

**EFFECTS OF RH-WMA ADDITIVE ON THE
RHEOLOGICAL PROPERTIES OF RECLAIMED
ASPHALT BINDERS AND THE ENGINEERING
PROPERTIES OF RECYCLED MIXTURES**

LILLIAN @ LILIA GUNGAT

UNIVERSITI SAINS MALAYSIA

2017

**EFFECTS OF RH-WMA ADDITIVE ON THE RHEOLOGICAL
PROPERTIES OF RECLAIMED ASPHALT BINDERS AND THE
ENGINEERING PROPERTIES OF RECYCLED MIXTURES**

by

LILLIAN @ LILIA GUNGAT

**Thesis submitted in fulfillment of the
requirements for the degree of
Doctor of Philosophy**

March 2017

I would like to dedicate this thesis to my beloved husband, Teo Jeck Hoe for his unconditional love and moral support, to my parents for their prayer and encouragement and also to my lovely children Clement, Adriel and Sarah Elina for all your patience and support during mommy's Ph.D studies.

ACKNOWLEDGEMENTS

First of all, I praise God for His grace and mercy that granting me the capabilities to proceed successfully. This thesis appears in its current form due to the assistance and guidance of several people. I would like to offer my sincere thanks to all of them.

I would like to express my utmost sincere thanks to my esteemed supervisor, Professor Dr Meor Othman Bin Hamzah for his guidance, motivation and endless supports during my study. I also would like to express my deepest thanks to my co-supervisor Dr Nur Izzi Bin Md Yusoff and Dr Goh Shu Wei for their guidance, valuable comments and willingness to help me to complete this thesis.

I would like to sincerely thank to every organization and individual who lend me hand in completing this study especially Universiti Malaysia Sabah and Ministry of Higher Education, Malaysia for the financial support. I am also indebted to the technicians of Highway Engineering Laboratory, Universiti Sains Malaysia, Mr. Mohd Fouzi Bin Ali and Mr. Zulhairi Bin Ariffin for their excellent support, co-operation and guidance throughout my laboratory works. Furthermore, I would like to acknowledge Mr. Mohd. Shahrom Zakaria a senior engineer at Kuad Kuari Sdn. Bhd. for providing useful information on reclaimed asphalt pavement in Malaysia. I would like to express my gratitude to my lab mates Noor Halizah for knowledge sharing, encouragement and assistance during my study.

A special thanks to my family for their unconditional moral support and love throughout my study. The existence of this thesis is possible because of your support, prayer and encouragement.

Keep your eyes on the stars, and your feet on the ground

Theodore Roosevelt

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	ii
TABLE OF CONTENTS	iii
LIST OF TABLES	ix
LIST OF FIGURES	xiv
LIST OF PLATES	xx
LIST OF SYMBOLS	xxi
LIST OF ABBREVIATIONS	xxiv
ABSTRAK	xxviii
ABSTRACT	xxx
CHAPTER ONE: INTRODUCTION	
1.1 Background	1
1.2 Problem Statement	3
1.3 Objectives of Research	5
1.4 Significance of the Research	6
1.5 Scope of Work	7
1.6 Thesis Organization	8
CHAPTER TWO: LITERATURE REVIEW	
2.1 Introduction	10
2.2 Reclaimed Asphalt Pavement	10
2.3 Warm Mix Asphalt	14
2.3.1 Classification of WMA Technology	15
2.3.2 Benefits and Drawbacks of WMA	18
2.4 Background of Reclaimed Asphalt Pavement with WMA	19
2.5 Benefits of Reclaimed Asphalt Pavement with WMA	21
2.5.1 Reduction of Production Temperature	21

2.5.2	Improvement of Workability and Blending	22
2.6	Properties of Asphalt Binder Containing Reclaimed Asphalt and WMA	25
2.6.1	Empirical Properties	25
2.6.2	Rheological Properties	26
2.6.3	Rheological Properties at High Temperatures	27
2.6.4	Rheological Properties at Intermediate Temperatures	31
2.6.5	Rheological Properties at Low Temperatures	31
2.6.6	Physicochemical Properties	32
2.7	Storage Stability	35
2.8	Characterization of Reclaimed Asphalt Pavement Materials	36
2.8.1	Gradation of Reclaimed Asphalt-Aggregate	38
2.8.2	Warm Mix Asphalt Additive	38
2.8.3	Binder Content of Reclaimed Asphalt	40
2.8.4	Mixing and Compaction Temperatures	42
2.9	Laboratory Studies of Reclaimed Asphalt Pavement and WMA	45
2.9.1	Resistance to Rutting	45
2.9.2	Resistance to Moisture Damage	50
2.9.3	Resistance to Fatigue	53
2.10	Field Studies of Reclaimed Asphalt Pavement and WMA	57
2.11	Evaluation of Pavement Sustainability Related to Reclaimed Asphalt Pavement and WMA	60
2.12	Summary	62

CHAPTER THREE: METHODOLOGY

3.1	Introduction	64
3.2	Materials	64
3.2.1	Asphalt Binder	64
3.2.2	Aggregate	64
3.2.3	Filler	65
3.2.4	WMA Additive	66

3.2.5	Reclaimed Asphalt Pavement	66
3.3	Preparation of Asphalt Binder Modified with RH-WMA Additive	68
3.4	Processing of Reclaimed Asphalt Pavement	68
3.4.1	Extraction and Recovery of Reclaimed Asphalt Binder	70
3.4.2	Processing and Fractionation of Reclaimed Asphalt	71
3.5	Preparation of Recycled Asphalt Binder Blends and RH-WMA Additive	73
3.6	Experimental Design	74
3.7	Physical Tests and Aging Methods	77
3.8	Storage Stability Test	78
3.9	Chemical Tests	78
3.9.1	Differential Scanning Calorimetry	78
3.9.2	Fourier Transform Infrared	79
3.10	Brookfield Rotational Viscometer Test	80
3.11	Dynamic Shear Rheometer Test	82
3.11.1	Temperatures Sweeps Test	84
3.11.2	Frequency Sweeps Test	85
3.11.3	Multiple Stress Creep and Recovery	86
3.12	Rheological Model	88
3.13	Mix Design and Optimization	93
3.13.1	Determination of Reclaimed Asphalt Binder in the Design Mix	94
3.13.2	Mixing Procedures of Reclaimed Asphalt Pavement with Virgin Materials	95
3.13.3	Design of Experiment	96
3.13.4	Specimen Preparation and Laboratory Tests	99
3.13.5	Statistical Analysis	100
3.13.6	Determination of the Optimum Binder Content	101
3.13.7	Mathematical Optimization	101
3.14	Evaluation of Mixture Performance	105
3.14.1	Indirect Tensile Strength Test	106
3.14.2	Resilient Modulus Test	106

3.14.3	Dynamic Creep Test	107
3.14.4	Diametral Fatigue Test	108

CHAPTER FOUR: PHYSICAL, CHEMICAL AND RHEOLOGICAL CHARACTERIZATION OF ASPHALT BINDERS INCORPORATING RECLAIMED ASPHALT WITH RH-WMA ADDITIVE

4.1	Introduction	112
4.2	Physical Properties of Asphalt Binder Containing RH-WMA Additive	114
4.3	Chemical Analysis of RH-WMA Additive	115
4.3.1	DSC Analysis	115
4.3.2	FTIR Analysis	116
4.4	Determination of Optimum RH-WMA Content	117
4.4.1	High Temperature Viscosity Analysis	117
4.4.2	Analysis of $G^*/\sin \delta$	122
4.4.3	Analysis of $G^*\sin \delta$	124
4.4.4	Analysis of Multiple Stress Creep and Recovery	126
4.5	Storage Stability at Optimum RH-WMA Additive	130
4.6	Physical Properties of Recycled Asphalt Binders Blend Incorporating RH-WMA Additive	131
4.7	Chemical Analysis of Recycled Asphalt Binders Blend Incorporating RH-WMA Additive	132
4.8	Viscosity Analysis at High Temperatures	136
4.9	Recycled Asphalt Binder Stiffness at High Temperatures Based on $G^*/\sin \delta$	143
4.10	Modeling the Rheological Master Curves using the 2S2PID Model	145
4.11	Statistical Goodness of Fit	154
4.12	Black Diagram	156
4.13	Frequency Dependency of Storage Modulus and Loss Modulus	157
4.14	Zero Shear Viscosity	161
4.15	Evaluation of Rutting Resistance at Various Temperatures	165
4.16	Summary	172

CHAPTER FIVE: MIX DESIGN AND OPTIMIZATION OF MIXTURES PRODUCTION USING RESPONSE SURFACE METHOD

5.1	Introduction	175
5.2	Evaluation of Reclaimed Asphalt	175
5.2.1	Reclaimed Asphalt Drying Experiment	175
5.2.2	Aggregate Gradation and Blending	177
5.2.3	Bulk Specific Gravity of Recovered Reclaimed Asphalt Aggregate	179
5.2.4	Binder Content of Reclaimed Asphalt	180
5.3	Optimum Binder Content of Control Mixture	181
5.4	Volumetric Properties of Recycled Asphalt Mixtures with RH-WMA Additive	182
5.5	Strength Properties of Recycled Asphalt Mixtures with RH-WMA Additive	192
5.6	Optimum Binder Content of Recycled Asphalt with RH-WMA Additive	195
5.7	Energy Consumption of RAM-WMA mixture production	197
5.8	Effects of Raw Materials Prices	202
5.9	Effects of Mixing Temperature on Fuel Usage and GHG Emissions	204
5.10	Production Optimization of Recycled Asphalt Mixtures with RH-WMA Additive	205
5.11	Comparison of GHG Emissions at Various Mixing Temperature	211
5.12	Summary	212

CHAPTER SIX: PERFORMANCE OF RECYCLED ASPHALT MIXTURES INCORPORATING RH-WMA ADDITIVE

6.1	Introduction	213
6.2	Analysis of Compaction Energy Index	214
6.3	Indirect Tensile Strength	215
6.4	Resilient Modulus	218
6.5	Dynamic Creep	221

6.6	Correlation between the Dynamic Creep and $G^*/\sin \delta$ and Non-Recoverable Creep Compliance	228
6.7	Correlation between Reclaimed Asphalt Content and Mixtures Performance	230
6.8	Fatigue Resistance Subjected to Combined Effects of Moisture and Aging	231
6.9	Summary	243

CHAPTER SEVEN: CONCLUSIONS AND RECOMMENDATIONS

7.1	Conclusions	245
7.2	Recommendations for Future Research	246

REFERENCES	250
-------------------	------------

APPENDICES

Appendix A: Asphalt Binder

Appendix B: Asphalt Mixture

LIST OF PUBLICATIONS

LIST OF TABLES

		Page
Table 1.1	Description of Terminologies Used in the Thesis	3
Table 2.1	Classification of WMA Technology	16
Table 2.2	Comparison of RAP Processing Methods (West et al., 2013)	39
Table 2.3	Some Research Findings on the Effects of Different Types of WMA Additives	40
Table 2.4	Field Performance of RAP with WMA Additive	58
Table 2.5	Some Previous Studies Related to Environmental and Cost Assessment of Reclaimed Asphalt Pavement	61
Table 3.1	Aggregate Gradation for JKR Mix Type AC 14 (JKR, 2008)	65
Table 3.2	Physical and Chemical Properties of PMD (Kakar, 2015)	66
Table 3.3	Physical and Chemical Properties of RH-WMA Additive (Zhonglu Gaoke Transportation Technology Group, 2013)	66
Table 3.4	Physical Tests and Aging Methods	77
Table 3.5	Test Conditions for Frequency Sweeps Test	86
Table 3.6	The 2S2PID Parameters Functions	92
Table 3.7	Matrix of Experimental Design for OBC Determination and Optimization	99
Table 3.8	JKR Specification and Responses in RSM	101
Table 3.9	Selected Goals and Criteria for Numerical Optimization in the Production Process of RAP containing WMA	104

Table 3.10	Test Parameters for Resilient Modulus Test	107
Table 3.11	Test Parameters for Dynamic Creep Test	108
Table 3.12	Test Parameters for Diametral Fatigue	111
Table 4.1	Designation for Asphalt Binder and Mixture Specimen	113
Table 4.2	Physical and Rheological Properties of the Virgin Asphalt Binder (PG64)	114
Table 4.3	Penetration and Softening Point of Asphalt Binders Containing Various Percentages of RH-WMA Additive	115
Table 4.4	Analysis of Variance on Viscosity	119
Table 4.5	Difference in AE After RTFO Aged	121
Table 4.6	Analysis of Variance of $G^*/\sin \delta$	123
Table 4.7	Effects of RH-WMA on Stress Sensitivity	128
Table 4.8	Physical Properties of Recovered RAP Binder from Various Sources	131
Table 4.9	Penetration of Recycled Asphalt Binder	132
Table 4.10	Increased in Sulfoxides and Carbonyl Peaks after RTFO Aged	135
Table 4.11	The $\nabla\eta$ RAP Equations for Viscosity of Unaged and RTFO Aged	141
Table 4.12	Analysis of Variance of $G^*/\sin \delta$ for Reclaimed Asphalt Binder	144
Table 4.13	Equations to Relate High Temperature Failure of Unaged and RTFO Aged Binders	145
Table 4.14	The 2S2PID Model Parameters for Unaged Reclaimed Asphalt Binders	146

Table 4.15	The 2S2PID Model Parameters for RTFO Aged Recycled Asphalt Binders	147
Table 4.16	Summary of SSE and MNE Statistical Goodness of Fit for Unaged and RTFO Aged Samples	155
Table 4.17	Summary of Statistical Goodness of Fit Based on SSE and MNE for Viscosity Prediction using Cross Model	163
Table 4.18	Stress Sensitivity of 40% RAP Binders at Various Temperatures	172
Table 5.1	Average Percentage Cumulative Passing of Recovered RAP Aggregate	178
Table 5.2	Bulk Specific Gravity of Virgin and Recovered RAP Aggregate	180
Table 5.3	Binder Content in RAP	181
Table 5.4	Mix Design of Control Mixtures	182
Table 5.5	Proposed Statistical Model Relationship for Volumetric and Strength Properties of RAP R2-RH	183
Table 5.6	Proposed Statistical Model Relationship for Volumetric and Strength Properties of RAP R2	184
Table 5.7	Proposed Statistical Model Relationship for Volumetric and Strength Properties of RAP R3-RH	185
Table 5.8	Analysis of Variance for Air voids, G_{mb} and VFA of R2-RH	186
Table 5.9	Analysis of Variance for Air voids, G_{mb} and VFA of R2	186
Table 5.10	Analysis of Variance for Air voids, G_{mb} and VFA of R3-RH	187
Table 5.11	Analysis of Variance for Strength Properties of R2-RH	193

Table 5.12	Binder Content of R2-RH at Various Compaction Temperatures	195
Table 5.13	Optimum Binder Content Based on JKR Standard Requirement	196
Table 5.14	Parameters for Determination of Energy Consumption (Jamshidi et al. 2012; Wen et al. 2015)	197
Table 5.15	Energy Consumption for Producing 1 Ton of RAM-WMA for RAP R2-RH	200
Table 5.16	Energy Consumption for Producing 1 Ton of RAM-WMA for RAP R3-RH	201
Table 5.17	Raw Material Price in November 2015	203
Table 5.18	Total Price of Raw Material for Production of 1 Ton RAM-WMA in November 2015	203
Table 5.19	Conversion Factor to Carbon Dioxide Equivalent Emissions	204
Table 5.20	Fuel Usage and GHG Emissions of RAM-WMA Production	205
Table 5.21	Optimized Parameters for Production of RAM-WMA	206
Table 5.22	Verification of Optimized Parameters	208
Table 5.23	Effects of RAP Price on the Production of RAM-WMA	209
Table 5.24	Effects of RAP and Fuel Price on Fuel Usage and Energy Consumption	210
Table 5.25	Comparison of GHG Emissions Produced from Various Mixing Temperature with Control Mixture	211
Table 6.1	Designation of Mixtures Subjected to Combined Effects of Moisture and Aging	214
Table 6.2	ANOVA Results of ITS Using General Linear Model	218

Table 6.3	ANOVA Results of Resilient Modulus Using General Linear Model	221
Table 6.4	ANOVA Results of Cumulative Permanent Strain Using General Linear Model	223
Table 6.5	Equations at Primary and Secondary Stage	225
Table 6.6	Linear Relationship Equation of Cumulative Strain and $G^*/\sin \delta$	231
Table 6.7	Linear Relationship Equation of Cumulative Strain and J_{nr} at 3.2 kPa	230
Table 6.8	Comparison of Slope between Unaged and Specimen Subjected to Moisture and Aging	233
Table 6.9	Fatigue Parameters	234
Table 6.10	Fatigue Curve Regression Parameters	237
Table 6.11	Statistical Analysis of N_f	240

LIST OF FIGURES

		Page
Figure 2.1	Estimated Cost of Asphalt Production (Copeland, 2011)	12
Figure 2.2	Usage and Potential of Various RAP content (Copeland, 2011)	13
Figure 2.3	Classification of the Type of Technology by Production Temperature and Fuel Usage Approximations (D'Angelo et al., 2008)	15
Figure 2.4	Layered System of RAP and Virgin Binder (Huang et al., 2005)	24
Figure 2.5	DSC Characterization of Different Types of Asphalt Binder (Das et al., 2013)	34
Figure 2.6	The Endotherms of Sasobit Modified Binder (Qin et al., 2014)	35
Figure 2.7	Components of RAM (Doyle et al., 2012)	37
Figure 2.8	Heating Duration of RAP to Reach the Mixing Temperature (West et al., 2013)	43
Figure 2.9	Reduction in Mixing Temperature of RAM-WMA	44
Figure 2.10	Typical Plot of Rutting Curve (Witczak, 2007)	49
Figure 2.11	Tensile Strain in Asphalt Layer Due to The Moving Wheel (Vieira et al., 2012)	56
Figure 3:1	Location of RAP Source	67
Figure 3:2	Flow Chart of RAP Processing and Basic Characterization	70
Figure 3:3	Flow Chart of Experimental Design	76

Figure 3:4	Fundamental Description of Viscoelastic Region by Linear Strain Sweeps (Peterson et al., 1994)	85
Figure 3:5	Typical Plot of MSCR Test (Adopted from Wasage et al., 2011; Anderson and Bukowski, 2012)	87
Figure 3:6	The 2S2PID Model (Olard and Di Benedetto, 2003)	89
Figure 3:7	Graphical Representation of the 2S2PID Parameters in Terms of Cole-Cole Diagram	92
Figure 3:8	Experimental Plan of OBC Determination and Optimization Process	98
Figure 3:9	Illustration of Desirability Function	102
Figure 3:10	Combined Effects of Aging and Moisture on the Stiffness of Asphalt Mixture (Hamzah et al., 2015)	109
Figure 4.1	DSC Heating Curve for RH-WMA Additive	116
Figure 4.2	Infrared Spectrum of RH-WMA Additive	117
Figure 4.3	Viscosity and RH-WMA Content Dependency	118
Figure 4.4	Effects of RH-WMA Additive on Construction Temperature	120
Figure 4.5	Effects of RH-WMA Additive on AE	121
Figure 4.6	Effects of RH-WMA Content on $G^*/\sin \delta$	122
Figure 4.7	Relationship between High Temperature Failure of Unaged and RTFO Aged	123
Figure 4.8	Relationship between $G^*\sin \delta$ with RH-WMA Additive	124
Figure 4.9	Relationship between RG and Temperature of RH-WMA Modified Binders	125
Figure 4.10	Cumulative Shear Strain at Different Stress Level	126

Figure 4.11	Creep Compliance and Recovery of Various RH-WMA Contents	128
Figure 4.12	FTIR Analysis of Unaged Recycled Asphalt Binders at Various RAP Contents	133
Figure 4.13	Aging Ratio after RTFO Aged	136
Figure 4.14	Effect of Temperature on Viscosity of Recycled Asphalt Binder	137
Figure 4.15	Relationship between Non-Dimensional Viscosity Index and Temperature of Unaged Recycled Asphalt Binder	139
Figure 4.16	Relationship between Non-Dimensional Viscosity Index and Temperature of RTFO Aged Recycled Asphalt Binder	140
Figure 4.17	Relationship between AE and RAP Content	142
Figure 4.18	High Temperature Performance Grade of Recycled Asphalt Binder	143
Figure 4.19	Relationship between High Temperature Failure of Unaged and RTFO Aged Binder	144
Figure 4.20	Comparison of Complex Modulus Master Curves between Measured and Model of Unaged Samples	148
Figure 4.21	Comparison of Phase Angle Master Curves between Measured and Model of Unaged Samples	149
Figure 4.22	Comparison of Complex Modulus Master Curve between Measured and Model of RTFO Samples	150
Figure 4.23	Comparison of Phase Angle Master Curve between Measured and Model of RTFO Samples	151
Figure 4.24	Black Diagram for Unaged and RTFO Samples from RAP R1	157

Figure 4.25	Storage Modulus and Loss Modulus of Unaged Samples	159
Figure 4.26	Storage Modulus and Loss Modulus of RTFO Samples	160
Figure 4.27	Extrapolation of ZSV for Unaged Samples	162
Figure 4.28	Comparison of ZSV for Various Types of Binders and Aging Conditions	165
Figure 4.29	Cumulative Shear Strain of Recycled Asphalt Binder at Different Stress Levels	167
Figure 4.30	Average J_{nr} of Various RAP Content and Sources	169
Figure 4.31	Average Percent Recovery of Various RAP Content and Sources	170
Figure 4.32	Effects of Test Temperature on J_{nr} and Percent Recovery for 40% RAP	171
Figure 5.1	Changes in RAP Moisture Content	176
Figure 5.2	Aggregate Gradation of Recovered RAP Aggregate	178
Figure 5.3	Aggregate Gradation of Recovered RAP and Virgin Aggregate Based on Target Median	179
Figure 5.4	Aggregate Gradation of Recovered RAP and Virgin Aggregate Based on Target Lower Limit	179
Figure 5.5	Volumetric and Strength Properties for Determination of OBC for PG64	181
Figure 5.6	Volumetric and Strength Properties for Determination of OBC for PG64-RH	182
Figure 5.7	Volumetric Properties of RAP R2-RH	189
Figure 5.8	Volumetric Properties of RAP R2	190
Figure 5.9	Volumetric Properties of RAP R3-RH	191

Figure 5.10	Strength Properties	194
Figure 5.11	Thermal Characteristics of Granite Aggregate	198
Figure 5.12	Specific Heat Capacity of Granite (Wen et al., 2015)	199
Figure 5.13	Energy Consumption for Production of 1 Ton RAM-WMA	202
Figure 5.14	Total Price of Raw Materials for Production of 1 Ton RAM-WMA	204
Figure 5.15	Response Surface of Overall Desirability for Different RAP Content, Mixing Temperature and Binder Content	207
Figure 6.1	Comparison of Compaction Energy Index between RAM and RAM-WMA	215
Figure 6.2	Indirect Tensile Strength and RAP Content	216
Figure 6.3	Relationship between ITS and RAP Content	217
Figure 6.4	Resilient Modulus and RAP Content	219
Figure 6.5	Relationship between Resilient Modulus and RAP Content	220
Figure 6.6	Cumulative Permanent Strain of R1	222
Figure 6.7	Cumulative Permanent Strain of R2	222
Figure 6.8	Cumulative Permanent Strain of R3	222
Figure 6.9	Number of Cycle at the Primary Stage	226
Figure 6.10	Relationship between Cumulative Permanent Strain and Time	227
Figure 6.11	Correlation between Cumulative Strain and $G^*/\sin \delta$	229

Figure 6.12	Correlation between Cumulative Strain and J_{nr} at 3.2 kPa	229
Figure 6.13	Relationship between Resilient Modulus, Indirect Tensile Strength and Accumulated Strain	231
Figure 6.14	Relationship between Stress and Number of Cycle to Failure of Unaged Specimen	232
Figure 6.15	Relationship between Stress and Number of Cycle to Failure of Specimen Subjected to Moisture and Aging	232
Figure 6.16	Fatigue Curve of Unaged Specimen	236
Figure 6.17	Fatigue Curve of Specimen Subjected to Moisture and Aging	236
Figure 6.18	Fatigue Life Obtained From Fatigue Equation	238
Figure 6.19	Strain Development at Various Forces of Unaged Specimen	241
Figure 6.20	Strain Development at Various Forces of Specimen Subjected to Moisture and Aging	242

LIST OF PLATES

		Page
Plate 3.1	RH-WMA Additive	66
Plate 3.2	Sealed Plastics Barrel for RAP Storage	69
Plate 3.3	Processing of RAP in the Laboratory	69
Plate 3.4	Ignition Using NCAT Asphalt Content Tester	72
Plate 3.5	Equipment Used for Simulating The Aging of Asphalt Binder	77
Plate 3.6	Low Temperature Differential Scanning Calorimetry	79
Plate 3.7	Shimadzu FTIR Machine	80
Plate 3.8	Rotational Viscometer Test	81
Plate 3.9	DSR Machine with Spindle and Specimens	83
Plate 3.10	Temperature Correction of DSR	84
Plate 3.11	Conditioning of Sample Subjected to the Combined Effects of Moisture and Aging	110

LIST OF SYMBOLS

E_{ct}	Activation Energy
RAP_{bc}	Binder Content of RAP Binder
G_{sb}	Bulk Specific Gravity of Aggregate
G_{mb}	Bulk Specific Gravity of Compacted Specimen
G^*	Complex Modulus
η^*	Complex Viscosity
ωc	Cross Over Frequency
$\Delta\theta$	Difference Between the Ambient Temperature and Mixing Temperature
ω	Frequency
Y_j	Fitted Value of The Response
G_g	Glassy Modulus When $\Omega \rightarrow \infty$
ITS	Indirect Tensile Strength
d_j	Individual Desirability Function For Response Number J
η_{∞}	Infinite Viscosity
G'	Loss Modulus
MQ	Marshall Quotient
m_i	Mass Of Material Type I
$max f_j$	Maximum Actual (Experimental) Value of Response

$min f_j$	Minimum Actual (Experimental) Value of Response
J_{nr}	Non-Recoverable Creep Compliance
n	Number of Responses Included in the Optimization
D	Overall Desirability Function (Geometric Mean of the Individual Desirability Functions)
R	Percent Recovery
$RAP_{binder,mix}$	Percentage of RAP Binder in the Total Binder of a Mixture
RAP_{agg}	Percentage of RAP Aggregate in the Mixture
RAP_{actual}	Percentage of Actual RAP Including RAP Binder Added in the Mixture
δ	Phase Angle
KBr	Potassium Bromide
ϵ_r	Recovery After One Cycle of Loading
RG	Relative $G \cdot \sin \delta$
A	Regression Parameter
ϵ_{10}	Shear Strain at the End of One Cycle of Loading
ϵ_1	Shear Strain at the End of 1 Second of Loading
c_i	Specific Heat Capacity of Material Type I
G_0	Static Modulus When $\Omega \rightarrow 0$
G''	Storage Modulus
SIP	Stripping Inflection Point