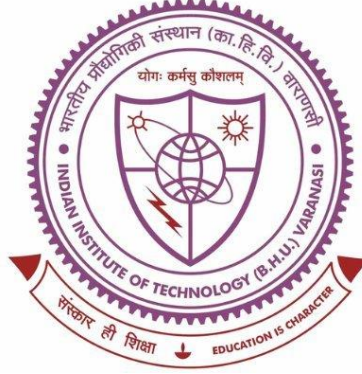


**Tribological and Performance Assessment of Binders
Modified with Warm Mix Asphalt Additives**
**वार्म मिक्स डामर एडिटिक्स के साथ संशोधित बाइंडरों का
ट्रिबोलॉजिकल और कार्य मूल्यांकन**



*Thesis submitted in partial fulfillment
for the Award of Degree*

Doctor of Philosophy

By

Vivek Pratap Wagh

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2024

CERTIFICATE

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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.


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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.

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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.

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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.

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LIST OF TABLES

Table 2-1. Foaming technologies used for temperature reduction.....	26
Table 2-2. Organic additives used for temperature reduction.....	27
Table 2-3. Chemical additives used for temperature reduction	28
Table 2-4. Comparative reduction (in %) in gas emission using WMA technology	50
Table 2-5. Range of production temperature reduction achieved using WMA technology.....	56
Table 2-6. Representative list of proposed methods for the prediction of production temperatures	60
Table 2-7. Detailed description of various tests used for tribological characterization of the asphalt binder.	75
Table 2-8. Key features of various tests used for tribological characterization of the asphalt binder. .	77
Table 2-9. Parameter influencing lubricating behaviour of asphalt binder.....	82
Table 2-10. The Influence of warm mix additives on the lubrication properties.....	84
Table 2-11. The relation of coefficient of friction with asphalt binder and mixture properties.....	85
Table 2-12. Effect of WMA additives on physical properties of asphalt binders	89
Table 2-13. Results of previous studies on the effect of WMA additives on rutting	91
Table 2-14. Results of previous studies on the effect of WMA additives on fatigue cracking.....	97
Table 2-15. Inferences from past studies on the bonding behaviour of WMA mixtures	101
Table 2-16. Effect of WMA technologies on various moisture sensitivity parameters.	102
Table 2-17. Effect of WMA technology on aging of asphalt binder	105
Table 2-18. Performance summary of PMB-WMA interaction.....	110
Table 3-1. Physical properties of the asphalt binders	125
Table 3-2. Physical and chemical properties of WMA additives.....	132
Table 3-3. Nature of different aggregate type.....	133
Table 3-4. Physical properties of aggregates	134
Table 3-5. Mineral composition of various aggregate type	140
Table 3-6. Terminology used in the present study.....	141
Table 3-7. Asphalt binder grading based on J_{nr} at 3.2 kPa stress level [358].....	171
Table 4-1. Range of mixing temperature using different test methods for VG30 as base binder.....	196
Table 4-2. Range of compaction temperature using different test methods for VG30 as base binder	196
Table 4-3. Range of mixing temperature using different test methods for PMB40 as base binder	197
Table 4-4. Range of compaction temperature using different test methods for PMB40 as base binder	197
Table 4-5. Physical properties of different polymer modified binders used in phase angle method. .	200
Table 4-6. MT and CT obtained using phase angle method for different polymer modified binders.	200
Table 4-7. MT and CT obtained using phase angle method for WMA modified binders.	200

Table 5-1. Review of tribology studies related to WMA technology	208
Table 5-2. Material selection summary.....	211
Table 5-3. Surface roughness details of the plates.....	219
Table 5-4. Configuration of workability prototype.....	222
Table 5-5. Summary of mix design.....	228
Table 5-6. Ranges of coefficient of friction for determination of production temperature.....	242
Table 5-7. CoF at production temperature of viscosity grade binders	249
Table 5-8. Reference torque values for base asphalt binder (VG30) for different aggregate type.	267
Table 5-9. MT and CT obtained from workability approach.....	268
Table 6-1. Results of previous studies on the effect of WMA additives on rutting, fatigue, and moisture damage performance	283
Table 6-2. Performance test used for WMA modified binders	293
Table 6-3. Failure strains for WMA modified binders for both the base binders at different temperatures	312
Table 6-4. Threshold value of BSR based on reliability level	336
Table 7-1. Summary of three-way ANOVA at 95% confidence level for Carbonyl index.	343
Table 7-2. Summary of three-way ANOVA at 95% confidence level for non-recoverable creep compliance and % recovery.	346
Table 7-3. Summary of three-way ANOVA at 95% confidence level for fatigue life at 2.5% strain level.	348
Table 7-4. Summary of three-way ANOVA at 95% confidence level for bond strength parameters.	350
Table 7-5. Ranking methodology.....	357
Table 7-6. Results for different dosages of Sasobit for ranking analysis.....	357
Table 7-7. Normalised values and ranking allocation for different dosages of Sasobit.....	357
Table 7-8. Optimum dosage of various WMA additives for VG30 and PMB40 binder.	358
Table 7-9. Results of MSCR test and reduction in MT and CT for ranking analysis.	363
Table 7-10. Normalised values and ranking allocation for different WMA additives in VG30.....	363
Table 7-11. Selection summary of WMA additives.....	365

LIST OF FIGURES

Figure 2-1. Production temperatures of asphalt mixtures technologies	25
Figure 2-2. Low energy asphalt process for asphalt foaming	32
Figure 2-3. Double barrel green nozzle for asphalt foaming	33
Figure 2-4. Water bearing additives a) Asphamin b) Advera	34
Figure 2-5. Range of production temperature reduction achieved using WMA technology	56
Figure 2-6.(a) Tribology as interdisciplinary science, (b) tribology in various domains of science, (c) application of tribology in various industries	69
Figure 2-7. Tribo-system (Two Bodies separated by Lubricant).....	71
Figure 2-8. Different tribological geometries used for asphalt binder a) Tribo-Rheometry testing fixture and sample loading b) Asphalt lubricity tester (four ball test) and its assembly c) Asphalt boundary lubrication test apparatus proposed by Puchalski d) Ball-on-three-plates test mounted on dynamic shear rheometer.	75
Figure 2-9. Percent reduction in Carbonyl and Sulfoxide index due to WMA technologies a) After short term aging b) After long term aging	108
Figure 3-1. Methodology adopted in the study	124
Figure 3-2. Warm mix additives a) Sasobit b) Asphaltan A c) Iterlow d) Rediset LQ1102CE.....	127
Figure 3-3. FTIR spectra for Sasobit	128
Figure 3-4. FTIR spectra for Asphaltan A	129
Figure 3-5. FTIR spectra for Iterlow.....	130
Figure 3-6. FTIR spectra for Rediset	131
Figure 3-7. XRD pattern of aggregates a) Dolomite b) Dolerite c) Basalt d) Granite e) Sandstone...	138
Figure 3-8. Match software a) Interface of Match software b) XRD pattern of Dolomite obtained from Match Software.....	139
Figure 3-9. Stepwise preparation of WMA modified binders.....	141
Figure 3-10. Test setup (a) Penetration, (b) Softening point, and (c) Viscosity	145
Figure 3-11. Experimental setup for elastic recovery test using ductilometer a) elongation phase b) recovery phase	146
Figure 3-12. Dynamic shear rheometer (DSR)	147
Figure 3-13. Penetration value of different WMA binders (a) VG30 and (b) PMB40	149
Figure 3-14. Softening point of different WMA binders (a) VG30 and (b) PMB40	150
Figure 3-15. Effect of WMA additives on absolute viscosity of VG30.....	151
Figure 3-16. Effect of WMA additives on elastic recovery of PMB40.	152
Figure 3-17. True failure temperature and PG of different WMA binders (a) VG30 and (b) PMB40154	
Figure 3-18. Brookfield viscometer used for determination of MT and CT.....	156

Figure 3-19. a) Ball-on-three plates arrangement mounted on DSR b) Schematic of the ball-on-three-plates test.....	158
Figure 3-20. Schematic of coating apparatus.....	161
Figure 3-21. Short term aging and long term aging of asphalt binders.....	164
Figure 3-22. STA and LTA of asphalt binders using USAT protocol	166
Figure 3-23. FTIR test setup	168
Figure 3-24. MSCR data for one cycle	171
Figure 3-25. Bitumen bond strength test setup used for assesement of moisture damage of WMA modified binders	175
Figure 3-26. Sample preparation for BBS test.....	176
Figure 3-27. Sample for BBS test by considering different aggregate types	176
Figure 4-1. Research methodology adopted in this chapter.....	184
Figure 4-2. Determination of MT and CT using EQ method.....	185
Figure 4-3. Determination of ZSV using Cross-Williamson model	186
Figure 4-4. Determination of MT and CT using ZSV method.	186
Figure 4-5. Determination of MT and CT using S-ZSV method.....	187
Figure 4-6. Determination of MT and CT using HSR-O approach.	188
Figure 4-7. Determination of MT and CT using HSR-E approach.....	189
Figure 4-8. Determination of MT and CT using flow behaviour (100000 s^{-1}) approach.....	190
Figure 4-9. Determination of MT and CT of PMB40 using phase angle method.....	192
Figure 4-10. Behaviour of polymer and WMA modified binders over the range of temperatures.....	203
Figure 5-1. Research methodology adopted in this chapter.....	210
Figure 5-2. Ball-on-three-plates arrangement mounted on DSR	214
Figure 5-3. a) Free body diagram b) Distribution of normal force among the plates c) determination of frictional force.....	215
Figure 5-4. The procedure adopted for the preparation of aggregates plates.....	218
Figure 5-5. Plates and ball used in the study a) Pictorial view b) Schematic view c) Different plates used in the study	218
Figure 5-6. Line diagram of developed workability prototype	223
Figure 5-7. Deposition of material (a) fine aggregate on the walls of the container and (b) agglomerated chunk.....	225
Figure 5-8. Example of the raw data obtained from workability test along with the average trend ...	226
Figure 5-9. Aggregate gradation used in the study	228
Figure 5-10. Schematic representation of experimental setup for coating.....	230
Figure 5-11. Details of software (a) Front Interface, (b) Colour sample in RGB format, and (c) About the developer.....	231

Figure 5-12. Image captured (a) Uncoated Aggregates, (b) Coating at 100°C, (c) Coating at 130°C, and (d) Coating at 160°C.	231
Figure 5-13. Production temperature using EQ method a) MT b) CT.....	233
Figure 5-14. Variation of CoF with temperature for different speed a) 3N b) 5N c) 10N.....	237
Figure 5-15. Variation of CoF with temperature for WMA modified asphalt binder at 0.3 m/s a) 5N b) 3N c) 1N.....	238
Figure 5-16. Variation of CoF with temperature for different plates a) VG 30 b) S2 c) R0.5.....	240
Figure 5-17. Variation of CoF with temperature for various WMA modified binders using steel plates	240
Figure 5-18. Ranges of production temperature determined using tribological approach a)Mixing temperature b) Compaction temperature.....	243
Figure 5-19. Effect of WMA additives on frictional characteristics of VG30 as base binder (a) Sasobit (S),(b) Asphaltan A (A) (c) Rediset (R), (d) Iterlow (I).....	246
Figure 5-20. Variation of CoF with temperature for various polymer modified binders using steel plates	247
Figure 5-21. Effect of WMA additives on frictional characteristics of PMB40 as base binder (a) Sasobit (S), (b) Asphaltan A (A) (c) Rediset (R), (d) Iterlow (I).....	248
Figure 5-22. Determination of MT and CT using tribological approach for Rediset	250
Figure 5-23. Production temperatures using tribological approach for WMA additives in VG30 as base binder a) Organic additives b) Chemical additives	253
Figure 5-24. Production temperatures using tribological approach for various polymer modified binders	254
Figure 5-25. Production temperatures using tribological approach for WMA additives in PMB40 as base binder a) Organic additives b) Chemical additives	255
Figure 5-26. Reduction in MT and CT of VG30 a) Organic additives b) Chemical additives	256
Figure 5-27. Reduction in MT and CT of PMB40 a) Organic additives b) Chemical additives	257
Figure 5-28. Torque values for different asphalt mixtures prepared with Granite and VG30 (a) Sasobit (S),(b) Asphaltan A (A) (c) Rediset (R), (d) Iterlow (I).....	260
Figure 5-29. Torque values for different asphalt mixtures prepared with Dolerite and VG30 (a) Sasobit (S),(b) Asphaltan A (A) (c) Rediset (R), (d) Iterlow (I).....	261
Figure 5-30. Torque values for different asphalt mixtures prepared with Granite and PMB40 (a) Sasobit (S),(b) Asphaltan A (A) (c) Rediset (R), (d) Iterlow (I).....	262
Figure 5-31. Torque values for different asphalt mixtures prepared with Granite and VG30 (a) Sasobit (S),(b) Asphaltan A (A) (c) Rediset (R), (d) Iterlow (I).....	263
Figure 5-32. Torque values for different asphalt mixtures prepared with Dolerite and PMB40 (a) Sasobit (S),(b) Asphaltan A (A) (c) Rediset (R), (d) Iterlow (I).....	264
Figure 5-33. Effect of aggregate type on torque values of asphalt mixture	265

Figure 5-34. Effect of binder type on torque values of asphalt mixture	265
Figure 5-35. Correlation between CoF and torque a) Granite b) Dolerite	271
Figure 5-36. Validation of tribological approach with workability approach a) Granite b) Dolerite .	272
Figure 5-37. Validation of tribological approach with phase angle method	273
Figure 5-38. Validation of tribological approach with using coating ability test a) VG30 as base binder b) PMB40 as base binder	275
Figure 5-39. Validation of MT of PMBs obtained using tribological approach using coating ability test	276
Figure 5-40. Validation of tribological approach with using compactibility test a) VG30 as base binder b) PMB40 as base binder	277
Figure 5-41. Validation of CT of PMBs obtained using tribological approach using compactibility test	278
Figure 6-1. Phases of asphalt aging	283
Figure 6-2. Experimental plan	289
Figure 6-3. Aging indices for organic additives in VG30 as base binder (a) Carbonyl index after STA (b) Sulfoxide index after STA (c) Carbonyl index after LTA (d) Sulfoxide index after LTA	296
Figure 6-4. Aging indices for chemical additives in VG30 as base binder (a) Carbonyl index after STA (b) Sulfoxide index after STA (c) Carbonyl index after LTA (d) Sulfoxide index after LTA	297
Figure 6-5. Aging indices for organic additives in PMB40 as base binder (a) Carbonyl index after STA (b) Sulfoxide index after STA (c) Carbonyl index after LTA (d) Sulfoxide index after LTA	298
Figure 6-6. Aging indices for chemical additives in PMB40 as base binder (a) Carbonyl index after STA (b) Sulfoxide index after STA (c) Carbonyl index after LTA (d) Sulfoxide index after LTA	299
Figure 6-7. Effect of aging on polymeric network (transbutadiene index) of PMB40 a) organic additives b) chemical additives	300
Figure 6-8. Non-recoverable creep compliance (J_{nr}) for VG30 as base binder at 0.1 kPa.....	303
Figure 6-9. Non-recoverable creep compliance (J_{nr}) for PMB40 as base binder at 0.1 kPa a) organic additives b) chemical additives	304
Figure 6-10. Non-recoverable creep compliance (J_{nr}) for VG30 as base binder at 3.2 kPa a) organic additives b) chemical additives	305
Figure 6-11. Non-recoverable creep compliance (J_{nr}) for PMB40 as base binder at 3.2 kPa a) organic additives b) chemical additives	306
Figure 6-12. Percent recovery (%R) for VG30 as base binder at 3.2 kPa a) organic additives b) chemical additives	309
Figure 6-13. Percent recovery (%R) for PMB40 as base binder at 3.2 kPa a) organic additives b) chemical additives.....	310

Figure 6-14. Strain response curve for Sasobit and Rediset for VG30 as base binder a) at 10°C, b) at 20°C, c) at 30°C, d) Variation of strain response with temperature, e) Variation of strain response with binder type	314
Figure 6-15. Fatigue law parameter for different WMA modified asphalt binders a) Parameter A and b) Parameter B.....	316
Figure 6-16. Fatigue law parameter for different base asphalt binders a) Parameter A b) Parameter B	317
Figure 6-17. Variation of fatigue life for Sasobit modified asphalt binder with strain at (a) 10°C; (b) 20°C; and (c) 30°C.....	319
Figure 6-18. Variation of fatigue life for Rediset modified asphalt binder with strain at (a) 10°C; (b) 20°C; and (c) 30°C.....	320
Figure 6-19. Variation of fatigue life for both asphalt binder at 20°C.....	320
Figure 6-20. Fatigue life (N_f) for WMA additives in VG30 at a) 2.5% strain level; b) 5% strain level	322
Figure 6-21. Fatigue life (N_f) for WMA additives in PMB40 at a) 2.5% strain level; b) 5% strain level.	323
Figure 6-22. Effect of aggregate type and binder type on POTS a) Dry POTS b) Wet POTS (c) BSR	326
Figure 6-23. Effect of WMA additives on POTS and BSR value for VG30 as base binder a) Dolomite b) Dolerite c) Basalt d) Granite e) Sandstone	330
Figure 6-24. Effect of WMA additives on POTS and BSR value for PMB40 as base binder a) Dolomite b) Dolerite c) Basalt d) Granite e) Sandstone	333
Figure 6-25. Failure patterns for different aggregate-binder combinations	334
Figure 7-1. Main effect plot for Ico Index a) After STA b) After LTA.....	344
Figure 7-2. Main effect plot a) J_{nr} at 3.2 kPa b) %Recovery at 3.2 kPa.....	347
Figure 7-3. Main effect plot for N_f at 2.5% strain level.	349
Figure 7-4. Main effect plot a) Dry POTS b) Wet POTS c) BSR.....	352
Figure 7-5. Fatigue life comparison for 4% of Sasobit with VG30 binder.....	358
Figure 7-6. Rutting parameters comparison for 0.7% of Rediset a) J_{nr} b) % R	359

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
NO _x	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
$G^* \cdot \sin\delta$	Superpave Fatigue Parameter
$G^*/\sin\delta$	Superpave Rutting Parameter
G_{mm}	Theoretical Specific Gravity of Mix
T	Torque
η	Viscosity