Tribological and Performance Assessment of Binders Modified with Warm Mix Asphalt Additives

वार्म मिक्स डामर एडिटिव्स के साथ संशोधित बाइंडरों का ट्रिबोलॉजिकल और कार्य मूल्यांकन

Thesis submitted in partial fulfillment

for the Award of Degree

Doctor of Philosophy

By

Vivek Pratap Wagh

विवेक प्रताप वाघ

Department of Civil Engineering
INDIAN INSTITUTE OF TECHNOLOGY
(BANARAS HINDU UNIVERSITY)
VARANASI – 221005

19061502 **2024**

CERTIFICATE

It is certified that the work contained in the thesis titled " **Tribological and Performance Assessment of Binders Modified with Warm Mix Asphalt Additives** " by "**Mr. VIVEK PRATAP WAGH**" has been carried out under our supervision and that this work has not been submitted elsewhere for a 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.

29/08/2024

Supervisor
Dr. Ankit Gupta
Associate Professor and MoRTH Chair Professor
Department of Civil Engineering
Indian Institute of Technology (BHU)
Varanasi, Uttar Pradesh

Associate Professor
Department of Civil Engineering
Indian Institute of Technology (B.H.U)
Varanasi-221005

DECLARATION BY THE CANDIDATE

I, **VIVEK PRATAP WAGH,** certify that the work embodied in this thesis is my own bonafide work and carried out by me under the supervision of **Dr. ANKIT GUPTA** from JAN 2020 to AUGUST 2024 at the **Department of Civil Engineering, Indian Institute of Technology, (BHU) Varanasi**. 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 lifted up any other's work, paragraphs, text, data, results, *etc*., reported in journals, books, magazines, reports dissertations, thesis, *etc*., or available at websites and included them in this thesis and cited as my own work.

Date: 29/08/2024

Place: Varanasi

Signature of the Student

(VIVEK PRATAP WAGH)

CERTIFICATE BY THE SUPERVISOR

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

29/08/2024

Supervisor
Dr. Ankit Gupta
Associate Professor and MoRTH Chair Professor
Department of Civil Engineering
Indian Institute of Technology (BHU)
Varanasi, Uttar Pradesh

Associate Professor
Department of Civil Engineering
Indian Institute of Technology (B.H.U)
Varanasi-221005

29.08.24

Signature of Head of the Department

विभागाध्यक्ष/HEAD
जानपद अभियांत्रिकी विभाग
Department of Civil Engineering
भारतीय प्रौद्योगिकी संस्थान (बी.ए.
Indian Institute of Technology (B.H.
वाराणसी-221005/Varanasi-221005

COPYRIGHT TRANSFER CERTIFICATE

Title of the Thesis: Tribological and Performance Assessment of Binders Modified with Warm Mix Asphalt Additives

Name of the Student: Vivek Pratap Wagh

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: 29/08/2024

Place: Varanasi

Signature of the Student

(Vivek Pratap Wagh)

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

ACKNOWLEDGEMENT

As I look back on the twisting path that led to the completion of my PhD thesis, I am reminded of a story filled with extraordinary support and friendship. This journey, with all its twists and turns, was not a solitary mission but a collective effort, woven together by the contributions of a few remarkable individuals.

First and foremost, I thank the almighty God and Baba Vishwanath who showered his blessings, without which it would have not been possible for me to complete the dissertation in the present form.

According to Sanskrit Shlokas (Verse), the God is described as follows:

त्वमेव माता च पिता त्वमेव ।

त्वमेव बन्धुश्च सखा त्वमेव ।

त्वमेव विद्या द्रविणम् त्वमेव ।

त्वमेव सर्वम् मम देव देव ॥

Tvam-Eva Maataa Ca Pitaa Tvam-Eva |

Tvam-Eva Bandhush-Ca Sakhaa Tvam-Eva |

Tvam-Eva Viidyaa Dravinnam Tvam-Eva |

Tvam-Eva Sarvam Mama Deva Deva ||

It means

'Lord! You are my mother and father; relation and friend; knowledge and wealth; truly, my everything, my Lord!'

According to Vedas (Sacred Hindu Transcripts), the Guru is described as follows:

ॐ अज्ञानतिमिरान्धस्य ज्ञानाञ्जनशलाकया ।

चक्षुरुन्मीलितं येन तस्मै श्रीगुरवे नमः ॥

OM Ajnyaana Timira Andhasya Jnyaana Aajana Shaalaakayaa |

Chakssur Unmilitam Yena Tasmai Shri Gurave Namah ||

it means

Salutations to the Guru who removes the darkness of ignorance from our (inner) eyes by applying the collyrium of the light of knowledge | By whom our (inner) eyes are opened; salutations to that Guru |

These are the words come to my mind to describe my supervisor, **Dr. Ankit Gupta**, Associate Professor and MoRTH chair professor, IIT (BHU), Varanasi. Ever since, I started working on my PhD topic, he has supported me not only by providing a research assistantship and top-notch research facilities, but also intellectually and emotionally through the rough road to finish this thesis. It all began in the blessed halls of academia, where he became the guiding star in my scholarly journey. Picture this: a young researcher, filled with excitement and nervousness, stepping into his office for the first time. His office, lined with books and decorated with awards and honours, seemed to promise wisdom and guidance. And indeed, he delivered on that promise. His expertise in transportation engineering was not just a source of learning but an inspiration that illuminated the path ahead. I remember sitting in his office, wrestling with a particularly challenging aspect of my thesis, when he offered not just a solution but a renewed sense of purpose. His advice and financial support to me, always precise and insightful, was a guiding light during the foggiest moments of my journey. His belief in my potential was a constant encouragement that kept me moving forward. I bow to his relentless pursuit in making his students as specialists in their respective fields and projecting their work to the local and international venues or organisations. I am deeply grateful from the bottom of my heart for having him as my supervisor. I want to extend my heartfelt thanks to **Mrs. Sonal Gupta Madam and Gungun** for warmly welcoming me into their home. Her hospitality and kindness have made my time here not only fruitful but also enjoyable. Her motherly care during my illness is never forgettable part of this journey.

I am grateful to my principle investigator and advisor **Dr. Nikhil Saboo**, Associate Professor, IIT Roorkee for their encouragement and practical advice. I am also thankful to him for commenting on my views and helping me understand and enrich my ideas. I will never forget his great assistance, motivation and encouragement in introducing me to the craft of scientific research in initial days of my Ph.D. Journey. I am grateful to him for enhancing my critical thinking skills and contributing to my research.

My sincere thanks to **Dr. Agnivesh P**, Assistant Professor, Department of Civil Engineering, Indian Institute of Technology (BHU), for his unwavering motivation and encouragement. His critical insights and impartial feedback during my presentations greatly enhanced the quality of my research. His motivational skills and inspiring talks not only taught me how to overcome negative thoughts but also boosted my confidence and ease during presentations.

I am deeply grateful to **Dr. Abhisek Mudgal** for his insightful feedback. I also extend my sincere thanks to the faculty of the Department of Civil Engineering, Indian Institute of Technology (BHU), for their firm support and encouragement throughout this journey.

I wish to convey my sincere gratitude to **Prof. Amit Patra**, Director, Indian Institute of Technology (BHU), for all the institutional support during the course of this study. I would like to thank **Prof. Shyam Bihari Dwivedi**, Dean of Academic Affairs, for his support. I also express my thanks to **Prof. Sasankasekhar Mandal**, Professor, and Head of the Department of Civil Engineering, Indian Institute of Technology (BHU), for making departmental facilities available for the research work every time. Additionally, his continuous assistance with the documentation was one of the most significant aspects of my Ph.D. experience.

I would like to extend my heartfelt thanks to **Prof. A.P. Harsha**, Professor at Department of Mechanical Engineering, Indian Institute of Technology (BHU), for his invaluable contributions as a member of the Research Progress Evaluation Committee (RPEC). His

insightful feedback and exceptional suggestions during the progress presentations greatly enriched my research.

I would like to acknowledge the technical staff of the Transportation Engineering Laboratory, **Mr. Roshan Bhandari** and **Mr. Amit Singh**, for their unforgettable assistance and valuable practical advice throughout my research work. I also wish to extend my sincere appreciation to **Mr. Suraj Kharwar (Tycoon of TEG lab)** for his prompt and helpful support during laboratory work. Additionally, I am deeply grateful for the support provided by the administrative staff, particularly **Mr. Rajesh Ji**, **Mr. Ajit Ji** and **Mr. Mintoo Ji**, from the Department of Civil Engineering, IIT (BHU). Their contributions have been of immense value to my work. I would like to thank the administrative staff, Dean R&D, **Mr. Shivlal Ji**, for their advice and support for smooth running of my fellowship during my project duration.

Yet, the path to this achievement was not walked alone. It was illuminated by the solid support of extraordinary friends, each of whom played a unique and vital role in this journey. Support me through the peaks and valleys of this process.

There a beautiful *subhashitam* (Sanskrit Verse) in Sanskrit on friendship, that my teacher taught me when I was in 10th Standard. The Sanskrit verse is:

पापान् निवारयति योजयते हिताय |

गुह्यानि गूहति गुणान् प्रकटीकरोति |

आपद्गतम् च न जहाति ददाति काले |

सन्मित्रलक्षणमिदम् प्रवदन्ति सन्तः ||

Paapaannivaarayati yojayate hitaaya.

Guhyam nigoohati gunaan prakateekaroti.

Aapadgatam cha na jahaati dadaati kaale.

Sanmitra-lakshanamidam pravadanti santaah.

It means

One who tries to remove your defects, advises you well and steers you on a righteous path, tells others about your positive qualities, does not desert you in times of trouble, and gives (money, support, time, etc.) in times of need, is a good friend - so say the wise.

These are the words come to my mind to describe my friends. First, I would like to extend my heartfelt thanks to **Dr. Mohit Chaudhary (BHAU)** for treating me like his younger brother. He is like a reliable compass. Whenever I found myself lost in the complicated details of my research, he was there, ready to listen and offer a fresh perspective. His ability to turn complex problems into manageable tasks helped me regain clarity when I needed it most. Our conversations, filled with both serious dialogue and light-hearted joking, were a lifeline. Our time together over a cup of tea was more than just a break, it was a chance to relax, chat, and find encouragement. Thank you for making **"TEA"** sessions so meaningful and memorable. Unforgettable credit to **Dr. Mayank Sukhija (SARDAR)** who was my anchor in the stormy seas of research. His ability for handling complex issues and offering a fresh viewpoint was a support during moments of Ph.D. journey. Whether we were brainstorming ideas or just talking things through, his extraordinary support was a constant reminder of the strength and relief that true friendship provides. **His enthusiasm, workaholic approach and positivity** were a constant reminder of the importance of recognizing and appreciating every milestone along the way. Then there is **Annadasu Nirmal Prasad Naidu (ANNA BABU)**, whose practical help is nothing short of a gift whenever Ph.D. journey is in trouble and his practical solutions from helping organize data to offering technical advice is unbelievable. He brought a different kind of magic to the table. Our time together is filled with laughter and shared experiences that provided much-needed break from the rigors of my work. His Ability to infuse joy and lightness during a cup of tea is a crucial counterbalance to the academic pressures, reminding me of the importance of enjoying the journey. Our shared enjoyment of music (especially "**Bhojpuri Music"**) and cricketing discussion during free time is memorable moment of Ph.D

journey. A big thanks to Mr. Abhinav Kumar **(HoD Sahab)** for his help during various aspect of this journey. His hands-on support and willingness to assist is never forgettable moment. A special thanks to **Mrs. Sadiya Shaikh** being my biggest supporter, always there to celebrate the small wins and offer support during tough times. Her enthusiasm and positivity reminded me to appreciate every milestone along the way. I would like to extend my heartfelt thanks to **Mr. Aakash Singh** for his assistance, help, and cooperation in lab during the research work. I am grateful to my seniors **Dr. Jayvant Choudhary**, **Dr. Satyajit Mondal**, and **Dr. Gaurav Verma** for their guidance and insightful discussions during initial days of Ph.D. Special thanks to **Mr. Saurabh Kumar** for his technical assistance during the research work. I owe a special debt of gratitude to my roommate, **Mr. Abhijeet Babar**, who has been a trusty friend throughout this PhD journey. Thank you for being a part of this journey and for making our home a place of comfort and motivation. I offer special thanks to **Mr. Amit Singh (Mitro)** for his moral support during the journey. Thank you for creating my interest in ancient history of India. His story telling about ancient history is always been a treat. I would like to extend my heartfelt thanks to my dear friend and roommate **Mr. Amit Kumar Ram (Chacha)** whose motherly care and unwavering support have been priceless throughout this PhD journey. I would like to express my deepest gratitude to **Mr. Harish Babu Jallu** for his moral support and assistance in the journey.

I want to extend my deepest thanks to my friends **Manasi, Avinash, Jhuna Rani Ojha, Ashish Kumar Chouksey, Saroj Kanta Behera, Mayank Nishant, Agnivesh Tiwari, Hrithik Mahour, Dr. Chintaman, Anurag Namuduri, Vishal Kushwaha, Pawan Ojha, Manish Tiwari, Amardeep Pandey, Rohit Rodhia, and Gulshan.** Their support and care helped me overcome setbacks and stay focused on my research study. I greatly value their friendship, and I deeply appreciate their belief in me. Their financial support, patience and encouragement

made a big difference during the long hours of study and research. I would like to thank all my cricketing friends for making this journey memorable and enjoyable.

In Sanskrit verse, the family is described as: "कुटुम्बं सर्वमिति" (kuṭumbaṁ sarvamiti), which literally means "family is everything". I want to express my deepest gratitude to my family, particularly my father **Mr. Pratap Wagh,** my mother **Mrs. Usha Wagh**, my sister **Mrs. Madhuri Sonawane**, my brother-in-law **Mr. Jitendra Sonwane,** and my **niece Hindavi.** Their unconditional love and constant encouragement were instrumental in helping me achieve my goals. They generously supported my dreams and gave me the space and motivation to succeed. I want to give special thanks to my wife **Mrs. Nishigandha Jukte** (Research Scholar, IIT Delhi) for her solid support and love throughout this journey. Her patience, encouragement, and understanding have been my greatest source of strength. Thank you for standing by me, cheering me on, and being a constant source of inspiration and comfort. Her support has been invaluable, and I am deeply grateful for everything she has done for me.

And to the rest, I am extremely thankful to those people, whose names have been unknowingly left, thank you very much for your support and prayers. It really helped me a lot.

Lastly, I am grateful to the Science and Engineering Research Board (SERB), Department of Science and Technology (DST), India, for supporting the project (ECR/2018/000654). This assistance was essential for carrying out my research work. A big thanks and appreciation to the Indian Institute of Technology (BHU) for providing me such great research infrastructure and financial help in the form of institute fellowship for the study.

Vivek Pratap Wagh

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

A	Asphaltan A
AASHTO	American Association of State Highway and Transportation Officials
A_{APS}	Area of the Pull-out Stub
A_g	Contact Area of Reaction Plate with the Gasket
AFM	Atomic Force Microscopy
ANOVA	Analysis of Variance
APA	Asphalt Pavement Analyzer
AS	Anti-Stripping
ASCE	American Society of Civil Engineers
ASTM	American Society of Testing and Material
AV	Air Voids
BBS	Bitumen Bond Strength
BIS	Bureau of Indian Standards
BC	Bituminous Concrete
BP	Burst Pressure
BS	Bond strength
BSR	Bond Strength Ratio
CA	Calcareous Aggregates
CI	Coating Index
CI_N	Normalized Coating Index
CMA	Cold Mix Asphalt
CO_2	Carbon dioxide
CO	Carbon Monoxide
CoF	Coefficient of Friction
CRMB	Crumb Rubber Modified Bitumen
CRRI	Central Road Research Institute
CT	Compaction Temperature
C-Y	Carreau-Yasuda

DAT	Dispersed Asphalt Technology
DOT	Department of Transportation
DSR	Dynamic Shear Rheometer
EQ	Equi-Viscous
FBM	Flow Behaviour Method
FHWA	Federal Highway Administration
FPE	Functionalized Polyolefin Polymer
FS	Frequency Sweep
FT	Fischer-Tropsch
FTIR	Fourier Transform Infrared Spectroscopy
GHG	Greenhouse Gas
H_2	Hydrogen
HSR	Higher Shear Rate
HSR-E	High Shear Rate Evolution Approach
HSR-O	High Shear Rate Method
HMA	Hot Mix Asphalt
HWMA	Half Warm Mix Asphalt
I	Iterlow
IIT	Indian Institute of Technology
IIT (BHU)	Indian Institute of Technology (Banaras Hindu University)
IRC	Indian Road Congress
IRC SP	Indian Road Congress Special Publication
IS	Indian Standards
ITS	Indirect Tensile Strength
LAS	Linear Amplitude Sweep
LCA	Life Cycle Assessment
LEA	Low Energy Asphalt
LEAB	Low Energy Asphalt Binder
LTA	Long-Term Ageing

LVE	Linear Viscoelastic
MoRTH	Ministry of Road Transport and Highways
MSCR	Multiple Stress Creep and Recovery
MT	Mixing Temperature
NAPA	National Asphalt Pavement Association
NCAT	National Centre for Asphalt Technology
NCHRP	National Cooperative Highways Research Program
NH_3	Amine
NMAS	Nominal Maximum Aggregate Size
NOx	Nitrogen Oxide
OBC	Optimum Binder Content
PA	PMB40+Asphaltan A
PAM	Phase Angle Method
PAT	Pneumatic Adhesion Tester
PATTI	Pneumatic Adhesion Tensile Testing Instrument
PAV	Pressure Ageing Vessel
PEN	Penetration Grade
PI	PMB40+Iterlow
PG	Performance Grade
PMB	Polymer Modified Binder
POTS	Pull-out Tensile Strength
$POTS_{Dry}$	Pull-out Tensile Strength for unconditioned sample
$POTS_{Wet}$	Pull-out Tensile Strength for moisture conditioned sample
PR	PMB40+Rediset
PS	PMB40+Sasobit
R	Rediset
RAP	Recycled Asphalt Pavement

RAPM	Recycled Asphalt Pavement Material
RGB	Red-Green-Blue
RMS	Root Mean Square
RPM	Rotation Per Minute
RV	Rotational Viscometer
RTFO	Rolling Thin Film Oven
S	Sasobit
SA	Siliceous Aggregate
SBS	Styrene Butadiene Styrene
SiC	Silicon Carbide
SFE	Surface Free Energy
SLR	Systematic Literature Review
SMA	Stone Matrix Asphalt
SO_2	Sulphur Dioxide
SR	Sasobit Redux
SSF	Steady Shear Flow
STA	Short-Term Ageing
S-ZSV	Simplified Zero Shear Viscosity
TSR	Tensile Strength Ratio
TTSP	Time Temperature Superposition Principle
UA	Unaged
USAT	Universal Simple Ageing Test
VECD	Viscoelastic Continuum Damage
VFB	Voids Filled with Bitumen
VG	Viscosity Grade
VMA	Voids in Mineral Aggregate
VOC	Volatile Organic Compounds
WMA	Warm Mix Asphalt
XRD	X-ray Diffraction
ZSV	Zero Shear Viscosity

ω	Angular Frequency
α	Angle Between the Plates and the Horizontal Plane
R_a	Average Surface Roughness
G_{mb}	Bulk Specific Gravity of Mix
C=O	Carbonyl Group
I_{CO}	Carbonyl Index
μ	Coefficient of Friction
G*	Complex Shear Modulus
J_c	Critical Strain Energy Release Rate
φ	Deflection Angle
N_F	Fatigue Life
F_F	Frictional Force
N_{92}	Gyrations Required to Reach 92% of G_{mm}
J_{nr}	Non-Recoverable Creep Compliance
%R	Percent Recovery
δ	Phase Angle
F_N	Normal Force
P_D	Perpendicular Distance
r_{ball}	Radius of the Ball
R_q	Root Mean Square Value
V_S	Sliding Velocity
N	Speed of Shaft in Rotation
S=O	Sulfoxide Group
I_{SO}	Sulfoxide Index
G*. Sinδ	Superpave Fatigue Parameter
G*/Sinδ	Superpave Rutting Parameter
G_{mm}	Theoretical Specific Gravity of Mix
T	Torque
η	Viscosity