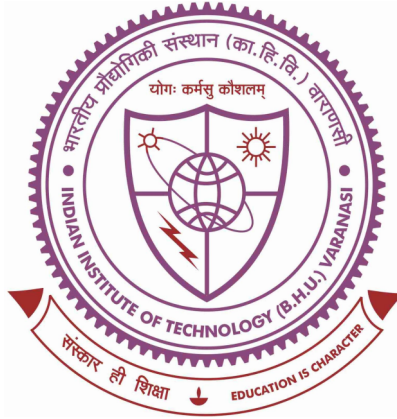


MECHANICAL AND TRIBOLOGICAL PROPERTIES OF COATED FIBER REINFORCED POLYMER COMPOSITES



Thesis submitted in partial fulfillment for the
Award of Degree

Doctor of Philosophy

By

Mayank Singh

DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY
(BANARAS HINDU UNIVERSITY)
VARANASI - 221005
INDIA

Roll No. 21131003

Year 2025



**INDIAN INSTITUTE OF TECHNOLOGY
(BANARAS HINDU UNIVERSITY)
VARANASI-221005**

CERTIFICATE

It is certified that the work contained in the thesis titled “**MECHANICAL AND TRIBOLOGICAL PROPERTIES OF COATED FIBER REINFORCED POLYMER COMPOSITES**” by “**Mayank Singh**” has been carried out under our supervision and that this work has not been submitted elsewhere for a degree. A thesis submitted in partial fulfillment for the Award of Degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy, and SOTA for the award of Ph.D. Degree.

D. Srihari
Dr. Srihari Dodla
(Supervisor)

Department of Mechanical Engineering
Indian Institute of Technology (BHU)
Varanasi-221005, India

Rakesh Kumar Gautam
Prof. Rakesh Kumar Gautam
(Co-Supervisor)

Department of Mechanical Engineering
Indian Institute of Technology (BHU)
Varanasi-221005, India



**INDIAN INSTITUTE OF TECHNOLOGY
(BANARAS HINDU UNIVERSITY)
VARANASI-221005**

DECLARATION BY THE CANDIDATE

I, “MAYANK SINGH”, certify that the work embodied in this thesis is my own bonafide work and carried out by me under the supervision of “**Dr. SRIHARI DODLA, and Prof. RAKESH KUMAR GAUTAM**” from “**JULY 2021**” to “**MAY 2025**”, at the “Department of Mechanical Engineering”, Indian Institute of Technology (BHU), Varanasi, India. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other’s work, paragraphs, text, data, results, *etc.*, reported in journals, books, magazines, reports dissertations, theses, *etc.*, or available at websites and have not included them in this thesis and have not cited as my own work.

Date:

Place: IIT (BHU), Varanasi

Mayank Singh

(MAYANK SINGH)

CERTIFICATE BY THE SUPERVISORS

It is certified that the above statement made by the student is correct to the best of our knowledge.

D. Srihari

**Supervisor
(Dr. Srihari Dodla)
IIT (BHU), Varanasi
INDIA**

Rakesh Kumar Gautam

**Co-Supervisor
(Prof. Rakesh Kumar Gautam)
IIT (BHU), Varanasi
INDIA**

[Signature]
Signature of Head of Department

यांत्रिकी अभियान्त्रिकी विभाग/Deptt. of Mechanic.
भारतीय प्रौद्योगिकी संस्थान/Indian Institute of Techno.
(का०हि०टी०/B.H.U.)
वाराणसी-२२१००५/Varanasi-221005

COPYRIGHT TRANSFER CERTIFICATE

Title of the Thesis: **MECHANICAL AND TRIBOLOGICAL PROPERTIES OF
COATED FIBER REINFORCED POLYMER COMPOSITES**

Name of the Student: **Mayank Singh**

Copyright Transfer

The undersigned hereby assigns to the Indian Institute of Technology (Banaras Hindu University), Varanasi all rights under copyright that may exist in and for the above thesis submitted for the award of the **Doctor of Philosophy**.

Date:

Place: Varanasi

Mayank Singh
(Mayank Singh)

Note: However, the author may reproduce or authorize others to reproduce material extracted verbatim from the thesis or derivative of the thesis for the author's personal use provided that the source and the Institute's copyright notice are indicated.

ACKNOWLEDGEMENT

The author is pleased to express his sincere gratitude beyond words to his supervisor, Dr. Srihari Dodla, and co-supervisor, Prof. Rakesh Kumar Gautam, for their unwavering support, encouragement, and invaluable discussions throughout the entire duration of this research. Their profound involvement and dedicated efforts were instrumental in the successful completion of this thesis. They have continuously motivated the author to explore research challenges and emphasized the importance of perseverance in achieving meaningful outcomes. The author remains truly indebted to them.

Besides his supervisors, the author extends his heartfelt thanks to his RPEC members, Dr. Debashis Khan and Dr. Nikhil Kumar, for their insightful comments and encouragement. The author also acknowledges his deep gratitude to the current and former Heads of the Department of Mechanical Engineering, IIT (BHU), Varanasi, for providing all necessary research facilities, which enabled the successful completion of this work. I would like to show an immense sense of gratitude to Prof. A.P Harsha, Dr. U.S Rao, Dr. Amit Tyagi, Dr. P. C Mani, Dr. Joy Prakash Mishra and all the faculty members of the Department of Mechanical Engineering, IIT (BHU), Varanasi for their cooperation and inspiration. I am also thankful to all office staff and all technical staff from CIF. I would like to express my immense gratitude to my mother Mrs. Geeta Singh and father Mr. Chandra Bhan Singh for their constant support and motivation in moments of trouble at IIT (BHU) Varanasi.

The author is also deeply thankful to his friends, Dr. Prashant Kumar, Dr. Chitrance Srivastava, Mr. Gulshan Verma, Mr. Rupesh Kumar, Mr. Kartik Srivastava, Ms. Pammi Raj Gupta, Mr. Vatsalya Raghuvansh, Mr. Kishor Kumar, Ms. Akhila, Ms. Shrishti Mr. Satyabrat Pandey, Mr. Mudit Mishra, Mr. Lalit Kumar Yadav, Mr. Sankata Tiwari, Mr.

Navneesh Kumar Sonkar, Mr. Ansu Raj, Mr. Govind Kumar Verma, Mr. Vikash Diwakar and all Seniors and Juniors for their constant encouragement, companionship, and for making life at IIT (BHU), Varanasi, both joyful and memorable, through moments of happiness and challenges alike. The author is also grateful to all the lab and office staff of the department, specially Mr. Ravi Prakash, Mr. Jagdish Singh, Mr. Shambhu Prasad, Mr. S. P Singh, Mr. Sudhakar Patel and all the office and CIF staff.

The author also takes this opportunity to pay homage to Bharat Ratna Mahamana Pandit Madan Mohan Malaviya Ji for founding the beautiful and inspiring campus of Banaras Hindu University. Lastly, deep reverence and gratitude are extended to the holy city of Kashi and Baba Vishwanath, whose spiritual presence and blessings provided the author with strength and courage throughout this journey.

Mayank Singh

(MAYANK SINGH)

List of Figures

Fig. No.	Title	Page No.
Fig. 1.1	Classification of Composites	4
Fig. 1.2	Classification of polymer matrix	5
Fig. 1.3	Different arrangement of reinforcement in polymer composites	11
Fig. 2.1	Classification of synthetic fibers	18
Fig. 2.2	Dip Coating Method of nanoparticles on fibers	32
Fig. 2.3	Electrophoretic Deposition Method of nanoparticles on fibers	33
Fig. 2.4	Spray Coating Method of nanoparticles on fibers	35
Fig. 2.5	Chemical Grafting Method of nanoparticles on fibers.	36
Fig. 2.6	Classification of the polymer composite processing	38
Fig. 2.7	Fabrication method of polymer composite (a) Compression Molding, (b) Hand lay-up method, (c) Resin transfer molding, (d) Spray coating, and (e) Vacuum-assisted resin infusion.	39
Fig. 2.8	Various components and aspects of polymer composite materials.	53
Fig. 3.1	Bi-directional woven fiber mat, (a) Aramid fiber, (b) Carbon fiber	58
Fig. 3.2	SEM image of (a) CNTs and (b) GO	60
Fig. 3.3	EVO-SEM MA15/18 (Carl Zeiss Microscopy Ltd.)	65
Fig. 3.4	Nicolet iS5 spectrophotometer	66
Fig. 3.5	TGA-50 instrument (Shimadzu Asia Pacific Pvt Ltd)	66
Fig. 3.6	Vickers micro hardness instrument	67
Fig. 3.7	Universal Testing Machine	68

Fig. 3.8	Impact Testing Machine	70
Fig. 3.9	TPS 500 thermal conductivity analyzer	70
Fig. 3.10	Reciprocating Friction Monitor	72
Fig. 3.11	Air-jet Erosion Tester (TR-471-800)	73
Fig. 4.1	FTIR spectra of (a) Untreated CNT, (b) Chemically treated CNT	78
Fig. 4.2	FTIR spectra of (a) Untreated aramid fiber, (b) Chemically treated aramid fiber	79
Fig. 4.3	TGA curves of uncoated aramid fiber and CNT-coated aramid fiber	80
Fig. 4.4	FE-SEM images of (a) CNT, (b) FCNTs	82
Fig. 4.5	FE-SEM micrograph of (a) CAF, (b) CAF-FCNTs	82
Fig. 4.6	Vickers hardness value for AF/epoxy and CAF-FCNT/Epoxy polymer composites	84
Fig. 4.7	Microhardness indentation images of (a) AF/epoxy, (b) CAF-FCNT/Epoxy.	84
Fig. 4.8	Stress-strain curves of AF/Epoxy and CAF-FCNT/Epoxy polymer composites	86
Fig. 4.9	Tensile strength and tensile modulus of AF/Epoxy and CAF-FCNT/Epoxy polymer composites	86
Fig. 4.10	Thermal conductivity samples of (a) AF/Epoxy, (b) CAF-FCNT/Epoxy	88
Fig. 4.11	Thermal conductivity of AF/Epoxy and CAF-FCNT/Epoxy	88
Fig. 4.12	Variation of COF with time for AF/epoxy and CAF-FCNT/epoxy polymer composite at (40 N, 8Hz, 30°C)	90

Fig. 4.13	Variation of (a) wear in gram and (b) specific wear rate of AF/epoxy and CAF-FCNT/epoxy at (40 N, 8Hz, 30°C)	90
Fig. 4.14	Variation of COF with load at a constant temperature and frequency of 30° C and 8 Hz, respectively	92
Fig. 4.15	Variation of COF with frequency at a constant temperature and load of 30o C and 40N, respectively	92
Fig. 4.16	Variation of COF with the temperature at a constant frequency and load of 8 Hz and 40N, respectively	93
Fig. 4.17	3D surface profile of COF at two different parameters simultaneously (a), (c), and (e) is AF/epoxy and (b), (d), and (f) is CAF-FCNT/epoxy composites	95
Fig. 4.18	SEM images of the wear surface of the CAF-FCNT/Epoxy sample were tested at 40 N load, 30°C temperature, and 8 Hz frequency (a) Delamination wear, (b) Fiber fragments	96
Fig. 4.19	SEM photo of the worn surface under the same condition of (50 N, 8 Hz, 30°C) (a) AF/epoxy and (b) CAF-FCNT/epoxy composite	97
Fig. 4.20	SEM of the worn surface of CAF-FCNT/epoxy polymer composites at (30N, 8Hz, 30°C)	98
Fig. 5.1	FTIR spectra of (a) Untreated Carbon fiber, (b) Chemically treated Carbon fiber	102
Fig. 5.2	TGA curves of uncoated carbon fiber, CNT-coated aramid fiber, GO-coated carbon fiber, and (CNTs/GO) hybrid-coated carbon fiber	103

Fig. 5.3	The surface morphology of carbon fiber (a) uncoated CF, (b) CNTs coated CF, (c) GO coated CF, (d) CNTs/GO hybrid coated CF	104
Fig. 5.4	Vickers hardness value of different fiber reinforced polymer composites	106
Fig. 5.5	Stress-strain curves of different fiber-reinforced polymer composites.	107
Fig. 5.6	Tensile strength (a) and tensile modulus (b) of fiber-reinforced polymer composites.	108
Fig. 5.7	Flexural strength (a) and flexural modulus (b) of fiber-reinforced polymer composites.	110
Fig. 5.8	ILSS of fiber-reinforced epoxy composites.	111
Fig. 5.9	Impact energy of fiber-reinforced epoxy composites.	113
Fig. 5.10	Thermal conductivity of fiber-reinforced epoxy composites.	113
Fig. 5.11	Coefficient of friction vs time for CFRE, CCFRE, GCFRE, and composite at (40 N, 8Hz).	115
Fig. 5.12	Variation of (a) wear in gram and (b) specific wear rate of CFRE, CCFRE, GCFRE, and HCFRE composite at (40 N, 8Hz).	116
Fig. 5.13	Variation of Friction coefficient with load at a constant frequency of 8 Hz.	117
Fig. 5.14	Variation of Friction coefficient with frequency at a constant load of 40 N.	118

Fig. 5.15	SEM images of worn surfaces of (a) CFRE, (b) CCFRE, (c) GCFRE, and (d) HCFRE under the same condition (40 N, 8Hz).	120
Fig. 6.1	Representative (a) SEM images of Aluminum oxide erodent particles, (b) Particle size distribution of erodent (Al ₂ O ₃).	124
Fig. 6.2	Representatives (a) Erosion test composite samples, and (b) Steps were carried out for the erosion investigate of polymer composites.	125
Fig. 6.3	Impact of influencing variables on erosion wear rate (Mean of S/N ratios).	128
Fig. 6.4	Impact of influencing variables on erosion wear rate (Mean of Means).	128
Fig. 6.5	Erosion wear rate of C1, C2, C3, and C4 polymer composites at impact velocity of 60 m/s, discharge rate of 4 g/min, and an impingement angle of 60°	132
Fig. 6.6	SEM image of erodent surface of (a) C1, (b) C2, (c) C3, and (d) C4 polymer composites under the same condition, the impact velocity of 60 m/s, discharge rate of 4 g/min, and an impingement angle of 60°.	133
Fig. 6.7	SEM image of C4 under conditions (a) impact velocity of 40 m/s, discharge rate of 4 g/min, and an impingement angle of 15°, (b) impact velocity of 60 m/s, discharge rate of 3 g/min, and an impingement angle of 90°.	135
Fig. 6.8	SEM image of C1 under conditions (a) impact velocity of 30 m/s, discharge rate of 3 g/min, and an impingement angle of	136

30°, (b) impact velocity of 90 m/s, discharge rate of 5 g/min, and an impingement angle of 90°.

- Fig. 7.1 The architecture of the artificial neural network (ANN) consists of a three-layer perceptron with an input layer, hidden layers, and an output layer. 143
- Fig. 7.2 Spearman rank's feature correlation coefficient matrix heatmaps for COF 143
- Fig. 7.3 Schematic architecture of the RF model, featuring decision trees and a voting process. 145
- Fig. 7.4 Algorithm for minimizing the loss function in gradient boosting machines. 147
- Fig. 7.5 AF/Epoxy and CAF-FCNT/Epoxy composites' predicted COF data compared to experimental data using the (a) ANN, (b) RF, and (c) GBM models, respectively. 155
- Fig. 7.6 Using the models (a) GBM and (b) RF, the relative relevance of input variables for predicting the COF is based on feature importance. 156

List of Tables

Table No.	Title	Page No.
Table 1.1	Applications of Synthetic fibers and their composites	14
Table 2.1	Mechanical properties of synthetic fibers	20
Table 2.2	Various predicted governing factors for different wear evaluations of polymer composites.	52
Table 4.1	Density calculation CAF-FCNT/Epoxy and AF/Epoxy polymer composites	83
Table 5.1	Density calculation of CFRE, CCFRE, GCFRE, and HCFRE composites.	105
Table 6.1	Comprehensive details regarding composite notations and specifications	125
Table 6.2	Controlling factors and levels of the variables used in Air jet erosion tester	126
Table 6.3	Taguchi (L16) parameters and Erosion rate results of epoxy composite samples.	127
Table 6.4	Signal-to-noise (S/N) ratio response table for minimum erosion rate (From Taguchi analysis)	129
Table 6.5	The Mean of the means response table for minimum erosion rate (from the Taguchi analysis)	129
Table 6.6	ANOVA analysis of polymer composites	130
Table 7.1	Data collected for the purpose of creating an ML model for polymer composites from Chapter 4.	149

Table 7.2	Optimization of COF models.	150
Table 7.3	Performance metrics of COF prediction models	151
Table 7.4	Comparison of the predicted COF by the ANN, RF, and GBM models with the experimental COF data.	152
Table 7.5	Experimental data and absolute error percentage	154

Abbreviations/Symbols

Abbreviation/Symbols	Description
CNTs	Carbon Nanotubes
GO	graphene oxide
C	Carbon
O	Oxygen
H	Hydrogen
=	Double bond
N	Newton
Hz	Hertz
°C	Degree Celsius
mm	Millimetre
%	Percentage
TGA	Thermogravimetric analysis
SEM	Scanning electron microscopy
CFRE	Carbon fiber reinforced epoxy
HCFRE	Hybrid CNTs/GO-coated carbon fiber reinforced epoxy
ILSS	Interlaminar shear strength
ANOVA	Analysis of variance
m	Meter
s	Second
g	Gram
min	Minute
ML	Machine Learning

COF	Coefficient of friction
ANN	Artificial Neural Network
GBM	Gradient Boosting Machine
RF	Random Forest
R ²	Coefficient of determination
PMCs	Polymer matrix composites
MMCs	Metal matrix composites
CMCs	Ceramic matrix composites
CFRPs	Carbon-fiber-reinforced polymers
GFRPs	Glass-fiber-reinforced polymers
UV	Ultraviolet
SiC	Silicon carbide
Al ₂ O ₃	Alumina
FRCs	Fiber-reinforced composites
PRCs	Particulate reinforced composites
FRPs	Fiber Reinforced Polymer
PEEK	Polyether ether ketone
RTM	Resin transfer molding
SFRPCs	Synthetic Fiber Reinforced Polymer Composites
FRPCs	Fiber-reinforced polymer composites
FTIR	Fourier-transform infrared spectroscopy
SFs	Synthetic fibers
NFs	Natural Fibers
MPa	Mega-Pascal
GPa	Giga-Pascal

cm	Centimeter
3D	Three-dimensional
GNPs	Graphene nanoplatelets
PTFE	Polytetrafluoroethylene
AFM	Atomic force microscopy
NaOH	Sodium Hydroxide
KOH	Potassium Hydroxide
HNO ₃	Nitric acid
H ₂ SO ₄	Sulfuric acid
CVD	Chemical vapor deposition
GF	Glass fiber
SHM	Structural Health Monitoring
rGO	reduced graphene oxide
AF	Aramid fibers
CF	Carbon fiber
EPD	Electrophoretic deposition
V	Voltage
VARTM	Vacuum-Assisted Resin Transfer Molding
PAMAM	Poly amido amine
THF	Tetrahydrofuran
PU	Polyurethane
wt. %	Weight percentage
kg	Kilogram
EP	Epoxy
PP	Polypropylene

PDA	Polydopamine
PEI	Polyethylene-imine
MWCNT	Multi-walled carbon nanotube
PMMA	Polymethyl methacrylate
MoS ₂	Molybdenum disulfide
PTFE	Polytetrafluoroethylene
HDPE	High-density polyethylene
UHMWPE	Ultra-high molecular weight polyethylene
ZrO ₂	Zirconium Oxide
SiO ₂	Silicon dioxide
PPS	Polyphenylene sulfide
CNF	Carbon nanofibers
MAE	Mean absolute error
MSE	Mean squared error
RMSE	Root mean square error
AI	Artificial intelligence
μm	Micrometer
Gsm	Grams per Square Meter
nm	Nanometer
v/v	Volume by volume
pH	Potential of Hydrogen
CAF-FCNT/epoxy	Functionalized CNTs coated on chemically treated aramid fabric reinforced epoxy
kPa	Kilopascal

CCFRE	Carbon Nanotubes Coated Carbon Fiber Reinforced Epoxy
GCFRE	Graphene Oxide Coated Carbon Fiber Reinforced Epoxy
HCFRE	Hybrid (CNTs/GO) Coated Carbon Fiber Reinforced Epoxy
ASTM	American Society for Testing and Materials
IR	Infrared
M	Molar
HV	Vickers Hardness
SBS	Short Beam Shear
W/mK	Watts per meter kelvin
S/N	Signal-to-noise