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

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

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

Signature of Head of Department

यान्त्रिकी अभियान्त्रिकी विभाग/Deptt. of Mechanic...
भारतीय प्रौद्योगिकी संस्थान/Indian Institute of Techno...
(का०हि०वि०/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:

Mayank Singh

Place: Varanasi **(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

List of Tables

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_2O_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_2SO_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