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Effect of ceramic particles on the mechanical and tribological properties of short carbon fibre reinforced epoxy composites

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Abstract: In this investigation, an effort has been made to develop the short carbon fibre stiffened epoxy composites (CFSEC) mixed with multi-walled carbon nano-tubes (MWCNT) and silicon carbide particles (SiCp) using a compression moulding process. The content of MWCNT varied as 0.5%, 1%, and 1.5%, and SiCp content was maintained at 10% by weight of the composite. The impact of the ceramic particles on mechanical characteristics such as hardness, tensile, flexural, and wear behaviour of CFSEC was investigated. For all the mechanical characteristics, the rise in the proportion of MWCNT in the composite has shown a significant improvement. The specific wear rate (SWR) and coefficient of friction (COF) of the composite were studied using the pin-on-disc tester. The wear parameters yielding the lowest SWR and COF were identified from the wear testing process parameters. The fractography analysis of tensile specimens was carried out using a scanning electron microscope (SEM).

Keywords: epoxy; carbon fibre; multi-walled carbon nano-tubes; silicon carbide; compression moulding; tribology.

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1 Introduction

Recently, a considerable investigation has been accomplished in polymer composites, particularly epoxy toughened with artificial fibres and nanofillers. Epoxy is a distinctive and frequently utilised predominant phase in a composite owing to more negligible shrinkage, remarkable adhesion, and a preferable impediment to solvent (Üstün et al., 2016; Kamaraj et al., 2021). There was a noteworthy enhancement in physical and mechanical properties at a meagre volume fraction of nanofillers compared to unfilled and micro particle-filled composites. Significant enrichments are often attained by nanofillers' larger aspect ratio and higher specific surface area (Kamaraj et al., 2019;

Rafique et al., 2016). There is a considerable need for multiphase composites with versatile properties to satisfy the requests of various applications. The combination of fibre as the significant strengthening part and the minor part as a nanofiller is probably viable to obtain multifunctional properties (Manjunath et al., 2016; Kumar et al., 2018).

Over the years, the availability of nanofillers has brought out an innovative area to fabricate hybridised composites with multifunctional properties. A substantial investigation showed enrichment in the multifunctional performance of carbon fibre (CF) stiffened epoxy composite with various nanofillers (Suresha et al., 2013; Ahmad et al., 2019; Yang et al., 2011; Pathak et al., 2016; Yao et al., 2015). Further, these nanofillers have favourably enhanced the hardness and stiffness of composites owing to their high inherent strength and surface area. Among the nanofillers, carbon nanotubes (CNTs) have been extensively adopted as a filler material for composites owing to their preferable mechanical and physical performances (Bozkurt et al., 2007; He and Li, 2012; Davis et al., 2011; Ashori et al., 2015).

Zhang et al. (2022) probed the consequence of CNT on the mechanical characteristics of carbon fibre stiffened epoxy and reported a significant improvement in the mechanical characteristics. Bakis et al. (2021) researched the mechanical characteristics of MWCNT/CF/epoxy composites and disclosed that the neat epoxy resin exhibited highly brittle characteristics; adding a low quantity of MWCNTs ensued in an enhancement of fracture toughness. Karaoglu and Kavrici (2021) examined the mechanical performance of CNTs, and nano clay strengthened epoxy/CF composite pipes and found that the mechanical characteristics start to boost substantially with increasing CNT and nano clay particles with CF/epoxy composite pipes.

Mirsalehi et al. (2021) probed the mechanical characteristics of MWCNT/CF/epoxy composites and confirmed the UTS and % elongation of a composite containing 1.0 wt.% MWCNTs enhanced up to 53% and 50% compared to epoxy/CF laminate. Praneeth et al. (2022) researched the consequence of CNT on the mechanical characteristics of CF/epoxy composites and reported that the inclusion of CNT ensued in an enrichment of tensile, flexural, and impact strength by 27.5%, 53.25%, and 40% respectively. Hammadi (2019) examined the effect of MWCNT on carbon fibre-reinforced composites and observed that adding MWCNTs improved mechanical properties. Improvement in mechanical strength was 36% for the samples with 0.3 wt% MWCNTs.

Goo and Cho (2017) analysed the wear characteristics of the CF/SiC composite and reported that the COF and wear were reliant on the temperature. Fan et al. (2011) researched the wear mechanisms of the C/SiC brake materials and disclosed that the porosity and carbon content influence the friction performance of the C/C-SiC composite. Naidu et al. (2022) reported that specimen with only hemp as a reinforcement component exhibited better physio-mechanical properties along with lower specific wear rate (1.5368×10^{-5} mm^3/Nm) and coefficient of friction (0.336) at optimum conditions. Singh et al. (2018) studied the tribological performance of water-based emulsion (lubricant) by blending carbon fillers such as graphene nanoplatelets and multiwall carbon nanotubes using a pin-on-disc tribometer. They observed that the addition of 0.8 wt.% concentration of MWCNT showed a 26.27% reduction in coefficient of friction and a 47.35% reduction in wear depth.

From the literature survey, it is evident that many of the works are concentrated on the addition of either carbon nano-tubes or SiCp on carbon fibre-strengthened epoxy. Further, mostly carbon fibre is used as a reinforcement in the continuous and woven form to develop the composites. The literature review clearly shows that none has concentrated on the combined effect of MWCNTs and SiCp in carbon/epoxy composite for brake pad applications. Brake pads used in automotive braking systems are generally made of composites involving multiple materials consisting of a binder, fibres, friction modifiers, and fillers for effective control of friction and wear performance. Although extensive improvement has been done on brake pads for vehicles, most recent materials used still encounter wear, friction, stopping distance, and time deficiencies. So, in this research work, epoxy was selected as a binder, short carbon fibre was used as a fibre, and MWCNTs and SiCp were utilised as fillers to develop the composites for brake pad application.

The main objective of this research work is to find whether the varying percentages of MWCNT have any effect on the composite properties, and then establish an optimum reinforcement required for the brake pad applications. So, to test the effects of adding various reinforcements into the composites, three composite panels were fabricated with varying percentages of MWCNTs (0.5–1.5%, with a step of 0.5%). A fourth panel with no MWCNT was also fabricated to compare the results with that of MWCNT-filled composites. The compression moulding process synthesised the composites containing MWCNT to investigate the mechanical and wear behaviour of the composites.

2 Experimental work

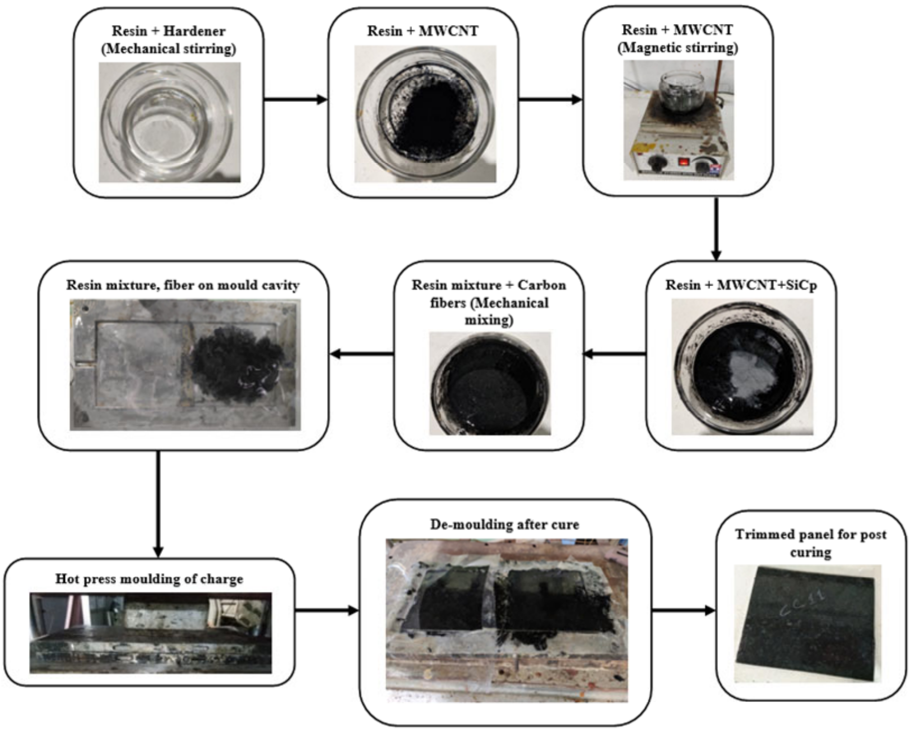
2.1 Materials

All the materials used in manufacturing the hybrid composite panel were sourced from local suppliers in Chennai, India. Short carbon fibres have a filament diameter of 7 μm and 3 mm in length. These carbon fibres elastic modulus and density are 230 GPa and 1.76 g/cc. MWCNTs have a diameter ranging from 110–170 nm, and their length varies from 5–9 μm. The density of selected MWCNTs is 2.1 g/cc, and the SiCp has a mesh size of 50 μm. The structural grade epoxy and readily available hardener chosen for this research work were LY556 and HY951, respectively.

2.2 Processing of hybrid composite panels

A mould was developed so that two hybrid composite panels of 200 mm × 150 mm × 4 mm can be made at a time. These composite panels were manufactured in a clean room environment and conformed to best industry practices for quality conformance. The steps followed during the manufacture of the composite panels are illustrated in Figure 1. First, the epoxy was blended with a curing agent with a proportion of 10:1 and agitated well. The composition of MWCNTs was varied as 0.5%, 1%, and 1.5% by weight. Based on the percentage of MWCNTs additive, the epoxy resin and MWCNTs were mixed for 10 minutes using a magnetic stirrer. The composition of SiCp was maintained at 10% (Nassar and Nassar, 2014) by weight and combined with the existing paste using a magnetic stirrer for about 8 minutes until the epoxy was fully formulated with constituent additives of MWCNTs and SiCp. According to the variation of the additives, the viscous black paste was mixed with 50% by weight of short carbon fibres using a mechanical stirrer for 10 minutes to fuse the fibres adequately with the epoxy resin, MWCNTs, and SiCp. This process was carried out at room temperature, and the mechanical stirring process was repeated 3 to 4 times until the mixture turned out as a homogenous moulding compound. All the trapped air bubbles due to mixing were entirely removed through heating in a thermal oven at 60°C for 3 minutes and through repeated volumetric measurements of the charge to achieve the best quality as per industrial practice.

Figure 1 The manufacturing procedure for hybrid composite panels (see online version for colours)



A mould with 2 rectangular cavities of 5 mm depth was developed for this project. This allows the moulding of standard test specimens of 3 to 4 mm thickness. A release film was laid over the mould, and then the mixed carbon epoxy composite with additives was poured into the cavity. The charge was evenly distributed and compacted over the entire mould cavity in a controlled manner. The exact process was repeated for pouring the second composition, which was already prepared, onto another mould cavity. Another layer of release film was laid over the charge, and the closing tray of the mould was clamped with the base mould. The closed mould was then placed in a compression moulding machine, and a pressure of 5 bar was applied. This compression mould was left for 12 hours to achieve a room-temperature cure. After cure, the panel was removed from the cavity of the mould using wedges and then trimmed by hand. All the trimmed edges were inspected for edge delamination through a close microscopic-based visual inspection to ensure an acceptable level of quality has been demonstrated. The trimmed panel was then put in a thermal oven for 30 minutes at 50°C to achieve the required post-curing characteristics recommended by the resin and additives suppliers' technical datasheets. Figure 2 shows the photographs of all manufactured short carbon fibrous epoxy composite test panels as per the compositions presented in Table 1.

Figure 2 Photographs of trimmed composite panels after post-cure (see online version for colours)

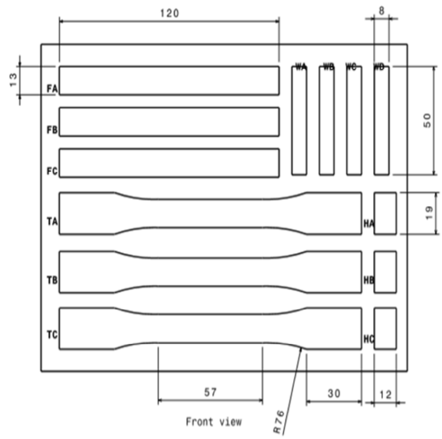
Table 1 Composition of composite panels

Composite	*Carbon fibre (%)*	*Epoxy (%)*	*SiCp (%)*	*MWCNT (%)*
CC00	50.0	40.0	10.0	0.0
CC11	50.0	39.5	10.0	0.5
CC12	50.0	39.0	10.0	1.0
CC13	50.0	38.5	10.0	1.5

2.3 Testing specimens' preparation

As per the ASTM standards, three specimens were prepared to establish the statistical mean values. A computer-aided design of the machining scheme for accurate extraction of the test specimens was used, as shown in Figure 3(a). The samples were labelled using a naming convention which was a combination of their panel composition (CC00, CC11, …, etc.). Characterisation tests, namely H, W, T, and F, infer hardness, wear, tension, and flexure, followed by letters A, B, and C for a chronological sequence of the same composition. The test specimens were machined using a water jet cutting machine which was programmed using the DXF/CAD file by ALIND Water Jet Cutting Service, Ambattur, Chennai. These cut specimens, as shown in Figure 3(b), were then hand polished to remove any leftover sharp/rough edges around the cutting holes.

Figure 3 (a) Drawing of the test specimens (b) Water jet cutting of test specimens (see online version for colours)



(a)

(b)

2.4 Characterisation of composite panels

The SEM was employed to conduct the microstructural investigation for the composite panels in order to examine the dispersion of the ceramic particles in short carbon fibre reinforced epoxy composite. Also, it was utilised to examine the fracture surface of the composite panels. The hardness of the composite panels with various compositions of MWNCTs and SiCp was characterised using a Rockwell Ball indenter of 1/16" diameter and a load of 60 kg in accordance with ASTM E18-17 standard. The tensile test specimens were prepared according to ASTM D638-14 standard. The gauge length and parallel edge lengths considered were 57 mm and 50 mm, respectively. The gauge width and maximum width of the 165 mm long specimen were 13.5 mm and 19 mm, respectively. The speed of testing was set to 0.5 mm/min. The load-extension curve was recorded for each specimen to establish the yield point and the load at the moment of rupture. The flexural strength test specimens were prepared according to ASTM D7264M-15 standard. The support roller span was maintained at 75 mm for all the specimens under a three-point bending fixture. Before the testing, the specimen dimensions were measured properly for width and thickness. The loading nose and the support rollers were correctly aligned over the specimen. The specimen was placed over the support rollers, and the loading was applied at the mid-span of the specimen at a crosshead rate of 0.5 mm/min. The force-deflection data were recorded throughout the test for each specimen testing. For each type of composite panel and mechanical testing, three trials were conducted and the average values were reported.

The wear test was performed using the Ducom pin-on-disc wear testing machine (Model No: TR20). The short carbon fibrous composite pin was prepared to have a cross-section of 8 mm × 4 mm and a span of 50 mm. The loaded composite pin was moved against an EN31 steel disc with a hardness of 60 HRC and a track diam of 70 mm. The pin specimens were polished with fine sandpaper paper to have a flat contact surface with the disc. The polished test specimen and the disc were wiped with acetone to remove left-over particles from the surface post abrasion. The test specimens were weighed using micro-balance (±0.0001 g tolerance), and their dimensions were measured for volume calculations. The sample was placed inside the pin holder and held against the steel counter face with an applied load (10, 20 and 30 N). The wear-testing machine was operated for a specified speed (300, 450 and 600 rpm) and a period of 30 minutes. From the duration of the test, the sliding distance was calculated using the track diameter. Then the specimen was removed from the holder and was wiped with acetone, and weighed again using micro-balance to calculate the weight loss.

Based on the weight loss (W), applied load (P), slide distance (L), and density of the pin (ρ), the specific wear rate (SWR) was computed using equation (1) (Atta et al., 2022).

$$SWR = \frac{W}{PL\rho} \tag{1}$$

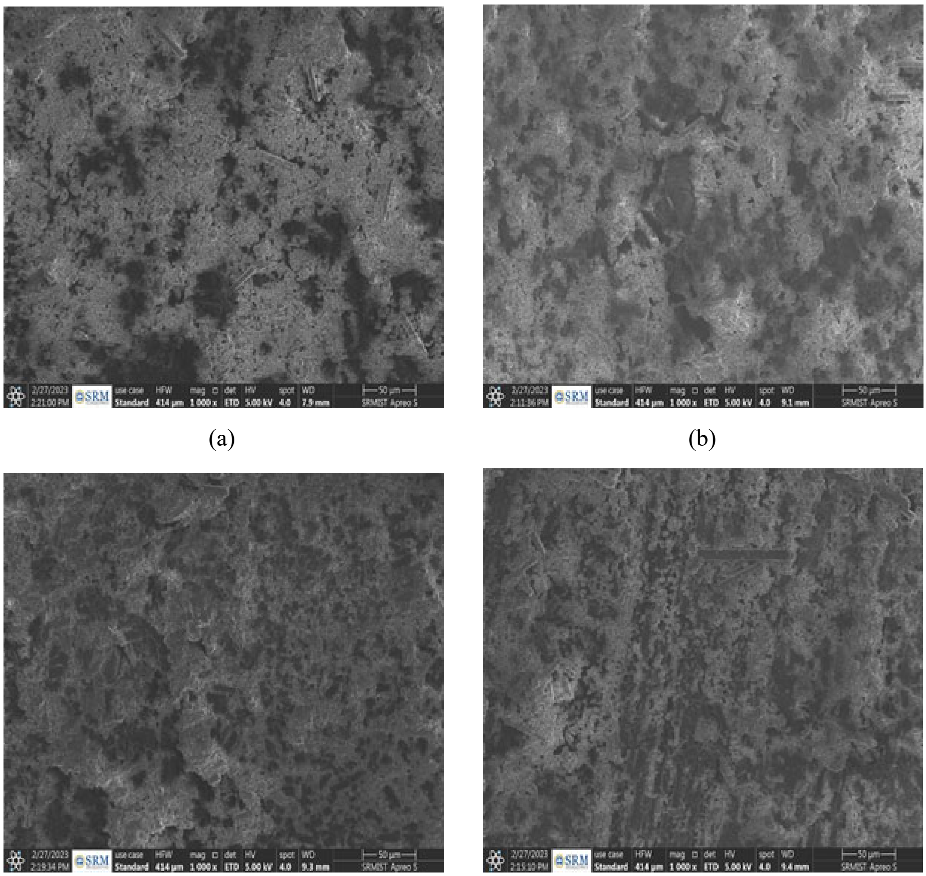
The COF was computed by dividing the tangential force by the applied load. The test equipment was fully computerised to control the wear parameters and obtain the results directly. For each type of composite panel and wear testing, three trials were conducted and the average values were reported. After the wear testing, the surface roughness test was carried out using the surface roughness tester (Surfcom 1400G, Carl Zeiss India Pvt Ltd, Chennai).

3 Results and discussion

3.1 Morphology of composites

The dispersion of ceramic particles on carbon fibre-reinforced epoxy was probed by scanning electron microscopy (SEM). Figure 4 shows the microstructure of SiCp and MWCNT particles filled short carbon fibrous epoxy composite panels. The SEM micrograph of the SiCp-filled short carbon fibrous epoxy composite is shown in Figure 4(a), which shows the homogeneous dispersion of SiCp in the composite and agglomeration in a few locations on the composite. The micrograph also showed the randomly oriented short carbon fibres on the epoxy. The SEM micrographs of the SiCp and MWCNT particles filled short carbon fibrous epoxy composite are shown in Figure 4(b)–4(c). The micrograph showed a uniform dispersion of SiCp and MWCNT particles in the short carbon fibrous epoxy composites while increasing the proportion of MWCNT. Similar findings have been documented by other researchers (Kamaraj et al., 2019; Mirsalehi et al., 2021) for GNP/flax/epoxy composites and MWCNT/carbon/epoxy composites. Adding MWCNTs into the epoxy boosted the internal energy of the system. From the micrographs, it is observed that a perfect bonding was established among the constituent materials of the composites. Figure 4(d) depicts the SEM micrograph of 1.5 wt% MWCNT particles filled short carbon fibrous epoxy composite. From the micrograph, it is observed that more agglomeration of MWCNT particles owing to their more weight fraction. Similar findings have been documented by other researchers (Kamaraj et al., 2019; Mirsalehi et al., 2021) for GNP/flax/epoxy composites and MWCNT/carbon/epoxy composites.

Figure 4 FESEM micrographs of the composite panels, (a) CC00 (b) CC11 (c) CC12 (d) CC13 (see online version for colours)



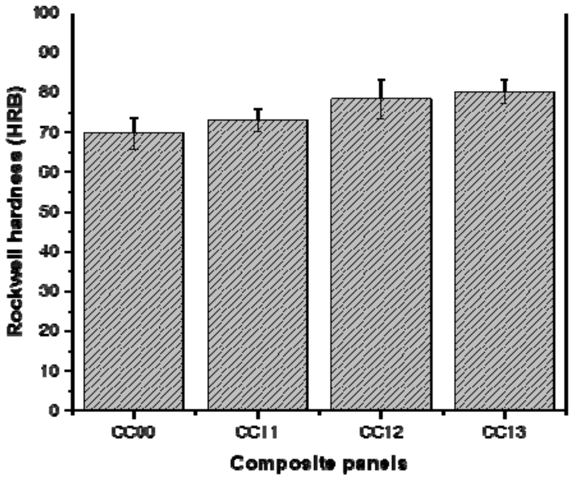
(a) (b) (c) (d)

3.2 Hardness

Figure 5 depicts the average hardness number of composite panels in terms of the variations in the weight fractions of MWCNTs. The hardness of the SiCp/carbon short fibrous composite is 67.9 HRB, which increased to 73.2 HRB when the composite is filled with 0.5 wt% MWCNT.

From the figure, it is noticed that the hardness number is straightaway enhanced by increasing the content of MWCNT from 0.5 to 1.5 wt%. The maximum hardness number of 80.3 HRB has been reported for the SiCp/carbon short fibrous composite filled with 1.5% MWCNT. This is 18% greater than the hardness number of SiCp/carbon short fibrous composite. The reason is due to the exceptional performance of MWCNT, which improved the hardness number. Sunil and Arun (2021) reported similar results for MWCNT/epoxy composites. The maximum hardness of 90 HRB was found for 0.5 wt.% MWCNT/epoxy which is 12.5 % higher than neat epoxy.

Figure 5 Hardness of composite panels

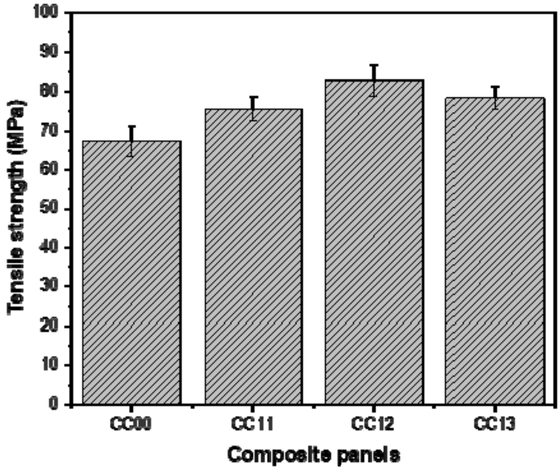


3.3 Tensile strength

Figure 6 depicts the tensile strength of the different composite panels in terms of the variations in the weight fractions of MWCNTs. The tensile strength of SiCp/carbon short fibrous composite is 67.3 MPa, which is increased to 75.6 MPa when it is filled with 0.5 wt% MWCNTs. The maximum tensile strength of 82.7 MPa is observed for the SiCp/carbon short fibrous composite filled with 1.0 wt% MWCNT. This is a 23% improvement in the tensile strength of SiCp/carbon short fibrous composite. This is owing to the uniform spreading of MWCNTs in epoxy resin, which increases the strength of the composites. The MWCNTs act as an obstacle to the deformation of SiCp/carbon short fibrous composite, which leads to an increase in strength. Similar findings have been documented by other researchers (Hammadi, 2019; Mirsalehi et al., 2021) for CNT/carbon/epoxy composites and MWCNT/carbon/epoxy composites. Hammadi (2019) reported that the composite containing 0.3 wt.% MWCNTs showed a 36% improvement in their mechanical strength compared to CF/epoxy composite. Mirsalehi et al. (2021) found that the composite containing 1.0 wt.% MWCNTs showed a maximum of UTS 42 MPa which is 53% greater than that of epoxy/CF composite.

Owing to the growth of an effective interface amidst epoxy, MWCNT, SiCp, and CF, the strength is enhanced. Further, the tensile strength of the SiCp/carbon short fibrous composite filled with 1.5 wt% MWCNT composite reduced to 78.3 MPa. This is because of the agglomeration of MWCNT in SiCp/carbon short fibrous composite, which brings down the distribution of stress amidst matrix and fibre. The MWCNT agglomeration causes dispersion problems in SiCp/carbon short fibrous composite, leading to a decrement in tensile strength. Furthermore, the composites are too brittle because of the higher content of MWCNT, developing low interfacial strength. Praneeth et al. (2022) found that the composite containing 2.0 wt.% CNTs showed a tensile strength of 255 MPa which is approximately 9% lower than that of 1.0 wt.% CNT/epoxy/CF composite.

Figure 6 Tensile strength of composite panels

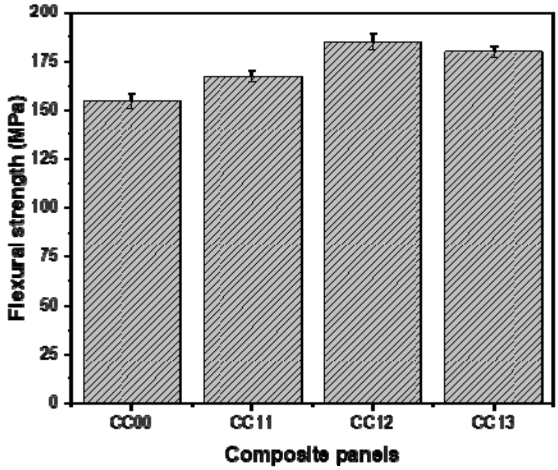


3.4 Flexural strength

Figure 7 shows the flexural strength of the different composite panels in terms of the variations in the weight fractions of MWCNTs. The flexural strength of SiCp/carbon short fibrous composite is 154.8 MPa, which is increased to 167.2 MPa when it is filled with 0.5 wt% MWCNTs. The maximum flexural strength of 184.7 MPa is observed for the SiCp/carbon short fibrous composite filled with 1.0 wt% MWCNT. This is a 19% improvement in the flexural strength of SiCp/carbon short fibrous composite. This is on account of the uniform spreading of MWCNTs in epoxy, which increases the strength of the composites. The addition of MWCNT in SiCp/carbon short fibrous composite increased the fracture toughness of the composite. MWCNT enhances the mechanical synergy amidst carbon fibre, SiCp, and epoxy in the interface, enhancing flexural strength. Similar findings have been documented by other researchers (Mirsalehi et al., 2021; Praneeth et al., 2022) for MWCNT/carbon/epoxy composites and CNT/carbon/epoxy composites. Mirsalehi et al. (2021) reported a flexural strength value of 1,374 MPa for composites containing 1.0 wt.% MWCNTs, which is 15% higher than that of the flexural strength of epoxy/CF composite. Praneeth et al. (2022) found that the composite containing 1.0 wt.% CNTs showed a maximum flexural strength of 19.2 MPa which is 58% greater than that of epoxy/CF composite.

Further, the flexural strength of the SiCp/carbon short fibrous composite filled with 1.5 wt% MWCNT composite reduced to 179.6 MPa. The reason for reduced flexural strength is the agglomeration of MWCNT in SiCp/carbon short fibrous composite. Praneeth et al. (2022) found that the composite containing 2.0 wt.% CNTs showed a flexural strength of 18.5 MPa which is 3.8% lower than that of 1.0 wt.% CNT/epoxy/CF composite.

Figure 7 Flexural strength of composite panels

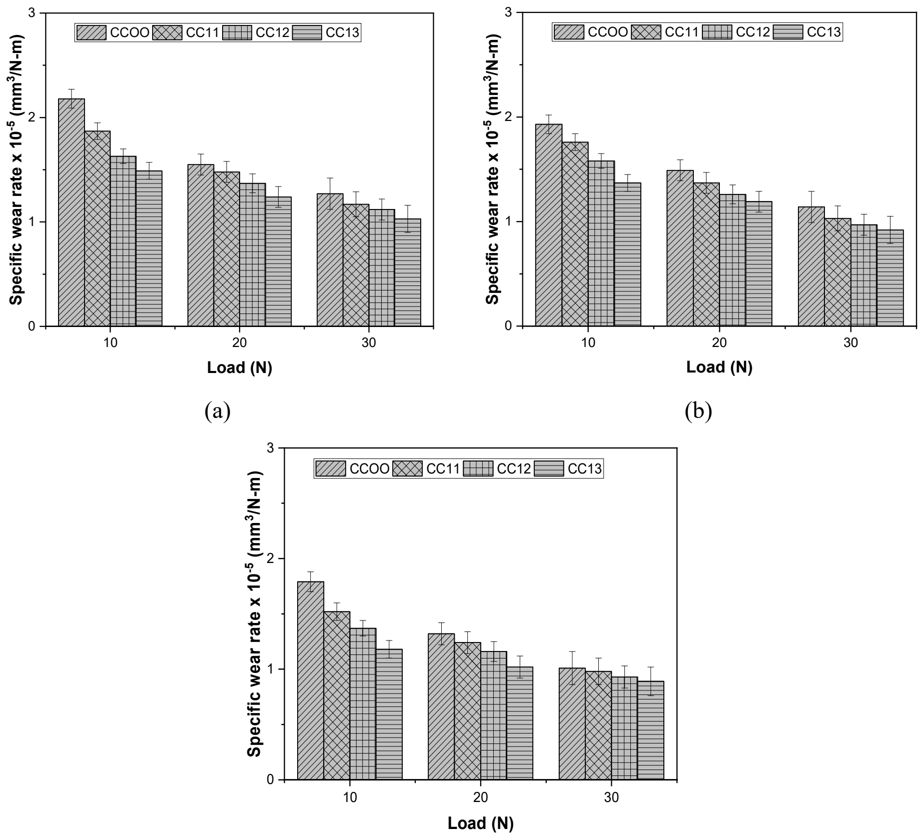


3.5 Specific wear rate

To explore the impact of loads, the SWR of composites as a function of load is depicted in Figure 8 for different sliding speeds. The wear rate decreases drastically with an increment in the loads for all the composites and sliding speeds. From Figure 8(a), it is peculiar to record that the maximum SWR was observed for all the composites at 10 N load and 300 rpm sliding speed. From the figure, it is noticed that the wear rate decreased for all the materials with an increase in the loads. At 10 N load, the SiCp/carbon short fibrous composite showed a maximum wear rate of 2.18×10^{-5} mm^3/N-m, which is reduced to 1.27×10^{-5} mm^3/N-m when the load is raised to 30 N. This is 42% lower than the value at 10 N normal load. Similar findings were reported by Wei et al. (2018) for MWCNTs filled with carbon/epoxy composites due to the synergistic effect of MWCNTs. The same trend of results is observed for MWCNT filled SiCp/carbon short fibrous composite.

A higher wear rate (2.18×10^{-5} mm^3/N-m) is noticed for SiCp/carbon short fibrous composite compared to MWCNT filled SiCp/carbon short fibrous composite. Raising the MWCNT quantity up to 1.5 wt% decreased the wear rate of SiCp/carbon short fibrous composite from 2.18×10^{-5} mm^3/N-m to 1.03×10^{-5} mm^3/N-m. This is 53% lower than SiCp/carbon short fibrous composite. The minimum wear rate is observed for SiCp/carbon short fibrous composite with 1.5 wt% MWCNT. The results revealed that adding MWCNTs into SiCp/carbon short fibrous composite significantly decreased the wear rate. This is because of the lubricating action of MWCNT filler and abrading nature of carbon fibres. The presence of MWCNT in SiCp/carbon short fibrous composite improved the interfacial bonding and mechanical properties. The MWCNT, SiCp, and epoxy take part in the course of rubbing in-wear experimentation. In such situations, MWCNT bears the epoxy from being separated by sharing the applied load. Hiremath et al. (2022) reported that the addition of nanofiller particles such as Al_2O_3 + SiC into carbon/epoxy composite decreased the wear rate significantly. Namdev et al. (2023) found that incorporating a considerable amount up to 0.5 wt.% of GNP significantly improved the wear performance of carbon fibre reinforced epoxy composites.

Figure 8 Specific wear rate of composites with load at (a) 300 rpm, (b) 450 rpm and (c) 600 rpm sliding speeds



(a)

(b)

(c)

A robust interface indicates, that applied load in the course of sliding would be effortlessly managed by the MWCNT, which in sequence increases the wear resistance. Adding MWCNT reduced the interface temperature between the sliding surfaces due to their intrinsic self-lubricating nature and better mechanical property. Moreover, the higher conductivity of MWCNTs increased heat dissipation and avoided the accumulation of heat energy. At lower loads, the temperature rise at the interface is low and not sufficient to form a lubricating layer which brings about a maximum wear rate. Further increase in loads increased the temperature at the boundary, which forms a lubricating layer that reduced the wear rate.

At greater loads, friction at the interface is more which generates excessive heat. The friction at a higher load generates a thick smooth friction film, which is peeled off at the time of the test. The transfer and peeling aspects encountered by the composites established less friction and wear. Similar results have been reported for hybrid epoxy composites containing SiC/carbon/ phenolic resin composites by Goo and Cho (2017). At the start of the sliding, the distorted debris of epoxy resin, SiCp, and MWCNT shielded the carbon fibre bundles. The entangling of wear debris amidst the contact surfaces establishes the formation of a friction layer. This layer is extremely changing the wear characteristics of the tribo system, which is related to the deterioration of the COF. The wear rate of composites as a function of loads at 450 rpm and 600 rpm sliding speeds are shown in Figures 8(b) and 8(c). The tendency of the wear rate plot was identical to those of Figure 8(a).

3.6 Coefficient of friction

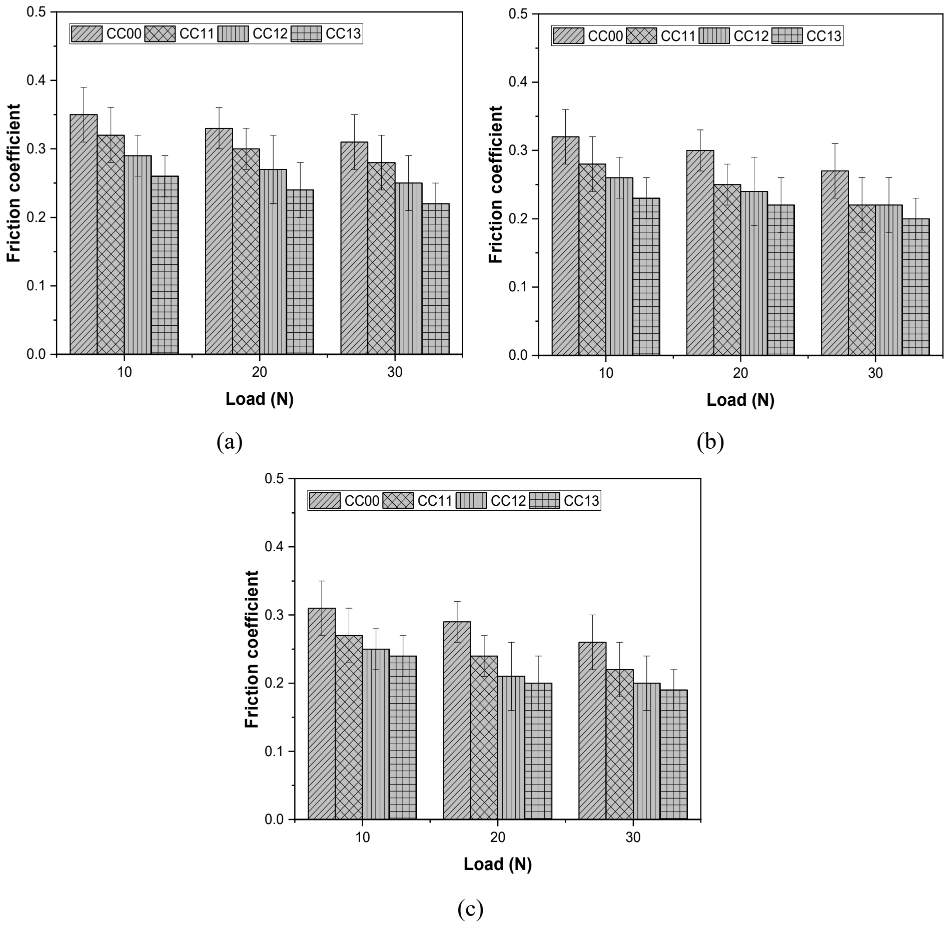
To probe the impact of loads, the friction coefficient of composites as a function of load is depicted in Figure 9 for different sliding speeds. The COF of composites diminishes while raising the load for all the speeds. From the figures, it is interesting to note that the lowest COF is observed for all the composites at 30 N load and 600 rpm sliding speed. The change in the COF of composites with loads at 300 rpm sliding speed is shown in Figure 9(a). The COF of SiCp/carbon short fibrous composite is diminished from 0.35 to 0.31 while increasing the load from 10 N to 30 N. The same trend of results is observed for MWCNT filled SiCp/carbon short fibrous composite. Similar findings reported by Wei et al. (2018) for MWCNTs filled with carbon/epoxy composites due to the synergistic effect of MWCNTs. The lubricating behaviour of MWCNT minimised the COF of the SiCp/carbon short fibrous composite. MWCNT particles departed from the matrix and entrapped at the interface, owing to this, the contact area amidst the sliding surfaces decreased, evidencing the reduction of the COF. Moreover, the development of the lubricating film wraps the pin surface, and this film performs as a solid lubricant amidst the tribo pair and, thereby coefficient of friction declines in composites. Similar findings were reported by Shinde et al. (2023) for CNTs filled with silicon rubber composites. Namdev et al. (2023) found that incorporating a considerable amount up to 0.5 wt.% of GNP significantly reduced the friction coefficient of carbon fibre-reinforced epoxy composites.

At lower loads, the contact pressure amidst the mating surfaces is low, which generates a low interface temperature due to lower friction. As the load rises, the contact pressure also rises, which proves an improvement in the interface temperature. The temperature at the interface increased to a value nearly equivalent to the glass transition temperature of the fabricated composites. At this temperature, the thermal softening of epoxy leads to get pull out of SiCp and MWCNT, which makes an intermediate tribo layer amidst the mating surfaces. This layer separates the contact surface from each other, which decreased the friction coefficient. Similar results have been reported for hybrid epoxy composites containing SiC/carbon/phenolic resin composites by Goo and Cho (2017). The friction coefficient of composites as a function of loads at 450 rpm and 600 rpm sliding speeds are shown in Figures 9(b) and 9(c). The tendency of the friction coefficient plot is identical to those of Figure 9(a).

3.7 Surface roughness

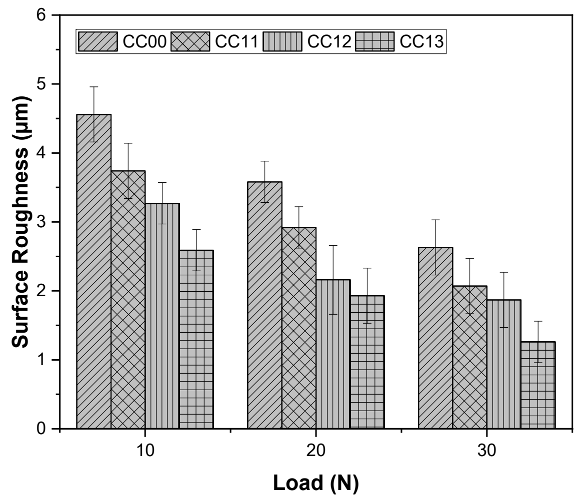
The mean surface roughness (Ra) values of CC00, CC11, CC12, and CC13 composite panels before wear testing are 5.23 μm, 4.67 μm, 4.18 μm, and 3.49 μm respectively. Figure 10 shows the surface roughness measurement value of composite panels after wear testing at 600 rpm speed with varying loading conditions. From the figure, it is observed that the mean surface roughness is higher for the 10 N loading condition, whereas it decreases with increasing loading conditions. It mainly occurs due to the surface morphological changes that occurred in both the testing sample and counter plate due to the asperity in contact. This can create an influence on the surface roughness profile of the worn-out surface as well as the counter surface. Moreover, for a composite panel, the surface layers are only subjected to the rubbing action which is generally a polymer phase. The change in the behaviour of epoxy from rigid phase to viscous due to the generation of heat can create transfer film formation at the counter surface.

Figure 9 Friction coefficient of composites with load at (a) 300 rpm, (b) 450 rpm and (c) 600 rpm sliding speeds



Therefore, at lower load and higher speed conditions, the epoxy matrix surface layer is softened and adhered to the asperity of the counter plate. Consequently, the molecular level removal of the epoxy matrix in the form of patches produced an irregular surface topography on the sample. This could be attributed to the occurrence of high surface roughness. However, at higher load and speed conditions, the roughness value decreased. This could be due to the polishing effect at the contact surface by the strong adhesion of transfer film with matrix and fibre debris. If the roughness values of the composite panels after wear are taken into account, it can be seen that samples with a higher wear rate (at 10 N load and 600 rpm speed) have high roughness values. Due to the high roughness values of these samples after wear, the friction on the contact surface increases due to the high surface interaction on rough surfaces. On the other hand, the lowest roughness values are observed in samples with a low wear rate and a low friction coefficient (at 30 N load and 600 rpm speed). Similar results have been reported for Cyperus pangorei fibre/polyester composites by Rajini et al. (2019) and glass fibre/polyester composites by İlhan and Feyzullahoğlu (2022).

Figure 10 Surface roughness values of the composite panels at 600 rpm speed with varying load conditions

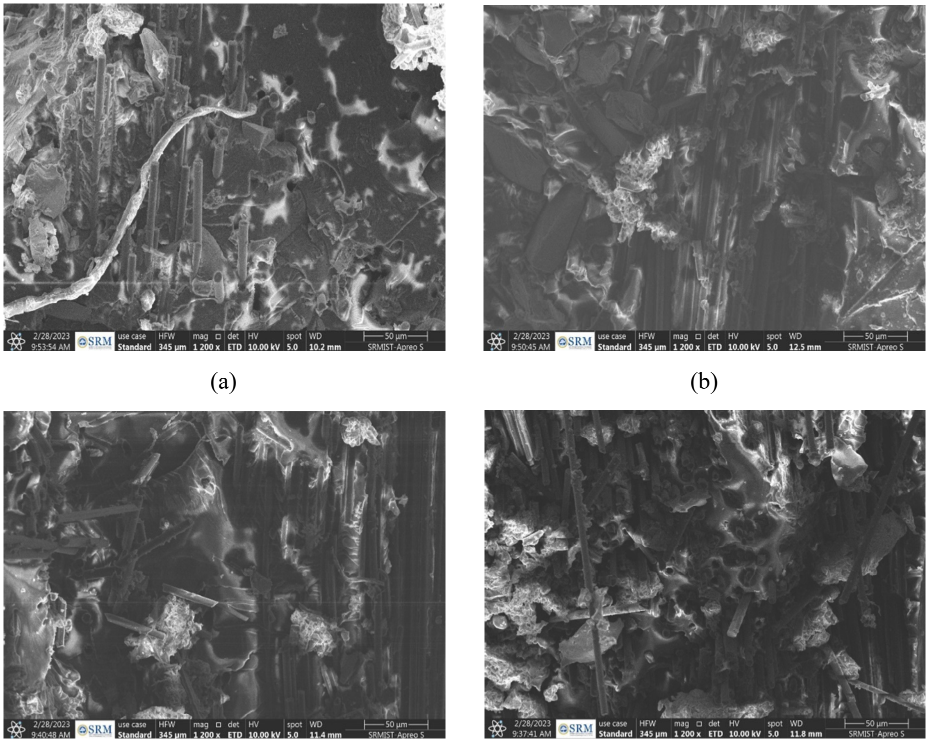


3.8 Fractography

The fractured surface of the SiCp/carbon fibre/epoxy laminate and MWCNT/SiCp/carbon fibre/epoxy laminate is presented in Figure 11. Figure 11(a) shows that no epoxy adhering to embedded carbon fibres caused the interfacial de-bonding in SiCp/epoxy/carbon fibre composite. There is a meagre attachment amidst the epoxy and carbon fibres registering a vulnerable interfacial bonding. So, the majority of the fibres are departed, which leads to low strength compared to the composites filled with MWCNT.

Adding MWCNTs changed the fracture surface of the composite that epoxy resin binds to the carbon fibres, denoting effective interfacial bonding [Figure 11(b)]. Therefore, some fibres departed, and some fibres and SiCp broke into many pieces owing to adequate interfacial bonding in this composite. Figures 11(c)–11(d) show the tensile fracture surface of 1 and 1.5 wt% MWCNT filled SiCp/carbon fibre/epoxy composites. Due to adequate interfacial bonding, few pulled out fibres, fibre breakage, and debris of epoxy, SiCp, and MWCNT were observed, improving the mechanical characteristics. Similar findings have been documented by other researchers (Mirsalehi et al., 2021; Ashori et al., 2015) for MWCNT/carbon/epoxy composites and GO/carbon/epoxy composites.

Figure 11 Tensile fracture surface of composites panels, (a) CC00 (b) CC11 (c) CC12 (d) CC13 (see online version for colours)



(a) (b) (c) (d)

4 Conclusions

In this research work, the materials were designed to develop the composite for brake pad application in automobile vehicles. The consequences of the MWCNT particles on the mechanical and tribological characteristics of SiCp/carbon short fibrous composite were investigated. The ensuing remarkable conclusions were drawn from the findings:

1 It was observed from the microstructure, the MWCNT dispersed homogeneously in the SiCp/carbon short fibrous composite.

2 There was an 18% enhancement in the hardness number of SiCp/carbon short fibrous composite filled with 1.5 wt% MWCNT.

3 The maximum tensile and flexural strength of 82.7 MPa and 184.7 MPa was observed for the SiCp/carbon short fibrous composite filled with 1.0 wt% MWCNT, respectively, which was 23% and 19% greater than the tensile and flexural strength of SiCp/carbon short fibrous composite.

4 The fractography of the tensile specimen showed that the composite failed due to fibre pull out, and breakage of epoxy, SiCp, and MWCNT.

5 The specific wear rate and coefficient of friction decrease linearly while increasing the loads for all the composites and sliding speeds.

6 The specific wear rate and coefficient of friction were found to be minimum at 30 N load and 600 rpm sliding speed.

From the experimental findings of this research, it is concluded that the composite developed in this study is recommended to be utilised for the brake pad application of automobile vehicles. While selecting a filler material such as graphene, nano clay, and metal oxides, there is a scope for getting better performance from the developed composite, which may be applied to other engineering applications.

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