⁰C is followed for 5min favors to enrich the adhesive quality of thecomposite [9]. The compressed composite layers are cured at ambient temperature with 65% relative humidity. The composites are subjected to a characteristics study.

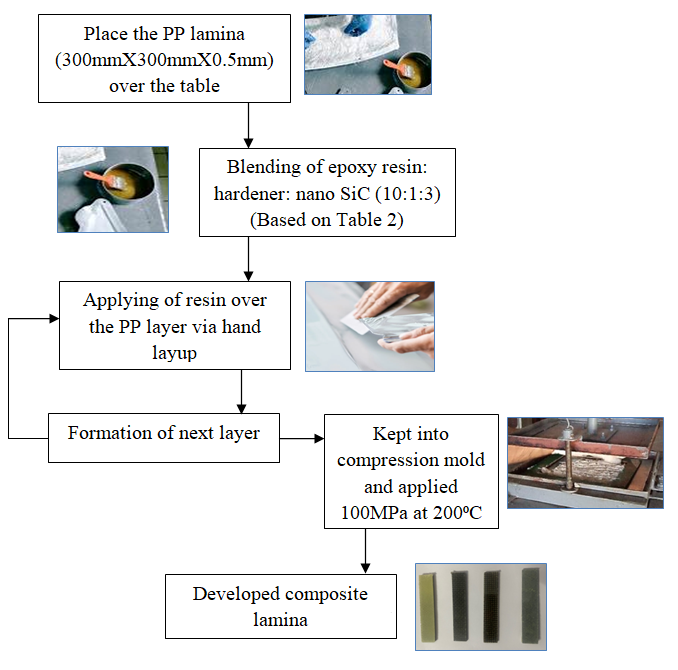


Fig. 1 Actual flow process layout for PP composites preparation

Table 2 Composite composition

|  |  |  |
| --- | --- | --- |
| Composite  samples | PP lamina | Epoxy resin: Hardener: Nano SiC in wt% |
| 1 | 300 mm X 300 mm  X 0.5 mm | 10:1:0 |
| 2 | 10:1:1 |
| 3 | 10:1:3 |
| 4 | 10:1:5 |

## Characteristics study

The Charpy impact toughness of the composite was rigorously evaluated using an ELMECH-IT30 model Impact Toughness machine, boasting a robust capacity of 300 J. This assessment adhered strictly to the ASTM D6110 standard [6], ensuring reliable and accurate results. For microhardness evaluation, we employed the Instron-make VM 30 model Vickers hardness tester, following the ASTM E384 standard [7, 40-42]. An applied load of 0.1kg for 10 seconds was used, providing precise measurements that reflect the material's quality. Tensile testing of the composite samples was performed with an advanced Instron-34 series universal testing machine, capable of sliding speeds from 0.05 to 200 mm/min. This procedure was carried out in accordance with ASTM D3039 standards [9-10], reinforcing the integrity of our findings. In our mechanical testing, we conducted three trials for each polypropylene (PP) composite and calculated the average of these trials to determine the composite's true performance. We established a test significance level of 5%, ensuring that our results are both trustworthy and credible [10].THERMOFISHER-TALOS, model F200Xtransmission electron microscope (TEM) is used to evaluated the microstructure of developed composite samples.

# Results and Discussion

## Charpy impact toughness

The charpy impact strength property of PP composite samples 1, 2, 3, and 4 prepared by 0, 1, 3, and 5wt% of nano SiC is shown in Figure 2. The Charpy impact strength property of the PP matrix (composite sample 1) is lower than the nano SiC-reinforced composite samples. The coarse grain structure with even dispersion of SiC makes a better pinning effect with the PP matrix, resulting in improved impact strength of the composite. The PP composite sample 1 depicts 2.4kJ/m2 impact toughness, and the composite sample 2 of PP with 1wt% of nano SiC recorded by 2.5kJ/m2. The addition of nano SiC with PP matrix has better bonding strength due to applied compression pressure [43-48].

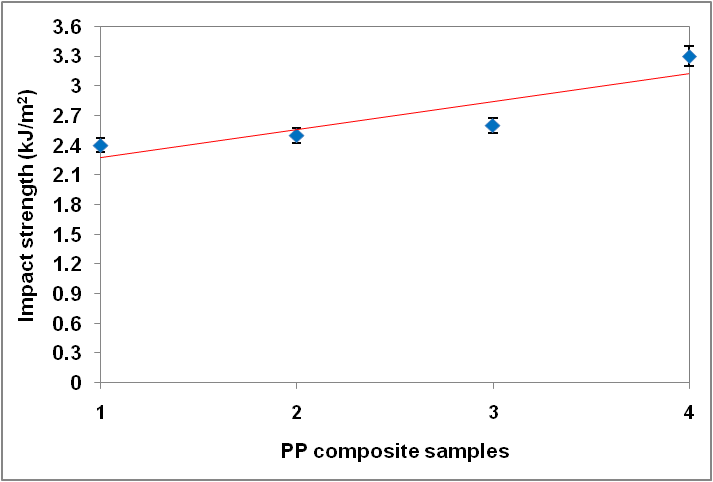


Figure 2 Charpy impact toughness behaviour of PP composite samples

Moreover, the impact of the toughness property of composite sample 3 of PP with 3wt% nano SiC shows the marginal enhancement in impact toughness (2.6kJ/m2), which is more than composite sample 1. However, composite sample 4 of PP with 5wt% nano SiC has an optimum impact toughness value (3.3kJ/m2), which is 37.5% better than composite sample 1. Effective bonding action between matrix to filler material formed by epoxy coupling agent followed by compression pressure.

## Microhardness

The microhardness property of composite samples 1, 2, 3, and 4 contained 0-5wt% of nano SiC is shown in Figure 3. The exposures nano SiC in the PP matrix have optimum hardness value, and the composite sample 1 of PP without filler is 14HV, which is lower than the other composite samples 2, 3, and 4). The 21HV is observed by composite sample 2, which is composed of 1wt% of nano SiC and marginally enhanced its hardness by 25HV due to even dispersion of nano SiC limits the indentation against the load [8]. Even blending of epoxy and nano SiC found uniform particle dispersion, and applied compression force favours better bonding strength property and results in optimum hardness of composite [12, 49].

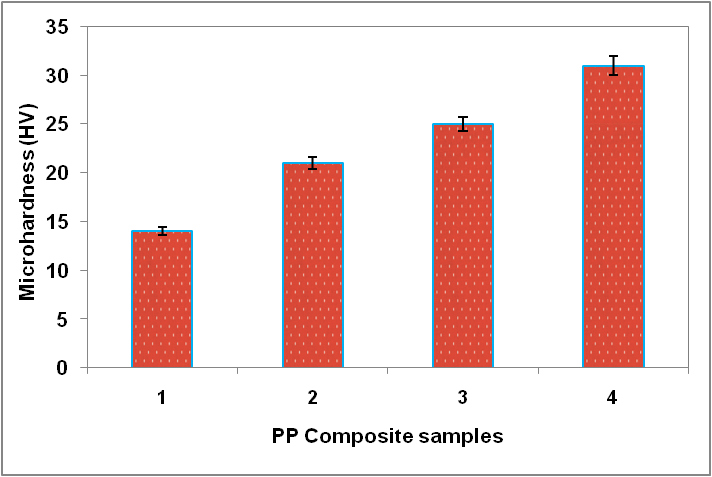


Figure 3 Microhardness of PP composite samples

Besides, composite sample 4 of PP with 5wt% of nano SiC has 31HV and improved by 121% than composite sample 1 of PP without filler.

## Tensile strength

Figure 4 illustrates the tensile behaviour of PP composites fabricated with 0-5wt% of nano SiC particles.The tensile strength behaviour of the PP composite is 46 MPa, and the composite sample made with nano SiC was recorded as higher than the value of PP without filler material. The tensile property of composite sample 2 is 47MPa, and 49MPa is seen in composite sample 3 of PP with 3wt% nano SiC. The effective contribution of nano SiC endures the maximum load and resists the crack initiation during the high load. However, the composite sample 4 of PP prepared with 5wt% of nano SiC exhibited maximum tensile strength, and its value is 57MPa. The contribution of the SiC nanoparticle withstands maximum stress concentration and limits the dislocation of particles [50-51].

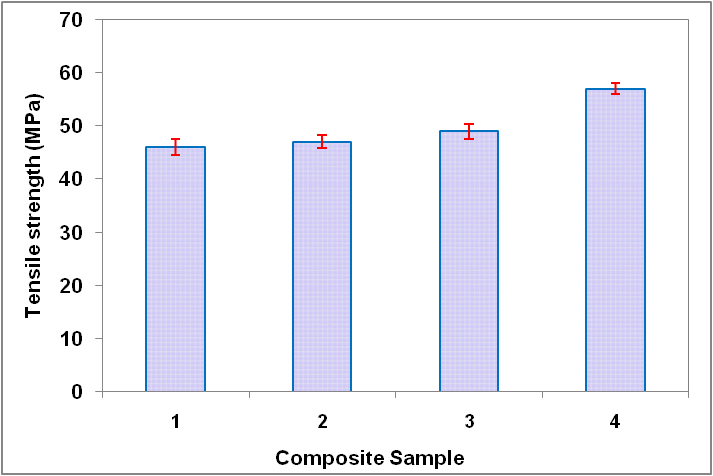


Figure 4 Tensile strength of PP composite samples

Moreover, the additions of nano SiC influences to reduce its elongation behaviour, and the PP composite made with 1, 3, and 5 wt% nano SiC is found to be 102, 100, and 98% for elongation behaviour due to the presence of hard SiC influences to brittle failure [13].

## TEM analysis

Figure 5 (a-d) indicates the TEM microstructure of developed PP and its composite samples. Figure 2 (a) indicates the microstructure of PP matrix without SiC nanoparticle. An applied compression force with 200⁰C leads to quality PP matrix without porosity. Figure 2 (b) indicates the microstructure of composite sample made with 1wt% of SiC nanoparticles. Uniform blending action of epoxy resin with nano SiC is found uniform dispersion in PP matrix and leads to better mechanical properties.

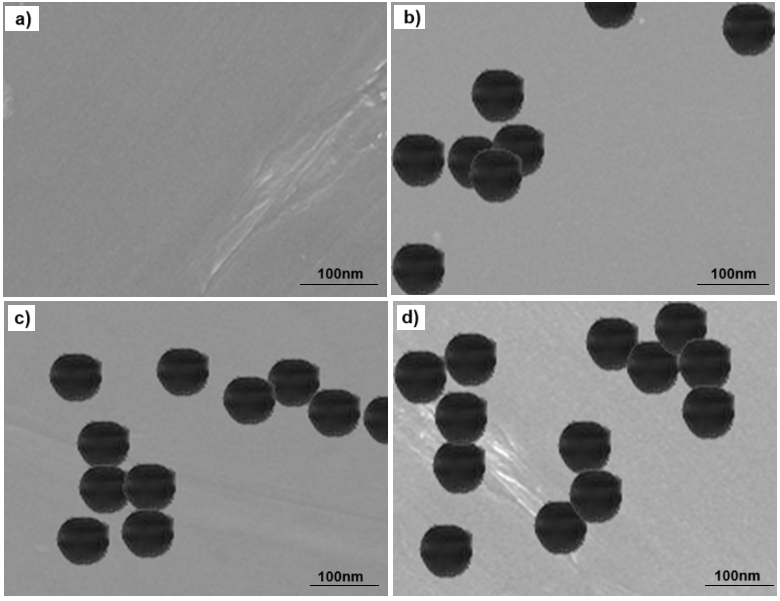


Figure 5 TEM analysis of a) PP sample 1, b) Composite sample 2, c) Composite sample 3, and d) Composite sample 4

Moreover, Figure 2 (c) presents the Tem microstructure of composite sample 3, which is made with 3wt% of SiC nanoparticles. An increased content SiC is widely dispersed with PP matrix and found good pinning effect with PP matrix resulting enhanced impact strength value of composite [10]. However, the composite sample 4 of PP with 5wt% nano SiC has found uniform dispersion with in the PP boundaries and leads to endures the maximum stress concentration behaviour [8].

# Conclusion

The technique of hand layup associated with the hot compression moulding process is successfully adopted for making the polypropylene composite integrated with 0, 1, 3, and 5 wt% of nano silicon carbide particle (SiC) with an epoxy coupling agent, which favours to optimum adhesive behaviour between the matrix and filler materials. Based on the investigational results, the composite prepared with 5wt% of nano SiC along with 10:1 ratios of epoxy resin: hardener on mechanical properties of composites are evaluated and followed by ASTM standards. The important conclusions are derived below.

The composite sample 4 of PP with 5wt% of nano SiC found superior mechanical properties than other composite samples.

The composite sample 4 of PP with 5wt% nano SiC has attained maximum impact toughness, and its value is 3.3kJ/m2, which is superior to the other composite samples.

The microhardness of composite sample 4 is identified by 31HV, which is superior to the monolithic PP matrix composite sample without filler materials.

The tensile strength of composite sample 4 is optimum, and its value is 57MPa. It is higher than the values of composite sample 1 without nanofiller.

The scope and future work involve wearing studies under different loads, distances and varied velocities. The optimum composite sample 4 of PP/with 5wt% nano SiC is used for automotive cabinet applications.

# References

1. Rosenthal, S., Maaß, F., Kamaliev, M., Hahn, M., Gies, S., &Tekkaya, A. E. (2020). Lightweight in Automotive Components by Forming Technology. Automotive Innovation, 3(3), 195–209. https://doi.org/10.1007/s42154-020-00103-3
2. Agarwal, J., Sahoo, S., Mohanty, S., &Nayak, S. K. (2020). Progress of novel techniques for lightweight automobile applications through innovative eco-friendly composite materials: A review. Journal of Thermoplastic Composite Materials. SAGE Publications Ltd. https://doi.org/10.1177/0892705718815530
3. Hangargi, S., Swamy, A., Raj, R. G., Aruna, M., Venkatesh, R., Madhu, S., …Kalam, M. A. (2023). Enhancement of Kevlar fiber-polypropylene composite by the inclusions of cotton stalk and granite particle: characteristics study. Biomass Conversion and Biorefinery. https://doi.org/10.1007/s13399-023-04817-2
4. Vigneshwaran, S., Sundarakannan, R., John, K. M., Joel Johnson, R. D., Prasath, K. A., Ajith, S., …Uthayakumar, M. (2020, December 20). Recent advancement in the natural fiber polymer composites: A comprehensive review. Journal of Cleaner Production. Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2020.124109
5. Raghuvaran, S., Vivekanandan, M., Kannan, C. R., Thirugnanasambandham, T., &Murugan, A. (2023). Evaluation of Thermal Adsorption and Mechanical Behaviour of Intralaminar Jute/Sisal/E-Glass Fibre-Bonded Epoxy Hybrid Composite as an Insulator. Adsorption Science and Technology, 2023. https://doi.org/10.1155/2023/9222562
6. Manalu, J., Numberi, J. J., Safanpo, A., Fitriyana, D. F., Wijaya, T. L., Siregar, J. P., …Jaafar, J. (2024). Characterization of eco-friendly composites for automotive applications prepared by the compression moulding method. Polymer Composites, 45(9), 8104–8118. https://doi.org/10.1002/pc.28327
7. Krishnaraj, M., Arun, R., &Vaitheeswaran, T. (2019). Fabrication and Wear Characteristics Basalt Fiber Reinforced Polypropylene Matrix Composites. In SAE Technical Papers. SAE International. https://doi.org/10.4271/2019-28-2570
8. Patil, J., Patil, H., Sankpal, R., Rathod, D., Patil, K., Kubade, P. R., &Kulkarni, H. B. (2021). Studies on mechanical and thermal performance of carbon nanotubes/polypropylene nanocomposites. In Materials Today: Proceedings (Vol. 46, pp. 7182–7186). Elsevier Ltd. https://doi.org/10.1016/j.matpr.2020.11.452
9. C. Dineshbabu et al. Investigation of aspect ratio and friction on barrelling in billets of aluminium upset forging. Materials Today: Proceedings, 21, pp.601-611.
10. V. Vijayan et al. 2016. Performance Evaluation of Multipurpose Solar Heating System. Mechanics & Mechanical Engineering, 20(4).
11. I. J. Isaac Premkumar et al. Combustion analysis of biodiesel blends with different piston geometries. Journal of Thermal Analysis and Calorimetry, 142(4), pp.1457-1467.
12. M. Vivekanandan et al. 2021. Experimental and CFD investigation of helical coil heat exchanger with flower baffle. Materials Today: Proceedings, 37, pp.2174-2182.
13. V. Vijayan et al. CFD modeling and analysis of a two-phase vapor separator. Journal of Thermal Analysis and Calorimetry, 145(5), pp.2719-2726.
14. S. Baskar 2022, July. Thermal management of solar thermoelectric power generation. In AIP conference proceedings (Vol. 2473, No. 1). AIP Publishing.
15. P. Sakthivel et al. Synthesis and Thermal Adsorption Characteristics of Silver-Based Hybrid Nanocomposites for Automotive Friction Material Application. Adsorption Science & Technology, 2023.
16. Chennai Viswanathan, Prasshanth, et al., Deep learning for enhanced fault diagnosis of monoblock centrifugal pumps: Spectrogram-based analysis. Machines 11.9 (2023): 874.
17. R. Anand, and S. Santhosh Kumar. Optimization of process parameters in TIG welding of AISI 4140 stainless steel using Taguchi technique. Materials today: proceedings 37 (2021): 1550-1553.
18. Balaji, S., Bharathiraja, G., Kaliappan, S., Veeman, D., &Mammo, W. D. (2021). Experimental investigation on mechanical properties of TiAlN thin films deposited by RF magnetron sputtering. Journal of Nanomaterials, 2021(1), 5943486.
19. Seeniappan and NehaGarg. Checking and supervisory system for calculation of industrial constraints using embedded system. 2023 4th International Conference on Smart Electronics and Communication (ICOSEC). IEEE, 2023.
20. Selvi, S., et al. Optimization of solar panel orientation for maximum energy efficiency. 2023 4th International Conference on Smart Electronics and Communication (ICOSEC). IEEE, 2023.
21. Sai, SamavedamAditya, et al. Transfer learning based fault detection for suspension system using vibrational analysis and radar plots. Machines 11.8 (2023): 778.
22. P. Sakthivel et al. Mechanical and thermal properties of a waste fly ash-bonded Al-10 Mg alloy composite improved by bioceramic silicon nanoparticles. Biomass Conversion and Biorefinery, pp.1-12.
23. A. Baraniraj et al. 2023. Silicon Carbide Particle Enriched Magnesium Alloy (AZ91) Composite: Physical, Microstructural and Mechanical Studies. Silicon, 15(15), pp.6367-6374.
24. M. V. Kumar et al. 2024. Development of Low-Density Polyethylene Nanocomposite with CNT FibreVia Injection Moulding: Performance Study. Journal of The Institution of Engineers (India): Series D, pp.1-5.
25. P. Chandramohan et al. Processing and Characteristics Evaluation of Polyester Resin Nanocomposite Synthesized with Natural Fiber. Journal of The Institution of Engineers (India): Series D, pp.1-5.
26. C. Angalaparameswari et al. Effective Utilization of Bast Fiber in High Density Polyethylene Nanocomposite Enriched by Alumina Nanoparticle: Mechanical Performance Evaluation. Journal of The Institution of Engineers (India): Series D, pp.1-5.
27. D. Dillikannan et al. 2024. An Approach of Nano-SiC-Filled Epoxy Nanocomposite Tensile and Flexural Strength Enriched by the Addition of Sisal Fiber. Journal of The Institution of Engineers (India): Series D, pp.1-5.
28. L. Kamaraj et al. 2024. Fabrication and Behavior Study of Natural Fiber Utilized Low-Density Polyethylene Nanocomposite via Injection Mold. Journal of The Institution of Engineers (India): Series D, pp.1-5.
29. Paranthaman et al., Influence of SiC particles on mechanical and microstructural properties of modified interlock friction stir weld lap joint for automotive grade aluminium alloy. Silicon 14.4 (2022): 1617-1627.
30. Sureshkumar, P., et al., Electrochemical corrosion and tribological behaviour of AA6063/Si3N4/Cu (NO3) 2 composite processed using single-pass ECAPA route with 120 die angle. Journal of Materials Research and Technology 16 (2022): 715-733.
31. M. Senthil Kumar. Influence of silicon carbide on tribological behaviour of AA2024/Al2O3/SiC/Gr hybrid metal matrix squeeze cast composite using Taguchi technique. Materials Research Express 6.12 (2020): 1265f9.
32. C. Devanathan et al. 2024. Significance of Hemp Fiber on Mechanical and Thermal Performance of Polypropylene Nanocomposite Developed by Compression Mould Technique. Journal of The Institution of Engineers (India): Series D, pp.1-5.
33. C. B. Priya et al. "Bio-degradable waste banana and neem fiber reinforced epoxy hybrid composites: characteristics study." Journal of Mechanical Science and Technology 38, no. 4 (2024): 1891-1896. <https://doi.org/10.1007/s12206-024-0322-7>
34. M. Aruna et al. "Alkali-Processed Flax Natural Made High-Density Polyethylene Waste Recycled Composites: Performance Evaluation." Journal of The Institution of Engineers (India): Series D (2024): 1-5. <https://doi.org/10.1007/s40033-024-00739-z>
35. Vaishali, Kokila R., et al., Guided container selection for data streaming through neural learning in cloud. International Journal of System Assurance Engineering and Management (2021): 1-7.
36. Yogeshwaran, S., et al., Experimental investigation on mechanical properties of epoxy/graphene/fish scale and fermented spinach hybrid bio composite by hand lay-up technique. Materials Today: Proceedings 37 (2021): 1578-1583.
37. Khimsuriya, Yogeshkumar D., et al., Artificially roughened solar air heating technology–A comprehensive review. Applied Thermal Engineering 214 (2022): 118817.
38. Kumar, M. Senthil, et al., Experimental investigations on mechanical and microstructural properties of Al2O3/SiC reinforced hybrid metal matrix composite. IOP Conference Series: Materials Science and Engineering. Vol. 402. No. 1. IOP Publishing, 2018.
39. Yogeshwaran, S., et al. Mechanical properties of leaf ashes reinforced aluminum alloy metal matrix composites. International Journal of Applied Engineering Research 10.13 (2015): 11048-11052.
40. M. SenthilKumar, and MukeshChaudhari. Optimization of squeeze casting process parameters to investigate the mechanical properties of AA6061/Al2O3/SiC hybrid metal matrix composites by taguchi and anova approach. Advanced Engineering Optimization Through Intelligent Techniques: Select Proceedings of AEOTIT 2018. Singapore: Springer Singapore, 2019. 393-406
41. PethurajManickaraj, and V. SakthiMurugan. "Featuring with Nano Alumina Made Hybrid Epoxy/Carbon Fiber Nanocomposite: Performance Evaluation." Journal of The Institution of Engineers (India): Series D (2024): 1-5. <https://doi.org/10.1007/s40033-024-00754-0>
42. De Poures, Melvin Victor et al. "Sodium Hydroxide Processed Natural Sisal Fiber Made Polypropylene Composite: Characteristics Evaluation." Journal of The Institution of Engineers (India): Series D (2024): 1-5. <https://doi.org/10.1007/s40033-024-00761-1>
43. K. Logesh et al. "Performance investigation of silicon nitride (SiNx) layer doped with twin thin films of gallium and zinc oxide for solar cell." Optical and Quantum Electronics 56, no. 7 (2024): 1-13.<https://doi.org/10.1007/s11082-024-07100-4>
44. R. Karthik et al. "Characteristics performance evaluation of AZ91-fly ash composite developed by vacuum associated stir processing." International Journal of Cast Metals Research (2024): 1-8.<https://doi.org/10.1080/13640461.2024.2364129>
45. Kaliappan, S., and Akshay Rajput. Sentiment Analysis of News Headlines Based on Sentiment Lexicon and Deep Learning. 2023 4th International Conference on Smart Electronics and Communication (ICOSEC). IEEE, 2023.
46. Josphineleela, R., and Upendra Mohan Bhatt. Intelligent Virtual Laboratory Development and Implementation using the RASA Framework. 2023 7th International Conference on Computing Methodologies and Communication (ICCMC). IEEE, 2023.
47. Suman, Turpati, et al., IoT based Social Device Network with Cloud Computing Architecture. 2023 Second International Conference on Electronics and Renewable Systems (ICEARS). IEEE, 2023.
48. S. Kaliappan. Mechanical Assessment of Carbon–Luffa Hybrid Composites for Automotive Applications. No. 2023-01-5070. SAE Technical Paper, 2023.
49. Muralidaran, V. Manivel, et al., Grape stalk cellulose toughened plain weaved bamboo fiber-reinforced epoxy composite: load bearing and time-dependent behavior. Biomass Conversion and Biorefinery 14.13 (2024): 14317-14.
50. Venkatesh, R., Kaliyaperumal, G., Manivannan, S., Karthikeyan, S., Mohanavel, V., Soudagar, M. E. M., & Karthikeyan, N. (2024). Characteristics of magnesium composite reinforced with silicon carbide and boron nitride via liquid stir processing (SAE Technical Paper).
51. Manivannan, S., Venkatesh, R., Kaliyaperumal, G., Karthikeyan, S., Mohanavel, V., Soudagar, M. E. M., & Karthikeyan, N. (2024). Magnesium alloy hybrid composite properties are featured with boron carbide particle for automotive seat frame usage (SAE Technical Paper).