ASSESSING THE IMPACT OF PRODUCTION TEMPERATURES ON THE PERFORMANCE OF WARM MIX ASPHALT

वॉर्म मिक्स डामर के गुणों पर उत्पादन तापमान के प्रभाव का आकलन

Thesis submitted in partial fulfillment

for the Award of Degree

Doctor of Philosophy

By

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I, **MAYANK SUKHIJA,** certify that the work embodied in this thesis is my own bonafide work and carried out by me under the supervision of **Dr. AGNIVESH P and Dr. NIKHIL SABOO** from **July 2018** to **July 2022** 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.

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Dedicated to Frontline
Corona Warriors and
My Beloved Family…

ACKNOWLEDGEMENT

Whenever I felt like giving up on this project, God's grace and my parents' belief in me would continually strengthen my intellect, encourage me to keep going, and offer new possibilities to explore. Countless people knowingly and unknowingly have supported my efforts in the research journey. I want to thank all the people who have helped me in the journey of completing this Ph.D. thesis and made my journey successful.

First and foremost, I wish to express my deep regards and sincere gratitude to **Dr. Nikhil Saboo**, Assistant Professor, Department of Civil Engineering, Indian Institute of Technology Roorkee, for his patience, inspiring guidance, valuable suggestions, constant encouragement, keen interest throughout the journey, and faith in me at every stage of this research. It has been an honor to be his first Ph.D. student. I am fortunate to work with a very compassionate and encouraging professor like him. I thank him for reminding me that I can do better, which enhanced my confidence and helped me improve my research methodologies. During my research, he helped me frame ideas by giving me intellectual freedom and demanding high-quality work. I've benefited immensely from his wealth of knowledge and efforts to improve my work. Not only through the Ph.D. research work, but he gave me opportunities to learn through various other projects and courses. I will be forever grateful for having him as my supervisor from the bottom of my heart.

I would like to express my appreciation and deepest gratitude to **Dr. Agnivesh P**, Assistant Professor, Department of Civil Engineering, Indian Institute of Technology (BHU), for his consistent support and suggestions in my research work and thesis writing. Though I got to work with him during the last phase of my Ph.D., his insightful comments and critical questions helped me to understand and enrich my research ideas. His motivational skills and inspirational stories taught me how to overcome negative thoughts and made me confident and comfortable during my presentations. Also, his consistent support in all the documentation work and finding great opportunities for me in the research world will always be the best part of my Ph.D.

A special thanks to **Dr. Ankit Gupta**, Associate Professor, and MoRTH Chair Professor, Department of Civil Engineering, Indian Institute of Technology (BHU), for continuously motivating me and encouraging me to do good quality work. His critical examination and unbiased suggestions during all my presentations led to tremendous improvement in the research work.

I express my heartfelt thanks and gratitude to **Dr. Abhisek Mudgal** and **Dr. Brind Kumar** for their technical guidance and elliptical suggestions during the research work. I am also thankful to all the other faculty members of the Department of Civil Engineering, Indian Institute of Technology (BHU), for their constant support during the research phase.

I wish to convey my sincere gratitude to **Prof. Promod Kumar Jain**, 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 their support. I also express my thanks to **Dr. Prabhat Kumar Singh Dikshit**, Professor, and Head of the Department of Civil Engineering, Indian Institute of Technology (BHU), for making departmental facilities available for the research work even during the COVID times.

I would like to express my sincere appreciation to the research progress evaluation committee (RPEC) member **Dr. Chandana Rath**, Associate Professor, School of

Materials Science and Technology, Indian Institute of Technology (BHU), for their valuable input and brilliant suggestions during the progress presentations.

I would also extend my acknowledgment to the technical staff, **Mr. Roshan Bhandari** and **Mr. Amit Singh**, of the Transportation Laboratory, for their consistent help and practical advice in one way or another. Special mention to **Mr. Suraj Kharwar** and **Mr. Om Prakash Badal** for always being readily available for their assistance during the laboratory work. The help and support from the administrative staff (especially **Mr. Amar** and **Mr. Nitin**) of the Department of Civil Engineering, IIT (BHU) is also greatly acknowledged.

I would like to acknowledge the assistance from my colleague **Mr. Mohit Chaudhary** who always stood beside me like a brother during my research tenure. Being inseparable, he has endured all my stupidity, fights, arguments, secrets, laughter, and technicality from the first day of my Ph.D. till the end. I'm indebted to my friend **Mr. Annadasu Nirmal Prasad Naidu,** for encouraging and building confidence in me at every stage. Despite his work and health issues, he helped me by providing critical insights and useful suggestions during the research work and thesis preparation. Special thanks to **Mr. Vivek Wagh** for his technical assistance while doing the experimental work. The timeless discussions and critical arguments he provided are the prominent parts that can never be overlooked. Appreciation is extended to my seniors **Dr. Jayvant Choudhary**, **Dr. Satyajit Mondal, Mr. Gaurav Verma, Dr. Arunabh Pandey,** and **Dr. Poonam Sharma** for their guidance and active discussions during the last four years.

I am grateful to other fellows at IIT BHU, including **Ashish Kumar Chouksey, Amit Kumar Ram, Abhinav Kumar, Saroj Kanta Behera, Sadiya Shaikh, Parul Rawat,**

Amit Singh, Abhijeet Babar, Abhinav Thakur, Ashutosh Kumar, Vishal Kushwaha, Mayank Nishant, Aakash Singh, Gaurav Singh, Sukeerti Bansal, Amardeep Pandey, and **Rohit Rodhia**. They all deserve a lot of thanks from me for their inspiration, help, and cooperation. I'll always remember the time I spent at IIT Roorkee, where I met many new people who all helped me along the way. I offer special thanks to **Mr. Harishbabu Jallu** for his moral support and for enduring my nagging. I am very thankful to **Dheeraj Mehta**, **Yashodhara Singh, Rashmi Choudhary, Surya Kant Sahdeo, Ankit Sharma, Priti Rai, Prakhar Aeron, Soumyadeep, Muskan Verma, Rishi Chhabra, Mohanshu, Bhavesh, Abhitesh, Sumit, Ayana, Sohel, Manish, Col. Avnish,** and **Major Amit** for their extensive cooperation during my stay there. I also express my appreciation towards the lab staff (especially **Mr. Rajeev Hooda,** and **Shahrukh**) at IIT Roorkee for their support and assistance.

I would also like to mention my close friends **Prachi, Rushil, Sagar, Rahul, Vishant, Shivam, Adheesh**, **Akshita, Hitesh, Parvez, Hansvi-Vadhyani, Dipanshu, Himani, Deepansh, Avantika, Rinki, Swati,** and **Deepak** who helped me in one or another way during the difficult years.

Last but not least, I would like to thank "**My Joint Family",** especially my mother **Mrs. Geeta Sukhija,** father **Mr. Kishan Sukhija** and brother **Mr. Rajat Sukhija,** for their unparalleled love and timely encouragement. They selflessly motivated me and gave me time to seek my dreams. Appreciation is extended to **Mrs. Preeti Saboo** for making me feel at home during the lockdown and afterward like her own family member. I would dedicate my thesis to my family for their unconditional love and trust in me. As half of my research tenure was spent during COVID, I would also like to dedicate my research to frontline corona warriors.

I'm thankful for the financial assistance in the form of a research fellowship and contingency grants provided by the Ministry of Human Resource and Development (MHRD), Government of India, for carrying out my research work.

Mayank Sukhija

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ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
AI	Ageing Index
Am	Aspha-Min
ARV	Average Rank Value
ASA	Antistripping Agent
ASCE	American Society of Civil Engineers
ASTM	American Society of Testing and Material
AV	Air Voids
BC	Bituminous Concrete
BIS	Bureau of Indian Standards
BS	Bond Strength
BSR	Bond Strength Ratio
BWT	Boiling Water Test
C	Cecabase
CCT	Cyclic Compression Test
CI	Coating Index
CI_N	Normalized Coating Index
CM	Creep Modulus
CMA	Cold Mix Asphalt
CO_2	Carbon dioxide
CO	Carbon Monoxide
CRMB	Crumb Rubber Modified Binder
CT	Compaction Temperature
C-Y	Carreau-Yasuda
DAm	Dolomite + VG30 + Aspha-Min
DC	Dolomite + VG30 + Cecabase
DP	Dolomite + PMB40
DPAm	Dolomite + PMB40 + Aspha-Min
DPC	Dolomite + PMB40 + Cecabase
DPR	Dolomite + PMB40 + Rediset
DPS	Dolomite + PMB40 + Sasobit
DPSR	Dolomite + PMB40 + Sasobit Redux
DR	Dolomite + VG30 + Rediset
DS	Dolomite + VG30 + Sasobit
DSR	Dolomite + VG30 + Sasobit Redux
DVG	Dolomite + VG30
E	Emissions from Energy Consumption

E&E	Energy Requirement and Environmental Burdens
EEF	Energy Emission Factors
ELCA	Environmental Life Cycle Assessment
EQ	Equi-Viscous
F	Fuel Consumption
FE	Fracture Energy
FI	Fatigue Index
FS	Frequency Sweep
FTIR	Fourier Transform Infrared Spectroscopy
GAm	Granite + VG30 + Aspha-Min
GAR	Global Average Rank
GC	Granite + VG30 + Cecabase
GHG	Greenhouse Gas
GP	Granite +PMB40
GPAm	Granite + PMB40 + Aspha-Min
GPC	Granite + PMB40 + Cecabase
GPR	Granite + PMB40 + Rediset
GPS	Granite + PMB40 + Sasobit
GPSR	Granite + PMB40 + Sasobit Redux
GR	Granite + VG30 + Rediset
GS	Granite + VG30 + Sasobit
GSR	Granite + VG30 + Sasobit Redux
GVG	Granite + VG30
GWP	Global Warming Potential
H	Heat Energy
HMA	Hot Mix Asphalt
HSR-E	Higher Shear Rate Evolution Approach
HSR-O	High Shear Rate Method
HWMA	Half Warm Mix Asphalt
Hz	Hertz
Ideal CT	Indirect Tensile Cracking Test
IIT	Indian Institute of Technology
IIT (BHU)	Indian Institute of Technology (Banaras Hindu University)
INR	Indian Rupee
IPCC	Intergovernmental Panel on Climatic Change
IRC	Indian Road Congress
IS	Indian Standards
ITS	Indirect Tensile Strength
LAST	Linear Amplitude Sweep Test
LCA	Life Cycle Assessment
LDO	Light Diesel Oil
LSHF	Low Sulphur Heavy Stock
LTA	Long-Term Ageing
LVE	Linear Viscoelastic

MI	Modification Index
MoRTH	Ministry of Road Transport and Highways
MS	Marshall Stability
MSCR	Multiple Stress Creep and Recovery
MT	Mixing Temperature
NCHRP	National Cooperative Highways Research Program
NMAS	Nominal Maximum Aggregate Size
NO_x	Nitrogen Oxide
OBC	Optimum Binder Content
PAM	Phase Angle Method
PAT	Pneumatic Adhesion Test
PATTI	Pneumatic Adhesion Tensile Testing Instrument
PAV	Pressure Ageing Vessel
PG	Performance Grade
PMB	Polymer Modified Binder
Q	Quantity of Fuel
R	Rediset
RAPM	Recycled Asphalt Pavement Material
RGB	Red-Green-Blue
RMS	Retained Marshall Stability
RP	Rutting Parameter
RPM	Rotation Per Minute
RV	Rotational Viscometer
S	Sasobit
SEM	Scanning Electron Microscopy
SLR	Systematic Literature Review
SO_2	Sulphur dioxide
SP	Special Publication
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
ZSV	Zero Shear Viscosity
ω	Angular Frequency
G_{mb}	Bulk Specific Gravity of Mix

Φ	Calorific Value of the Fuel
$I_{C=O}$	Carbonyl Index
G^*	Complex Shear Modulus
ρ	Density of Fuel
N_F	Fatigue Life
J_{nr}	Non-Recoverable Creep Compliance
α	Oxidation/Combustion Rate of Fuel
%R	Percent Recovery
δ	Phase Angle
$I_{S=O}$	Sulfoxide Index
$G^*.\mathrm{Sin}\delta$	Superpave Fatigue Parameter
$G^*/\mathrm{Sin}\delta$	Superpave Rutting Parameter
G_{mm}	Theoretical Specific Gravity of Mix
$\sum E$	Total GHG Emissions

ABSTRACT

WMA is a rapidly growing innovative technology that allows the mixing and compaction of asphalt mixtures at lower production temperatures compared to conventional HMA. The existing WMA additives can be divided into three broad categories depending on their working mechanism. These are organic, chemical, and foaming-based technologies. Although the working mechanism of these technologies may be different, the primary aim is to lower the production temperatures of asphalt mixtures. Several concerns have been raised regarding the determination of mixing and compaction temperatures (also termed as production temperatures) for WMA mixtures. Thus, more exploration is required in this direction for developing a rational approach to evaluate the production temperatures of asphalt mixtures, and to assess the impact of production temperatures on the performance of WMA.

Two base asphalt binders, viz. viscosity graded (VG), VG30, and polymer modified binder (PMB), PMB40, were taken in the present study. Two different aggregate sources (granite and dolomite) were incorporated to assess the effect of aggregate mineralogy on the behaviour of WMA technologies. Five different WMA additives, including two organic-based (Sasobit and Sasobit Redux), two chemical-based (Rediset and Cecabase) additives, and one foaming-based technology (Aspha-min) were incorporated to understand the influence of different WMA technologies.

This study revolved around the determination of production temperatures and their impact on the behavior of asphalt mixtures. Six objectives were defined in this direction. These objectives along with the obtained results are briefly discussed in the following paragraphs.

Objective 1

The first objective focused on the effect of WMA technologies on the morphological, chemical, and physical properties of asphalt binders. Scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), and a series of empirical and fundamental tests were carried out for the characterization. SEM and FTIR confirmed that the adopted blending technique is appropriate for obtaining uniform/homogeneous blend with pure physical interaction between WMA additives and asphalt binders. All the WMA binders, prepared either using VG30 or PMB40, displayed similar to better physical characteristics than the base asphalt binders.

Objective 2

Though a considerable amount of researches have been done on assessing the performance of WMA technologies, no standard approach is available for estimating their appropriate production temperatures. The EQ method was found to be suitable only for VG30. The second objective involved the development of a novel workability-based prototype that can evaluate the workability of asphalt mixtures. A new procedure, based on workability, was proposed and validated for rational evaluation of production temperatures. Additionally, coating ability and compactability tests were carried out to validate the obtained mixing and compaction temperatures, respectively. Further, the optimum dosage of WMA additives, pertaining to different technologies, were assessed based on the coating and compactability checks. About 5 °C-25 °C and 5 °C-37 °C reduction in mixing and compaction temperatures, respectively, were obtained for different WMA technologies. Despite being produced at lower production temperatures, WMA showed a consistent aggregate coating and density range as conventional HMA mixtures. It was found that the optimum dosage of WMA additives varies with the change in aggregate source and base asphalt binder.

Objective 3

The third objective envisioned to compare the performance of WMA binders (prepared at the optimum dosage) with their respective conventional asphalt binders (with no additives, i.e., VG30 and PMB40). The comparison was made based on the laboratory results concerning ageing, rutting, fatigue, and moisture characteristics at the binder level.

Carbonyl (C=O) and Sulfoxide (S=O) indices, determined through FTIR spectrums, were used to explicate the ageing behavior of WMA binders. Among different WMA additives, Chemical agents displayed lower values of $I_{C=O}$ and $I_{S=O}$, regardless of ageing condition.

A series of experiments were carried out using DSR to assess the rutting and fatigue performance. These test methods included the traditional Superpave rutting and fatigue parameters determined through frequency sweep (FS), multiple stress creep and recovery (MSCR) for rutting, and linear amplitude sweep test (LAST) for fatigue. MSCR test was performed at four different temperatures (40-70°C) and four different stress levels (0.1, 3.2, 5, and 10 kPa). A rutting parameter based on the Arrhenius equation (activation energy concept) was used in the present study to conceptualize the effect of multiple stresses and test temperatures. On the other hand, LAST was conducted at three temperatures ranging from 10-30°C, and the fatigue life of asphalt binders was determined. Despite the lower ageing temperature, Sasobit-modified asphalt binder exhibited higher rutting resistance in VG30, while its influence was found to be insignificant in the case of PMB40. The failure strain obtained by analyzing LAST results was found to be under a comparable range i.e. 6-11%, irrespective of the base asphalt binder. The fatigue life of WMA binders was comparable with the results of base asphalt binders, over a wide range of strain values at all the test temperatures.

Chemical-based WMA agents showed higher fatigue life as compared to organic-based WMA agents.

Bond strength (BS) between asphalt binder and aggregates was used to ascertain the suitability of WMA binders against moisture damage. Bond strength ratio (BSR) was evaluated for assessing the moisture resistance of asphalt mixtures. Chemical-based WMA agents exhibited antistripping characteristics that restrict moisture's effect, as indicated by higher BSR for Cecabase and Rediset.

Objective 4

The performance of HMA and WMA mixtures were evaluated and compared under the fourth objective of this study. Possible correlations between the test results of asphalt binders and mixtures were analyzed and the limiting values for different performance predictors were proposed. All the test parameters, except the mixing and compaction temperatures, were kept constant throughout the study for analyzing HMA and WMA mixtures. The mixing and compaction temperatures required for the preparation of WMA mixtures were obtained based on the proposed workability approach. A series of performance-based test methods including the Cyclic compression test (CCT) for rutting performance at 60°C and Indirect tensile cracking test (Ideal CT) for fatigue performance at 20°C, were carried out. A check against moisture damage was also ascertained by evaluating % stripping/coating using a boiling water test (BWT), Retained Marshall stability (RMS), and Tensile strength ratio (TSR).

Creep modulus (CM), determined by analyzing CCT test results, showed slightly lower performance of WMA mixtures, particularly for PMB40-based asphalt mixtures. Overall, Sasobit, an organic-based WMA additive, displayed higher rutting resistance among all the WMA. Fatigue resistance was evaluated using a proposed fatigue index

(FI). Based on the FI values, irrespective of base asphalt binder and aggregate source, WMA mixtures prepared with chemical agents showed better fatigue performance followed by foaming and organic technologies. Despite lower production temperature, the application of WMA technology seemed to facilitate moisture repellent characteristics, regardless of any test method. Rediset, combined with dolomite aggregates, can be considered as a potent combination for preparing moisture-resistant asphalt mixtures. The overall results also demonstrated appreciable correlations between the performance parameters of asphalt binders and mixtures.

Objective 5

The idea behind the fifth objective was to outline the energy-related cost and amount of GHG emissions imparted by producing WMA mixtures based on a theoretical approach. Different factors such as fuel type and type of WMA additive were varied during the analysis. Results displayed a reduction in heat energy with the addition of WMA additives ranging from 5-13% relative to conventional HMA mixtures. Rediset and Cecabase in VG30 with granite and dolomite aggregates, respectively, resulted in the lowest cost reduction, whereas in PMB40, the incorporation of Sasobit with any aggregate type, showed the lowest cost savings, irrespective of fuel type. The implementation of WMA technologies exhibits a pronounced reduction in GHG emissions relative to conventional HMA.

Objective 6

In the last objective (sixth), a simple ranking protocol was used to select the best WMA additive, relative to other WMA, based on their overall performance. WMA showed either similar/improved performance and therefore similar/higher rank than the reference HMA. Based on the global average ranking (*GAR*), Rediset, a chemical-based WMA agent, was found to be the best WMA additive.