ASPHALT BINDER AND MIXTURE PERFORMANCE USING
BATU PAHAT SOFT CLAY AS MODIFIER

ALLAM MUSBAH AL ALLAM

A thesis submitted in
fulfilment of the requirement for the award of the
Degree of Philosophy

Faculty of Civil and Environmental Engineering
Universiti Tun Hussein Onn Malaysia

AUGUST 2017
DEDICATION

I would like to announce my appreciation to Allah Almighty for his grace, guidance and protection of me during my Ph.D. study. I dedicate this dissertation with countless appreciation to my beloved parents, and to all my beloved family members who had supporting me throughout my study life.
ACKNOWLEDGEMENTS

I would like to acknowledge my committee members for their contribution to this dissertation. First, I thank my supervisor; Prof Mohd Idrus Bin Mohd Masirin for his supporting. He is completely devoted entirely to helping me finish this study. He took valuable time to review my manuscripts, giving constructive advice, correcting the problems of them. This research would not have been completed in a timely manner, if their collective efforts were not there. There were so many times that he put his thoughts into this research that it is impossible to keep track of all, but many of these mentoring occasions will be deeply impressed in my memory and will be a source of inspiration for me over my lifetime. Secondly, the same appreciation is extended to Assoc. Prof. Dr. Mohd Ezree Bin Abdullah who was also my co-supervisor during my Ph.D.’s study here in Universiti Tun Hussein Onn Malaysia. It is impossible for me to forget mentioning my appreciation of my research group members. I owe a great debt to Dr. Shaban Ismael Albrka Ali, and I also want to thank my friend who has shared ideas, Puan Nurul Hidayah Binti Mohd Kamaruddin and for her prayers.
ABSTRACT

Road construction is required to provide better mobility for the community. This research aims to evaluate the use of BPSC particles as additive in Hot Mix Asphalt (HMA) mixture which was previously introduced in powder form. The experimental work for this survey included the use of four BPSC ratios (2, 4, 6 and 8%) according to the weight of bitumen. A design for the hot mix asphalt was executed by using the Superpave method for each additive ratio. However, using soft clay as filler to modify asphalt binder and mixture was not intensively done by researchers. Additionally, physical properties results of penetration and softening point show that soft clay can increase the binder stiffness, while storage stability of modified asphalt binder had a good compatibility between the original and modified binder. The rheological properties results such as dynamic shear rheometer indicated that soft clay modified asphalt binder would increase the stiffness and the elastic behavior compared to unmodified binder at intermediate and high temperatures. It has also the lowest susceptibility for rutting and the temperature susceptibility. In addition, microstructure examinations of the asphalt binders were then achieved by using scanning electron microscopy, hence; images displayed that soft clay particles distributed uniformly in the asphalt matrix. In addition, asphalt mixture test such as indirect resilient modulus, indicated that the stiffness increased as the percentages of soft clay increased. Also, dynamic creep results showed that the adding soft clay to asphalt mixtures remarkably decreases its susceptibility to permanent deformation. As for the moisture susceptibility, all the samples pass the 80% tensile strength ratio, it could be noted that BPSC had improved adhesion strength between an aggregate and binder. Furthermore, ageing index values show that the susceptibility to oxidative ageing was significantly reduced with the increase of BPSC content after short-term aging, and also it was observed that short-term aging had given a good resistance to oxidation. Studies on correlation analysis between different rheological modified asphalt binder and mixture of HMA were also conducted. It was shown that a strong correlation exists among $G*/\sin \delta$ and rut depth. In conclusion, the introduction of BPSC has a bright potential as a new material of HMA which can be used in pavement construction in the future.
ABSTRAK

penambahan tanah liat lembut dalam campuran asphalt mengurangkan kerentanannya terhadap perubahan bentuk kekal. Bagi kerentanan kelembapan, semua sampel melepas nisbah kekuatan tegangan 80%, ini menunjukkan bahawa BPSC telah meningkatkan kekuatan lekatan antara agregat dan pengikat. Tambahan pula, nilai indeks penuaan menunjukkan bahawa kerentanan terhadap penuaan oksidatif berkurangan dengan peningkatan kandungan BPSC selepas penuaan jangka pendek. Ia juga diperhatikan bahawa penuaan jangka pendek telah memberikan ketahanan yang baik terhadap pengoksidaan. Kajian mengenai analisis korelasi antara pengikat asfalt diubahsuai dan campuran HMA juga telah dijalankan. Didapati bahawa korelasi yang kuat wujud di antara G*/sin δ dan kedalaman aluran. Kesimpulannya, pengenalan BPSC mempunyai potensi yang cerah sebagai bahan baru HMA yang dapat digunakan dalam pembinaan turapan di masa hadapan.
TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>TITLE</th>
<th>i</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEDICATION</td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGMENT</td>
<td>iv</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>v</td>
</tr>
<tr>
<td>ABSTRAK</td>
<td>vi</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>viii</td>
</tr>
<tr>
<td>LIST OF TABLE</td>
<td>xiv</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xvii</td>
</tr>
<tr>
<td>LIST OF ABBREVIATIONS</td>
<td>xxi</td>
</tr>
<tr>
<td>LIST OF SYMBOLS</td>
<td>xxii</td>
</tr>
<tr>
<td>LIST OF APPENDICES</td>
<td>xxiv</td>
</tr>
</tbody>
</table>

CHAPTER 1 INTRODUCTION  

1.1 Background  
1.2 Objectives of study  
1.3 Problem statement  
1.4 Scope of research  
1.5 Significance of study  
1.6 Thesis structure

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction  
2.2 Types of clay soil  
2.3 Batu Pahat Soft Clay (BPSC)  
2.3.1 The physical properties of BPSC  
2.3.2 Particle size distribution of soft clay
CHAPTER 3 RESEARCH METHODOLOGY
3.1 Introduction 46
3.2 Process framework 47
3.3 Experimental process and materials 48
  3.3.1 Specific gravity of asphalt binder 48
  3.3.2 Batu pahat soft clay 48
3.4 Cone-penetration test of soft clay 49
  3.4.1 Determine the plastic index and plastic limit of BPSC 50
  3.4.2 Aggregate structure design 50
3.5 Blending procedure 51
3.6 Physical properties of asphalt binder 52
3.7 Storage stability test 52
3.8 Temperature susceptibility 53
  3.8.1 Pen-Vis Number (PVN) 53
  3.8.2 Penetration index 54
3.9 Viscosity 54
3.10 Asphalt binder aging methods 55
3.11 Rheological properties of asphalt binder 56
  3.11.1 Dynamic Shear Rheometer (DSR) 56
3.12 Fourier transforms infrared spectroscopy 56
3.13 Scanning electron microscopy 57
3.14 Surface energy test 58
3.15 Superpave mix design method 58
  3.15.1 Superpave Specimens 60
3.16 Volumetric properties of asphalt mixture 61
  3.16.1 Maximum specific gravity (Gmm CoreLok) 62
3.17 Material selection of asphalt mixture 62
3.18 Ageing procedures of asphalt mixture 63
3.19 Performance testing of asphalt mixture 63
  3.19.1 Resilient modulus test 63
  3.19.2 Wheel tracking test 65
CHAPTER 4 RESULTS AND ANALYSIS ON ASPHALT INDE
4.13 Creep and recovery (unaged) 103
4.14 Creep and Recovery (short-term) 105
4.15 Multiple stress creep recovery (unaged) 109
4.16 Multi Creep and recovery (short-term) 111
4.17 Frequency sweep (unaged) 10 rad/s 114
4.18 Frequency sweep (short-term) 115
4.19 Rheological properties of base and BPSC modified binder 117
4.19.1 Isochronal plot (10 rad/s) 117
4.19.2 Master curve (unaged) 119
4.19.3 Master curve (short-term) 120
4.20 Summary 122

CHAPTER 5 ANALYSIS ON ASPHALT MIXTURES 124

5.1 Introduction 124
5.2 Materials and mix design D 124
5.2.1 Materials 124
5.2.2 Aggregate mix design and gradation 125
5.2.3 Superpave mix design 127
5.3 Performance tests of asphalt mixture 128
5.3.1 Resilient modulus 128
5.3.2 Dynamic creep 133
5.3.3 Wheel tracking 137
5.3.4 Moisture susceptibility 140
5.3.5 Indirect tensile strength 141
5.4 Contributions and Applications 143
5.5 Impact of Incorporation BPSC into Asphalt Mixtures 144
5.5.1 Durability 144
5.5.2 Rutting 146
5.6 Applications of BPSC in construction pavement engineering 146
5.6.1 Cost of construction 147
5.7 Correlations between asphalt binder and mixture 148
  5.7.1 Correlation between Mr and ITS 149
  5.7.2 Correlation between Mr and G*/sin δ short-term 151
  5.7.3 Correlations between wheel tracking and G*/sin δ (rutting) 152
5.8 Summary 152

CHAPTER 6 CONCLUSION AND RECOMMENDATION 154

6.1 Introduction 154
6.2 Conclusion 154
  6.2.1 Physical and rheological properties of asphalt binder 155
  6.2.2 Engineering Properties of Asphalt Mixture 156
  6.2.3 Oxidative aging effects in asphalt binders and mixtures 156
6.3 Recommendations 158

REFERENCES 159
APPENDICES 192
# LIST OF TABLES

2.1 Physical properties of Batu Pahat soft clay 10  
2.2 Typical moisture contents 10  
2.3 Generic classification of asphalt additives and modifiers 12  
2.4 Various factors affecting the permanent deformation 34  
3.1 Properties of Batu Pahat soft clay 49  
3.2 Gradation limit of 19.00 mm nominal maximum size 51  
3.3 Blending binder protocol 51  
3.4 The physical properties of asphalt binder 80/100 52  
3.5 Superpave compaction parameter 60  
3.6 Volumetric properties of superpave mix design criteria 61  
3.7 Design matrix for the asphalt mixture 62  
3.8 The parameters for resilient modulus (ASTM D4123) 64  
3.9 Rutting depth test parameters 66  
3.10 Dynamic creep test Parameters 67  
4.1 Results of liquid and liquid limit of BPSC 71  
4.2 Optimum blending time 72  
4.3 Comparison of significant difference level of ductility 76  
4.4 Post Hoc multiple comparison of ductility 76  
4.5 Comparison of significant difference level of loss on heating 78  
4.6 Comparison of significant difference level of storage stability 79  
4.7 Post hoc multiple comparison of storage stability test 79  
4.8 Aging index of viscosity 83  
4.9 The softening point aging index after Aging 85  
4.10 The penetration aging index after aging 86  
4.11 The PI and PVN for base and BPSC-modified-asphalt binder 87  
4.12 Chemical composition for unmodified binder 88  
4.13 Chemical composition of BPSC 89
4.14 Designations of main groups of modified asphalt binder 93
4.15 Comparison of significant difference of unaged for rutting 97
4.16 Post hoc multiple comparisons between modified and unmodified 98
4.17 Comparison of significant difference of unaged and S-T 101
4.18 Post hoc multiple comparisons between modified and unmodified 102
4.19 Comparison of significant difference of compliance creep for base and S-T 107
4.20 Post hoc multiple comparisons of compliance creep for base and S-T 108
4.21 Comparison of significant difference of multiple stress creep recovery for unaged and short-term aged 113
4.22 Post hoc multiple comparisons of multiple stress creep recovery for unaged and short-term aged 113
4.23 Comparison of significant difference of master curve of ageing conditions 121
4.24 Post hoc multiple comparisons of master curve of ageing conditions 122
5.1 Results of aggregate properties 126
5.2 Mix designations and nominal maximum size of aggregate 126
5.3 Specific gravity of course, fine aggregate and BPSC 126
5.4 Optimum binder contents and volumetric properties of BPSC 128
5.5 Comparison of significant difference for ageing conditions at 25°C 130
5.6 Post Hoc multiple comparisons between Base and BPSC-modified-asphalt mixture at 25°C (1000ms) 130
5.7 Ageing index for resilient modulus tests at 25 and 40°C (1000ms) 132
5.8 Comparison of significant difference of unaged and short-term aged 40°C 132
5.9 Comparisons between unmodified and modified asphalt
mixture at 40°C

5.10 Ageing index for dynamic creep test 40°C 133

5.11 Comparison of significant difference of resilient modulus at 40°C 135

5.12 Post hoc multiple comparisons of resilient modulus for unmodified and BPSC-modified-asphalt binder 136

5.13 Ageing index for wheel tracking test at 45°C 139

5.14 Significant difference of wheel tracking for unaged 139

5.15 Significant difference of wheel tracking for short-tem aged 139

5.16 Post hoc multiple comparison of unaged and aged mixtures 140

5.17 Significant difference of ITS for dry condition mixtures 142

5.18 Significant difference of ITS for wet condition mixtures 142

5.19 Post hoc multiple comparison of ITS for dry and wet condition 143

5.20 Summary of the impact of essential asphalt mixture parameters 146

5.21 Criteria for goodness of fit statistical parameters 149
LIST OF FIGURES

2.1 Soft clay area of RECESS Malaysia ................................................................. 9
2.2 Process of gradually filling the voids in compacted filler with binder .................... 19
2.3 Schematic of dynamic shear rheometer testing configuration ............................ 24
2.4 Dynamic shear rheometer test operations ....................................................... 24
2.5 General shape of an isothermal plot ............................................................... 28
2.6 General shape of an isochronal plot ............................................................... 29
2.7 Construction of a master curve with dynamic parameters ............................... 30
2.8 Failure zones under tire load ........................................................................... 32
2.9 Permanent deformation .................................................................................... 33
2.10 Influence of creep stress intensity on strain rate ............................................. 38
2.11 Cumulative plastic strains versus time for creep testing ................................. 39
2.12 The fillers effect on asphalt mix properties .................................................... 42
3.1 Flow chart of the experimental ....................................................................... 47
3.2 Equipment for producing BPSC ...................................................................... 49
3.3 Cone-penetration equipment ......................................................................... 50
3.4 Storage stability procedures .......................................................................... 53
3.5 Rolling thin-film oven test equipment .............................................................. 55
3.6 Fourier transforms infrared spectroscopy ....................................................... 57
3.7 Field emission scanning electron microscopy ................................................. 57
3.8 Schematic layout and device of surface energy method ................................... 58
3.9 Superpave gyratory compactor ...................................................................... 59
3.10 SGC mold configuration .............................................................................. 59
3.11 Indirect resilient modulus device ................................................................... 64
3.12 Wheel tracking device
3.13 Dynamic creep device
3.14 Moisture susceptibility
4.1 Plot result semi-log graph and determine the liquid limit
4.2 Optimum blending time
4.3 Softening point versus BPSC Contents
4.4 Penetration against BPSC contents at 25°C
4.5 Ductility versus different ratios of BPSC Contents
4.6 Loss on heating of RTFO versus BPSC Contents
4.7 Different in softening points between the top and bottom for BPSC modified binder
4.8 Viscosity of different percentages of BPSC modifier asphalt binder under unaged
4.9 Viscosity of different percentages of BPSC modifier asphalt binder under short-term
4.10 Viscosity ageing index of BPSC Contents at 135°C
4.11 Softening point ageing index of BPSC contents
4.12 Penetration aging index values of BPSC contents
4.13 Electron images of unmodified samples
4.14 Distribution of BPSC particles sizes in asphalt binder
4.15 Typical image during the contact angles measurement
4.16 Surface energy of BPSC contents
4.17 FTIR spectra of base and BPSC modified binder
4.18 Carbonyl index 1700 cm\(^{-1}\) of modified and unmodified binder
4.19 Sulfoxide index 1030 cm\(^{-1}\) of modified and unmodified binder
4.20 G*/sin δ of unaged binder against various ratios of BPSC at 64°C
4.21 Complex modulus (G*) against temperature
4.22 Phase angles (δ) against temperatures for unaged
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.23</td>
<td>$G^*/\sin \delta$ of short-term aged binder versus different ratios of BPSC at 64°C</td>
</tr>
<tr>
<td>4.24</td>
<td>Complex modulus ($G^*$) of short-term aged against temperature</td>
</tr>
<tr>
<td>4.25</td>
<td>Phase angles ($\delta$) of short-term aged against temperatures</td>
</tr>
<tr>
<td>4.26</td>
<td>High failure Temperatures of unmodified and modified binder</td>
</tr>
<tr>
<td>4.27</td>
<td>Compliance creep and recovery of unaged samples (3Pa)</td>
</tr>
<tr>
<td>4.28</td>
<td>Compliance creep and recovery of unaged samples (10Pa)</td>
</tr>
<tr>
<td>4.29</td>
<td>Compliance creep and recovery of unaged samples (50Pa)</td>
</tr>
<tr>
<td>4.30</td>
<td>Creep and recovery of short-term (3Pa)</td>
</tr>
<tr>
<td>4.31</td>
<td>Creep and recovery of short-term (10Pa)</td>
</tr>
<tr>
<td>4.32</td>
<td>Creep and recovery of short-term (50Pa)</td>
</tr>
<tr>
<td>4.33</td>
<td>Multiple stress creep recovery of unaged binder under stress level of (100 Pa)</td>
</tr>
<tr>
<td>4.34</td>
<td>Multiple stress creep recovery of unaged binder under stress level of (3200 Pa)</td>
</tr>
<tr>
<td>4.35</td>
<td>Multiple stress creep recovery of short-term aged binder under stress level of (100 Pa)</td>
</tr>
<tr>
<td>4.36</td>
<td>Multiple stress creep recovery of short-term aged binder under stress level of (3200 Pa)</td>
</tr>
<tr>
<td>4.37</td>
<td>Complex modulus ($G^*$) at 10 rad/s</td>
</tr>
<tr>
<td>4.38</td>
<td>Phase angle ($\delta$) at 10 rad/s</td>
</tr>
<tr>
<td>4.39</td>
<td>Complex modulus against temperatures at10 rad/s</td>
</tr>
<tr>
<td>4.40</td>
<td>Phase angle against temperatures at10 rad/s</td>
</tr>
<tr>
<td>4.41</td>
<td>Complex modulus versus temperatures at10 rad/s</td>
</tr>
<tr>
<td>4.42</td>
<td>Phase angle versus temperatures at10 rad/s</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>4.43</td>
<td>Complex modulus of master curve for unaged</td>
</tr>
<tr>
<td>4.44</td>
<td>Complex modulus of master curve for short-term aged</td>
</tr>
<tr>
<td>5.1</td>
<td>NMAS 19 mm aggregate gradation</td>
</tr>
<tr>
<td>5.2</td>
<td>Resilient modulus of unaged and short-term aged at 25°C</td>
</tr>
<tr>
<td>5.3</td>
<td>Resilient modulus of unaged and short-term aged at 40°C</td>
</tr>
<tr>
<td>5.4</td>
<td>Dynamic creep of unaged at 40°C</td>
</tr>
<tr>
<td>5.5</td>
<td>Dynamic creep of short-term aged at 40°C</td>
</tr>
<tr>
<td>5.6</td>
<td>Wheel tracking results of unaged</td>
</tr>
<tr>
<td>5.7</td>
<td>Wheel tracking results of short-term aged</td>
</tr>
<tr>
<td>5.8</td>
<td>Moisture sensitivity of asphalt mixture</td>
</tr>
<tr>
<td>5.9</td>
<td>Indirect tensile strength</td>
</tr>
<tr>
<td>5.10</td>
<td>Correlations between MR and ITS at 25°C for unaged</td>
</tr>
<tr>
<td>5.11</td>
<td>Correlations between MR and ITS at 25°C for short-term aged</td>
</tr>
<tr>
<td>5.12</td>
<td>Correlations between Mr at 40°C and G*/sin δ (unaged)</td>
</tr>
<tr>
<td>5.13</td>
<td>Correlations between Mr at 40°C and G*/sin δ (Short-term)</td>
</tr>
<tr>
<td>5.14</td>
<td>Correlations between rut depth and G*/sin δ (rutting)</td>
</tr>
</tbody>
</table>
LIST OF ABBREVIATIONS

F - Recovered Angle
G*/sin δ - Superpave™ rutting factor
G* - Complex shear modulus
δ - Phase angle
A - Thermal diffusivity
FTU - High failure temperatures of unaged asphalt binder
E - Cumulative micro-strain
FTS - High failure temperatures of short-term-aged asphalt binder
G’ - Elastic component or storage modulus
G’’ - Viscous component or loss modulus
Jnr - Creep compliance
Ω - Average angular recovery speed
[VMR]A - Rate of aging effect on resilient modulus due to long-term aging condition at 25°C
[VMR]T - Rate of test temperature effect on resilient modulus
ΔMR - Difference in resilient modulus
VMR - Resilient modulus gradient
γ - Ratio of the strain
σ - Constant applied load
PI - Penetration index
S.P - Softening point
Au - Gold
C - Carbon
S - Sulfur
Pt - Platinum
Cl - Chorine
Si - Silicon
O - Oxygen
Na - Sodium
## LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Aging</td>
</tr>
<tr>
<td>AI</td>
<td>Specific heat</td>
</tr>
<tr>
<td>AI</td>
<td>Asphalt Institute</td>
</tr>
<tr>
<td>AASHTO</td>
<td>American association of state highway and transportation officials</td>
</tr>
<tr>
<td>ASTM</td>
<td>American society for testing and materials</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
</tr>
<tr>
<td>AC</td>
<td>Aging Condition</td>
</tr>
<tr>
<td>BT</td>
<td>Asphalt Binder Type</td>
</tr>
<tr>
<td>BPSC</td>
<td>Batu Pahat Soft Clay</td>
</tr>
<tr>
<td>CGN</td>
<td>Compaction Gyration Number</td>
</tr>
<tr>
<td>DSR</td>
<td>Dynamic Shear Rheometer</td>
</tr>
<tr>
<td>DG</td>
<td>Dense-Grade</td>
</tr>
<tr>
<td>ESALs</td>
<td>Equivalent Single Axle Loads</td>
</tr>
<tr>
<td>$G_{sb}$</td>
<td>Bulk Specific Gravity of Aggregate</td>
</tr>
<tr>
<td>$G_b$</td>
<td>Specific Gravity of Asphalt</td>
</tr>
<tr>
<td>$G_{se}$</td>
<td>Effective Specific Gravity of Aggregate</td>
</tr>
<tr>
<td>$G_{mb}$</td>
<td>Specific Gravity of Aggregate</td>
</tr>
<tr>
<td>$G_{mm}$</td>
<td>Maximum Specific Gravity of Paving Mixture</td>
</tr>
<tr>
<td>HMA</td>
<td>Hot Mixture Asphalt</td>
</tr>
<tr>
<td>ITS</td>
<td>Indirect Tensile Strength</td>
</tr>
<tr>
<td>MSCR</td>
<td>Multiple Stress Creep Recovery</td>
</tr>
<tr>
<td>MT</td>
<td>Mixing Temperature</td>
</tr>
<tr>
<td>$N_{initial}$</td>
<td>Compaction Parameter</td>
</tr>
<tr>
<td>$N_{design}$</td>
<td>Compaction Parameter</td>
</tr>
<tr>
<td>$N_{maximum}$</td>
<td>Compaction Parameter</td>
</tr>
<tr>
<td>NAPA</td>
<td>National Asphalt Pavement Association</td>
</tr>
</tbody>
</table>
SHRP - Strategy Highway Research Program
OBC - Optimum Bitumen Content
$P_{be}$ - Effective Asphalt Content, percent by total weight of Mixture
$P_b$ - Asphalt. Percent by total weight of mixture
PG - Performance Grade
RTFO - Rolling Thin Film Oven
RV - Rotational Viscometer
SMA - Stone Matrix Asphalt
SFE - Surface Free Energy
STA - Short-Term-Aging
SGC - Superpave Gyratory Compactor
TSR - Tensile Strength Ratio
UTM - Universal Testing Machine
VFA - Voids Filled Asphalt
VMA - Voids Mineral Aggregate
VTM - Voids in Total Mixture
## LIST OF APPENDICES

<table>
<thead>
<tr>
<th>APPENDIX</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Physical Properties of Aggregate</td>
<td>193</td>
</tr>
<tr>
<td>B</td>
<td>Volumetric Properties and OBC of Asphalt Mixture</td>
<td>196</td>
</tr>
<tr>
<td>C</td>
<td>Asphalt mixture</td>
<td>205</td>
</tr>
<tr>
<td>D</td>
<td>Physical Properties of Asphalt Binder</td>
<td>213</td>
</tr>
<tr>
<td>E</td>
<td>Statistical Analysis Data Output</td>
<td>229</td>
</tr>
<tr>
<td>F</td>
<td>Statistical Analysis Data Output of Physical and</td>
<td>238</td>
</tr>
<tr>
<td></td>
<td>Rheological Properties</td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

1.1 Background

There are many potential ways to improve the performance of asphalt binder and mixture which are applied in the surfacing course of road pavements. Currently, researchers and engineers are still looking and take into consideration the most important user requirements of asphalt pavement towards economy and safety on road and highway construction [1]. Additionally, road pavement is always subjected to external loads including mechanical loading induced by heavy traffic and thermal loading [2]. Similarly, highway agencies stipulated the use of specific materials for highway pavement construction to assure positive performance of pavements. Hence, the tests used in the paving industry are only empirical in nature [3].

Asphalt binder is considered as the most applicable road pavement materials [4], and it is also the key function of an asphalt mixture. Its properties such as durability and viscoelasticity make it a necessary material in pavement engineering design and application. Thus, non-conventional modified asphalt binder and mixture materials are successfully applied to counter major early failures of pavement structures [5]. Subsequently, the asphalt binder properties could be enhanced by applying modifiers; thus asphalt technologists keep looking for new modified asphalt materials to enhance the resistance of asphalt pavement’s distresses, oxidation,
moisture sensitivity and permanent deformation (rutting). The scientists and engineers are constantly searching on equally important different methods to improve the performance of asphalt mix, and using some modifiers of hot mix asphalt [6].

More importantly, many research works have been implemented to modify the asphalt binder properties. Thereby, the modification of asphalt binder to improve the performance properties was significantly increased since the implementation of the Strategic Highway Research Program (SHRP) binder specifications [7]. The state highway agencies have appointed modifier content to be comprehensive in asphalt binder [8]. Moreover, asphalt modifiers were applied in the road construction industry as early as 1950s, that applicable in improving the performance of asphalt pavements in terms of increasing resistance to pavement distresses [9].

In order to enhance good quality of asphalt binder, polymer modification has become one of the most popular methods to obtain a good performance for road pavement materials [10]. Then again, modified binders have been utilized in Superpave mixtures of numerous state agencies with potential to ameliorate the mixtures [11]. In contrast, modifiers of asphalt binder were altered in function, efficiency, and evolution of modified asphalt material; also it may enhance the total performance of pavements [12]. However, the compatibility among asphalt binder and the modifier is not guaranteed, and segregation during storage at high temperature can affect the performance of asphalt binder [13].

Additionally, modified asphalt has shown a lot of attention during the past few years due to the enhanced mixture performance [14]. The usage of modify asphalt binder offers a promising method to improve the service-life of the highways even though the road experience unpredicted growing quantity of traffic volume [15]. Furthermore, modifying the asphalt mixtures with polymers appeared to have the greatest potential for successful application in the design of flexible pavements. These benefits can be realized by extending the service life of the pavement [16].
1.2 **Objectives of study**

The main objectives of this research are based on:

i. To investigate the physical, chemical and rheological properties of BPSC-modified-asphalt binder.

ii. To evaluate the effect of BPSC on performance tests of asphalt mixture.

iii. To determine which modified binders provide maximum initial durability benefit with minimum regression due to aging.

iv. To develop regression models among the performance of asphalt binder and mixture corresponding to the influence of BPSC in terms of permanent deformation.

1.3 **Problem statement**

Hot mix asphalt should satisfy and has sufficient stability, durability, flexibility, coefficient of friction, and workability for good pavement performance. In addition, to produce a mixture with those properties, a suitable coating of the aggregated grains by asphalt binder and suitable compaction up to designated air void ratio should be guaranteed [17]. Recently, the continuous increase in the traffic numbers may cause an accelerated deterioration of the road network [18]. Thus, the damage of road asphalt layers is considered as the biggest challenge faced by countries around the world today [19].

Certainly, the properties of asphalt binder are required to prevent the appearance of two main pavement distresses such as permanent deformation (rutting), and fatigue. The asphalt mixtures are sensitive to oxygen, ozone, and chemicals which they are exposed during the preparation, storage, and service [20]. Similarly, the durability of asphalt mixtures depends on two main factors: resistance to age
hardening and resistance to moisture damage. Antioxidants were used in the past to control age-hardening of asphalt mixtures with some successes [21]. Additionally, numerous attempts are still trying to resolve those factors in reducing the road maintenance cost and enhancing pavement design life. Therefore, it was important to acknowledge that some user agencies were indicated an increase of service life or reduced the risk of the early distresses development through the use of modified asphalt binders. Otherwise, asphalt mixes must be able to resist the existing heavy loads and expected future loads for an acceptable period of time. This demands some modifications to the reinforcement of asphalt binder [22].

In order to enhance the durability of asphalt mixture versus pavement distress, mineral filler are commonly used. Therefore, several paving technologist found that mineral filler plays a dual function in asphalt mixture by acting as mineral aggregate to fill voids and producing contact point among coarse aggregate particles to strengthen the asphalt mixture [23]. However, using soft clay as filler to modify asphalt binder and mixture was not intensively done by researchers. Moreover, the effect of soft clay as filler on the properties of asphalt mixture and binder should be studied.

1.4 Scope of research

In order to evaluate and approve the design of asphalt binder and mixture, several tests were conducted using state-of-the-art equipment, and those tests were conducted in the UTHM’s laboratory. The tests provide a strong indication of the inadequacies of the materials since the failure in the laboratory under ideal conditions usually represents the failure in the field. Therefore, in this study, laboratory work concentrates on the influences of BPSC-modified-asphalt binder and mixture. Moreover, several tests such as indirect resilient modulus, moisture damage,
dynamic creep and wheel tracking were conducted in order to observe the effect of BPSC on the asphalt mixtures. Meanwhile, storage stability, viscosity, physical and rheological properties tests for asphalt binder was also performed. Equally important, the asphalt binder and mixture were tested based on Superpave’s specification and its recommended criteria at high and intermediate temperatures, but the rheological properties at low temperatures were not investigated. Complementary to this procedure, specimens were subjected to aging condition with short-term aging by using rolling thin film oven (RTFO) according to ASTM D 2872.

1.5 Significance of study

This study was conducted to determine the most suitable and optimum BPSC particles in the asphalt mixture and expectant to produce a new road material and to contribute towards producing cheap and effective asphalt mixtures for road construction. Therefore, the performance of rheological properties of asphalt binder and mixture tests can provide superior indication to characterize the use of BPSC particles as a new additive for the best design selection of HMA. In the present study, the applications of BPSC particles were demonstrated for the first time to modify the asphalt binder and mixture. Hence, the benefit of using modification was expected to enhance the physical and mechanical properties of asphalt binder and mixture, as well as to resist the phase segregation among the asphalt and the modifier. This means to improve the storage stability of modified asphalt binder.

1.6 Thesis structure

This thesis structure is organized as follows:
• Chapter one explains an overview of the research, including the introduction, problem statement, expected outcome, and objectives.

• Chapter two provides previous studies related to BPSC history, and also study on the effect of fillers on asphalt binder and mixture of hot mix asphalt.

• Chapter three describes the experimental plan, such as laboratory equipment, materials properties of aggregates, binders, and mixture.

• Chapter four presents the results of rheological, chemical, and physical properties tests, which were conducted on the asphalt binder modified by BPSC contents. This chapter is also based on the detailed discussion and analysis of experimental data.

• Chapter five discusses the performance of asphalt mixture modified with BPSC. It also provides a discussion on experimental data acquired from conducted testing and presents the contribution and application of BPSC on the performance of asphalt mixture.

• Chapter six concludes the study and provides recommendations for further research.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents the summary review of related literature including scientific papers, technical reports, and dissertations that had been conducted on modification of asphalt binders and mixtures. Moreover, this literature review is presented in three fundamental parts: Batu Pahat Soft Clay (BPSC) history, additives and modifiers in hot mix asphalt, as well as the effect of fillers on asphalt binder and mixture.

2.2 Types of clay soil

There are many different types of soils, and each one has unique characteristics like color, texture, structure, and mineral content [24]. Clay soil is known as a group of soil and its particles sizes are flaky and the thickness is very small relative to their length and width [25]. However, expansive soils are typically clays that demonstrate extensive volume and strength changes at varying moisture content due to their chemical composition [26]. Clay soil that consists of silt, sand, and/or gravel are
primarily the result of physical and mild chemical weathering processes, and it retains much of the chemical structure of their parent rocks [27].

Soil classification in road and railway engineering is the ranking of different soils with respect to their use ability in mechanical and mechanical-physical way related to the long term performance of the road pavement or railway structure [28]. According to the latest available information of the unified soil classification system, the soil sample was classified as clay of high plasticity (CH). It composes of 23% sand, 15% silt, and 62% clay [29]. Furthermore, kaolin is a subgroup of the clay family of mineral which includes kaolinite, dickite, nacrite, and halloysite [30]. Alternatively, Huat and Ali [31] reported that mineral compositions of the tropical residual soils in Malaysia are mostly dominated by kaolinite which occurs from weathering processes. On the other side, their major clay mineral have been between the most important industrial raw materials [32]. Also, bentonites are the clay rocks modified from glassy igneous material such as a volcanic ash [33]. In the same way, bentonites are greatly affected from the acid activation, ion exchange, heating and hydrothermal treatments [34].

2.3 Batu Pahat Soft Clay (BPSC)

Soft clay soil can be categorized as problematic soil. Thus, clay mostly consist of alumina–silicates, which have a layered structure, and consist of silica $SiO_4$ tetrahedron bonded to alumina $AlO_6$ octahedron in a different ways [35]. Moreover, this study was carried out in Batu Pahat district, which is known to have abundance of soft clay. This type of clay called BPSC is available up to a depth of 4 meters from ground level [36]. Batu Pahat’s roads have various sorts of failures such as potholes, large surface deformation, and structural distortion of pavement layers. Hashim et al. [37] briefly outlined that in order to minimize those failures, Batu Pahat soft clay
needs to be applied for reducing imported soil from other places. Ho and Chan [38] stated that soft clays are introduced as cohesive soil, where water content is higher than its liquid limits. Mokhtar [39] pointed that the soft soil includes the term of soft clay soils, and have a big portions of fine particles such as clay soils and silts. More recently, Mohd and Zain [40] expressed the opinion that various types of soils are ranked as soft soils such as soft clays, peat soils, organic soft soils, and soft clays.

In addition, previous study [41] showed that BPSC may be a crucial factor to probable damage to the rural road structure. Based on the findings of Chan and Abdullah [42], had concluded that the engineering properties of these clay soils can be enhanced by adding ordinary Portland cement for modification. In other research, Malaysia is well known to have many areas with soft clay soil as the major soil distribution percentage. This is because Malaysia has many coastal areas and rivers. Soft clay has particle sizes of less than 0.002 mm. Therefore, when a soil has 50% or more particles with sizes of 0.002 mm or less, it is generally termed as clay [43]. The areas which consist of soft clay area in Peninsular Malaysia are shown in Figure 2.1.

![Figure 2.1: Soft clay area of RECESS Malaysia](image-url)
2.3.1 The physical properties of BPSC

Soft clay usually causes difficulty in construction process because of its strength and low hardness properties [44]. The physical properties of BPSC have been experimentally achieved by some previous studies as shown in Table 2.1.

Table 2-1: Physical properties of Batu Pahat soft clay

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Researchers</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2008</td>
<td>2009</td>
<td>2010</td>
</tr>
<tr>
<td>Bulk Density (Mg/m)</td>
<td>1.36</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>2.66</td>
<td>2.62</td>
<td>2.62</td>
</tr>
<tr>
<td>Plastic Limit (%)</td>
<td>31</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>Liquid Limit (%)</td>
<td>77</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>Plasticity Index (%)</td>
<td>46</td>
<td>36</td>
<td>-</td>
</tr>
<tr>
<td>Moisture Content (%)</td>
<td>-</td>
<td>48</td>
<td>85</td>
</tr>
</tbody>
</table>

Additionally, Rafidah and Chan [45] stated that the increment in the moisture content caused the clay to become smooth and sticky till it cannot retain its original shape when it is described as being in a liquid state as shown in Table 2.2.

Table 2-2: Typical moisture contents

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Moisture contents %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moist sand</td>
<td>5-15</td>
</tr>
<tr>
<td>Wet sand</td>
<td>15-25</td>
</tr>
<tr>
<td>Moist silt</td>
<td>10-20</td>
</tr>
<tr>
<td>Normally consolidated clay low plasticity</td>
<td>20-40</td>
</tr>
<tr>
<td>Over consolidated clay high plasticity</td>
<td>10-20</td>
</tr>
<tr>
<td>Organic clay</td>
<td>50-200</td>
</tr>
<tr>
<td>Extremely high plasticity clay</td>
<td>100-200</td>
</tr>
</tbody>
</table>

2.3.2 Particle size distribution of soft clay

Clay is a natural material of a very fine texture, usually plastic when wet, and hard compact when dry. It also consists of several minerals such as silica tetrahedron and
alumina octahedrons as its basic mineral units [25]. In addition, particles with size below 75µm are considered as fillers [46]. In the same way, soft clay is the finest of all and it can only be clearly monitored by using microscopic tools, with soil grains finer than 0.075mm [47]. Clay also has large surface area because of its fine size and platy character of the individual minerals, and it has different surface chemical reactions and different bulk physical properties [48]. Aside from this, clay and silt soil are part of cohesive soil because their particles are closed together and they tend to stick within its particles [49]. In the other research, Jordan [50] indicated that clay minerals are mostly specified by their small particle size, affinity for water, response to chemical alternates in their environment, and are referred for their crystallization.

2.4 Additives and modifiers in hot mix asphalt

Asphalt binder modifiers are used to enhance performance properties of flexible pavements. The study of Baumgardner [51] found that asphalt binder modification is a common method of improving Hot-mix Asphalt (HMA) performance by enhancing mix properties and reducing or delaying three general HMA distress types. Therefore, the modification of asphalt binder to enhance the performance properties has grown significantly since the application of the strategic highway research program binder specifications. Similarly, modification of the asphalt binder is one approach that can be taken to improve pavement performance [52]. In addition, the modification of asphalt binder enhances their performance properties in the United State for more than 50 years. [53]. That is the reason for the modifications of asphalt binder to grow significantly since the implementation of Strategic Highway Research Program (SHRP) binder specifications [51]. Meanwhile, Nuñez et al. [54] found that the modifications of asphalt binder is used as an substitution to enhance the original properties of material.
2.5 Chemical properties of additives

The Superpave asphalt binder specifications based on SHRP require the asphalt binders to meet stiffness criteria at both high and low pavement service temperatures. However, most regular asphalt binders are not qualified for the requirements in areas with extreme climate conditions. In the meantime, traffic volume and loads have increased significantly in recent years [55]. This has caused lots of premature rutting and cracking of HMA pavement constructed with neat asphalt binders. Modifications of asphalt binders become of considerable interest in the improvement of pavement performance and service life. Table 2.3 shows generic classification of asphalt additives and modifiers. Some specific technical reasons for using additives and modifiers in HMA are listed as follows:

- Obtaining stiffer mixtures at high service temperatures to minimize rutting.
- Obtain softer mixtures at low service temperatures to minimize thermal cracking.
- Improve fatigue resistance of HMA mixtures.
- Improve resistance to aging or oxidation; rejuvenate aged asphalt binders.
- Permit thicker asphalt films on aggregate for increased mix durability.
- Improve abrasion resistance of mixture to reduce raveling.
- Reduce flushing or bleeding; reduce structural thickness of pavement layers.
- Reduce life cycle costs and improve overall performance of HMA pavements.

Table 2-3: Generic classification of asphalt additives and modifiers

<table>
<thead>
<tr>
<th>Type</th>
<th>Generic Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filler</td>
<td>• Mineral Filler: crusher fines</td>
</tr>
<tr>
<td></td>
<td>lime</td>
</tr>
<tr>
<td></td>
<td>Portland cement</td>
</tr>
<tr>
<td></td>
<td>fly ash</td>
</tr>
<tr>
<td></td>
<td>• Carbon black</td>
</tr>
<tr>
<td>Type</td>
<td>Generic Examples</td>
</tr>
<tr>
<td>-----------------</td>
<td>-------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Extender</td>
<td>• Sulfur</td>
</tr>
<tr>
<td></td>
<td>• Lignin</td>
</tr>
<tr>
<td>Polymers</td>
<td>Rubber:</td>
</tr>
<tr>
<td></td>
<td>a. Natural latex</td>
</tr>
<tr>
<td></td>
<td>b. Synthetic latex</td>
</tr>
<tr>
<td></td>
<td>c. Block copolymer</td>
</tr>
<tr>
<td></td>
<td>d. Reclaimed rubber</td>
</tr>
<tr>
<td></td>
<td>Natural rubber</td>
</tr>
<tr>
<td></td>
<td>Styrene-butadiene or SBR</td>
</tr>
<tr>
<td></td>
<td>Polychloroprene latex</td>
</tr>
<tr>
<td></td>
<td>Styrene-butadiene-styrene (SBS),</td>
</tr>
<tr>
<td></td>
<td>Styrene-isoprene-styrene (SIS)</td>
</tr>
<tr>
<td></td>
<td>Crumb rubber modifier</td>
</tr>
<tr>
<td></td>
<td>Plastic</td>
</tr>
<tr>
<td></td>
<td>Polyethylene/Polypropylene</td>
</tr>
<tr>
<td></td>
<td>Ethylene acrylate copolymer</td>
</tr>
<tr>
<td></td>
<td>Ethyl-vinyl-acetate (EVA)</td>
</tr>
<tr>
<td></td>
<td>Polyvinyl chloride (PVC)</td>
</tr>
<tr>
<td></td>
<td>Ethylene propylene or EPDM</td>
</tr>
<tr>
<td></td>
<td>Polyolefins</td>
</tr>
<tr>
<td></td>
<td>Combination</td>
</tr>
<tr>
<td></td>
<td>Blends of polymers above</td>
</tr>
<tr>
<td>Fiber</td>
<td>• Natural: asbestos</td>
</tr>
<tr>
<td></td>
<td>rock wool</td>
</tr>
<tr>
<td></td>
<td>• Man-made: polypropylene</td>
</tr>
<tr>
<td></td>
<td>polyester</td>
</tr>
<tr>
<td></td>
<td>fiberglass</td>
</tr>
<tr>
<td></td>
<td>mineral</td>
</tr>
<tr>
<td></td>
<td>cellulose</td>
</tr>
<tr>
<td>Oxidant</td>
<td>Manganese salts</td>
</tr>
<tr>
<td>Antioxidant</td>
<td>• Lead compounds</td>
</tr>
<tr>
<td></td>
<td>• Carbon</td>
</tr>
<tr>
<td></td>
<td>• Calcium salts</td>
</tr>
<tr>
<td>Hydrocarbon</td>
<td>• Recycling and rejuvenating oils</td>
</tr>
<tr>
<td></td>
<td>• Hard and natural asphalts</td>
</tr>
<tr>
<td>Anti-stripping Agent</td>
<td>• Amines</td>
</tr>
<tr>
<td>Waste Materials</td>
<td>• Roofing shingles</td>
</tr>
<tr>
<td></td>
<td>• Recycled tires</td>
</tr>
<tr>
<td></td>
<td>• Glass</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>• Silicones</td>
</tr>
<tr>
<td></td>
<td>• Deicing calcium chloride granules</td>
</tr>
</tbody>
</table>

### 2.6 Mineral fillers

The term filler means an aggregate that mostly passes through a specified sieve (0.063 mm in Europe, 0.075 mm in the United States). Mineral fillers are added to asphalt paving mixtures to fill voids in the aggregate and reduce the voids in the
mixture. However, addition of mineral fillers has dual purpose when added to asphalt mixtures. A portion of the mineral filler that is finer than the asphalt film thickness mixed with asphalt binder forms a mortar or mastic and contributes to improved stiffening of mix. This modification to the binder that may take place due to addition of mineral fillers could affect asphalt mixture properties such as rutting and cracking [23].

Atkins [56] pointed out that the importance of mineral filler fraction was often overlooked even though it is one of the most important components of HMA. In general, filler have various purposes among which, they fill voids and hence reduce optimum asphalt content and increase stability, meet specifications for aggregate gradation, and improve bond between asphalt cement and aggregate [57]. Therefore, numerous studies have investigated utilize of mineral filler as an additive in hot mix asphalt. In addition, several types of filler materials such as fly ash, limestone, cement, hydrated lime, silica and fine sand were used as filler in asphalt binder composites as followed down:

2.6.1 Ordinary Portland cement

The use of cement in asphalt mixtures is not a new concept. Portland cement was used primarily as filler in hot mix asphalt to prevent stripping of the binder from previously dried aggregate [58]. Also, using cement dust as a replacement to conventional limestone of hot mix asphalt may increase the indirect tensile strength of clay [59]. Hence, cement dust can totally replace lime stone mineral filler in asphalt paving mixtures [60]. Furthermore, cement is also used as a filler material in asphalt mixture and it was found to enhance anti stripping properties of asphalt mixture [61].
Some fines have a considerable effect on the asphalt cement making it acts as a much stiffer grade of asphalt cement compared to the neat asphalt cement grade [62]. The filler has the ability to increase the resistance of particle to move within the mix matrix and works as an active material when it interacts with the asphalt cement to change the properties of the mastic [63].

2.6.2 Fly ash

Fly ash is a fine material resulting from the burning of pulverized asphalt coal. Hence, fly ash is a byproduct of coal fired electric power generation facilities. It has little cementations properties compared to lime and cement [64]. Then again, Torrey [65] found that the ash collected by the electrostatic precipitator contains a greater percentage of very small particles <1.5 μ. Recently, Santagata and Baglieri [66] found that fly ash can be used as replacement filler in asphalt mixtures resulting in a totally satisfactory road pavement performance. Moreover, fly ash has been applied in a wide range of applications: fill materials can be used in asphalt mixture [67]. On the other hand, fly ash has been successfully used as a filler for asphalt mixes for a long time and has the advantage of increasing the resistance of asphalt mixes to moisture damage [68]. In addition, in order to filling voids, fly ash was announced to have the ability to work as an asphalt extender [69]. Based on this study, using fly ash in asphalt mixture attributes to providing economic benefits by decrease asphalt content, and leading to long service life of pavement [70]. Similarly, filler replacement with fly ash provides a considerable economic benefit of asphalt binder and mixture [71]. In the same review, the purpose of using fly ash in asphalt binder is to enhance the performance and decrease the costs and environmental effect [72].
2.6.3 Diatomaceous earth

Diatomite has been used since ancient times for agriculture and grain storage. The Chinese used it 4,000 years ago for oriental medicine and agriculture. Therefore, diatomite has many importance industrial benefits because of its unique physical properties, such as high porosity (35-65%), lightweight, low density, low thermal conductivity, high liquid absorption capacity, chemically inert and large surface area [73]. The unique physical properties of diatomite make it useful in civil engineering application. Their stud indicated that the addition of raw diatomite to cement up to 10% has produced positive results, but increased addition of raw diatomite reduce strength due to higher water demands related to the porosity of diatomite [74]. It is also suggested that diatomite and sup plasticizing admixture could be applied to enhance the mechanical properties of conventional asphalt mixture. In asphalt, diatomite was used as a type of modifier to improve the performance of asphalt mixture. Yi-qiu et al [75] found that the low temperature properties of diatomite modifier asphalt mixture and found that it performance better at low temperatures than neat asphalt mixture. Also it was indicated that diatomite and glass fiber improved permanent deformation resistance and fatigue performance of asphalt mixture, also has a significant effect on the stiffness of asphalt mixture.

2.6.4 Hydrate lime

Hydrated lime has been categorized as a major additive in asphalt pavement because of its wide availability and relatively cheap cost. In addition, utilization of hydrated lime has been classified as a main additive in asphalt pavement due to its availability and comparatively cheap cost. Gardiner and Epps [76] found that the use of hydrated lime in asphalt mixture is useful, and still exists as the best method for adding lime to
asphalt mixture. Wang and Sha [77] examined the limestone and limestone filler effect upon hardness and found that it was significant compared to granite and granite fillers. Likewise, Behiry [78] stated that using hydrated lime gave better results than Portland cement, and had the ability to enhance the mechanical performance of asphalt mixture. In another study, hydrated lime would provide resistance to moisture damage and chemical ageing [79]. It was also determined that the modified asphalt mixture with recycled waste lime gave higher resistance against stripping than unmodified asphalt mixture [80]. Addition of hydrated lime to asphalt can increase penetration and lower the viscosities of asphalt binder [81]. Likewise, asphalt mixture with hydrated lime has slightly greater stability than the mixture with a crushed stone dust. This indicates that the hydrated lime improves the stability of the mixture [82]. Sangiori et al. [83] reported that waste bleaching clay can lead to an enhancement of mechanical properties of the asphalt mixture.

2.7 Asphalt binder

Asphalt binder is used as an adhesive material in roadway and roofing construction. However, there are many types of distress like low temperature cracking, fatigue, and permanent deformation that can reduce the quality and performance of road pavement during life service [84]. Recently, Pan [85] showed that the performance of asphalt binder is also highly related to its service conditions which involve climatic conditions and traffic conditions, such as temperature, moisture and traffic loads. The study of Kharghehpoush [86] showed that asphalt binder is highly particularly important material with respect to highways. Thus, national transportation agencies have expressed interest in asphalt binder modifiers from renewable resources [87].

In recent decades, strategic highway research program proposed new performance based on specifications for asphalt binders, and recognized as
performance grade [88]. Meanwhile, most asphalt binders adhesives that utilized for pavement materials are derived mostly from fossil fuels [89].

Asphalt binder additives can be defined as a material added in the binder to improve its properties, and also an ideal additive should be able to decrease the temperature susceptibility, control age hardening and must be compatible with any type of binder [90]. However, an internal report of the Asphalt Institute identified 48 types of binder modifiers comprising of 13 polymers, 10 hydrocarbons, 6 mineral fillers, 6 antioxidants, 6 anti-stripping additives, 4 fibers, 2 extenders, and 1 oxidant [91].

According to Zanzotto and Kennephl [92], asphalt additives should be capable to improve the binder properties at both low and high in-service temperatures, and it should be strong enough to withstand traffic loads at high temperature, which any cause permanent deformation, and flexible enough to avoid excessive thermal stresses at low asphalt temperatures.

2.8 Effect of filler in asphalt binder

Several studies have been investigated to understand the stiffness impact of mineral filler on asphalt binder. In addition, use hydrated lime with SBS modified binder had a good improvement of asphalt binder stiffness [93]. While, a study carried out by Cross and Brown [94] investigated that using various types of mineral fillers such as hydrated, cement, limestone lead to increase the stiffness of asphalt binder. An excess of filler leads to mastic stiffening and the increase of cracking susceptibility [95].

Anderson and Dongre [96] also reported that viscosity increased with penetration decrease, and softening point increase. This in turn increase the filler particles size which leads to increase the hardness of asphalt binder. Based on the
work done by Rostler and Dannenberg [97], the black carbon was applied as filler in asphalt binder, which leads to higher viscosity compared to the original sample. Meanwhile, Garrigues and Vincent [98] stated that the added of sulfur in the asphalt binder could improve the physical properties of asphalt binder. Figure 2.2 shows the process of gradually filling the voids in a compacted filler; the binder essentially plays two roles that of a lubricant making the relocation of grains easier and that of a liquid in which they can be suspended.

![Diagram showing the process of gradually filling the voids in compacted filler with binder](image)

**Figure 2-2:** Process of gradually filling the voids in compacted filler with binder [95]

Moreover, nanoclay would enhance the physical properties of asphalt binder and reduce the costs extensively [99]. Prowell et al. [100] reported that the addition of fines to the asphalt binder can improve the stiffness of asphalt binder. The higher asphalt content when apply in an incorporation with acid filler presents lower viscosity, whilst the main filler show a higher viscosity [101]. Anderson [102] pointed out that the rheological behavior of the asphalt binder was influenced by the
size of the filler particles. The addition of nanoclay enables to achieve better physical properties in conventional composites [103]. Incorporation of up to 5% nanoclay in asphalt binder lowered the penetration value and increased the softening point [104].

2.9 Filler interaction of asphalt binder

The asphalt and filler interaction have a significant role on the performance of asphalt mastic, and they have ability to effect by the temperature and loading frequency. To evaluate the asphalt and filler interaction, Hafeez and Kamal [105] found that the size of filler and interactions among asphalt binder and filler greatly affected by the reinforcement of asphalt mastic.

Zhang et al. [106] also found that the interaction ability of filler and asphalt could be reflected by the change in the rheological properties of asphalt mastic. On the other hand, Bhasin [107] explained that anti-striping property of asphalt aggregated in water is limited for the evaluation of the asphalt and filler interaction. It is well known that interaction between filler and asphalt binder is based on the coefficient of variation of phase angel [108]. Tan et al. [109] defined the complex viscosity coefficient to evaluate asphalt and aggregate interaction ability. Hence, the segregation is not evident for asphalt and aggregate. Clopotel et al. [110] assumed that the change in the viscosity of the matrix asphalt is entirely because of the change in the glass transition temperature. Thereby, asphalt and filler interaction capacity would be analyzed and evaluated by glass transition temperature and physicochemical interaction model [111].

Recently, in an attempt to evaluate the asphalt and filler interaction ability, Yiqiu and Guo [112] investigated that particle size allocation has a significant effect on interface interaction among asphalt binder and filler. Most important, Bahia and Hintz [113] reported that the filler properties such as size, shape, angularity, texture,
and composition a small number of chemical compounds impact asphalt filler interaction. Similarly, Anderson [63] found that the filler has the capability to boost the resistance of particle to move through the mix matrix and acts as an active material when it interacts with the asphalt binder to alternate the properties of the mastic. Most importantly, Hesami and Kringos [114] pointed out that the chemical compositions of asphalt binder on the surface of filler is rearranged when the asphalt and filler are mixed. Also Zhang [115] applied interface molecular models of chemical and aggregate oxide compositions of binder by molecular dynamics to analyse the interaction between binder and aggregate. It can be indicated that an alteration in temperature or chemical composition would impose segregation among the asphalt molecules [116].

In the other research, El-Shafie et al. [117] showed that addition of nanoclay to asphalt binder leads to increase in softening point, viscosity and decrease in penetration. It was concluded that nanoclay can improve properties such as stability, stiffness modulus and indirect tensile strength and resulted in excellent performance compared to that of unmodified binder [118]. Then again, the clay minerals, mostly specified by their small particle size, affinity for water, and response to chemical alternates in their environment are referred for their crystallization and viscosity-increasing capabilities in aqueous components [50].

Likewise, Van et al. [119] nanoclay modification would improve characteristics of asphalt binder and resistance to aging. Based on the ideas of Kim et al. [120], an interacting influence between physico-chemical filler and asphalt binder is related to the fineness and surface properties of the filler, which usually effects fatigue fracture characteristics. Whereas, Craus et al. [121] reported that the physico-chemical is related to higher surface activity which significantly contributes to strong bonds at the filler of asphalt binder interface.
2.10 Influence of fillers on aging resistance of asphalt binder

The principal cause of asphalt binder ageing in service is the atmospheric oxidation of certain molecules with the formation of highly polar and strongly interacts functional groups containing oxygen. Qin et al. [122] also mentioned that the aging can significantly change the rheological properties of asphalt binders and cause asphalt hardening. Hence, it is importance to have a good understanding of changes in rheology and structure of asphalt binders under aging environments. Aging phenomenon is considering as one of the main causes for the failure of wearing course. Therefore, the benefits of using filler to enhance the aging resistance are studied by many researchers.

Wu et al., [123] reported that an oxidation which occurs in asphalt roadway pavements during construction and service life can affect the rheological properties of binder. Shenoy [124] argued that asphalt binder ageing has implications during the construction of pavements and their long-term performance. Meanwhile, Moraes [125] stated that that the aging process in asphalt pavement might be detrimental when too much hardening is observed, and aging may be beneficial when a soft mixture hardens in an adequate pavement.

In contrast, Bautista [126] reported that the properties of the asphalt binder relied on the period of aging that can be considered in terms of rheological, and studied the effect of fillers on the aging of asphalt binder mixes.

On the other hand, Huang and Zeng [127] studied the impact of filler surface on the rheological properties of asphalt binder when exposed to long-term aging. Petersen et al., [128] demonstrated that the addition of filler to mixes leads to enhancement of asphalt binder, and it can delay the aging process. Likewise, Plancher et al., [129] claimed that calcareous fillers can cause both catalysts and
polar molecules to increase the viscosity of asphalt binder. It is well known that small particles sizes of filler prevent oxygen dispersal during asphalt binder [130].

Then again, fly ash appears to enhance the resistance of aging in asphalt binder. This leads to the increase in the service life of asphalt pavement [131]. Likewise, the asphalt mixture with hydrated lime had slightly greater stiffness which leads to reduce the ageing of asphalt binder [82].

2.11 Rheology properties of asphalt binder

Rheological characterization could be defined as a science dealing with the flow and deformation of different materials. Shafabaksh and Ani [132] claimed that the rheological of the asphalt binder would influence the performance of asphalt binder. Moreover, Yusoff et al. [133] reported that the fundamental rheological properties of binder materials are normally measured using DSR from low to high temperatures.

2.11.1 Dynamic shear rheometer

DSR was applied to describe the viscous and elastic behavior on asphalt binder at intermediate and high temperatures. It also determined the complex shear modulus (G*) and phase angle (δ) of asphalt binder at the desired temperature and frequency of loading [134]. DSR method for high temperatures require geometry gap of 1 mm and with spindle 25 mm, while for low temperatures 2mm gap and spindle of 8mm [135]. The schematic diagram of DSR testing configuration is shown in Figure 2.3.
The DSR testing procedure is given in AASHTO TP5. As shown in Figure 2.4, the asphalt binder sample is constrained between a fixed plate and an oscillating plate. Hence, all Superpave DSR test are conducted at a frequency of 10 radians per second, which is equivalent to 1.59Hz [136].
REFERENCES


155. Ferry, J.D., Viscoelastic properties of polymers. 1980


158. Lolly, R., Evaluation of Short Term Aging Effect of Hot Mix Asphalt Due to Elevated. 2013, Arizona State University.


173. Smith, B.J., Use of Asphalt Pavement Analyzer to Study In-Service Hot Mix Asphalt Mixture Performance. Master of Science in Civil Engineering, Mississippi State University, 2004.


Effect of short term aging on organic montmorillonite nano clay modified  
asphalt. *Indian Journal of Science and Technology*, 2013. 6(10): pp. 5434–  
5442.

Rheological properties of polymer modified bitumen from long-term field tests. *Fuel*,  

281. Firoozifar, S.H. & Foroutan, S.  
The effect of asphaltene on thermal properties  
2044-2048.

Evaluating and comparing different methods and models for generating relaxation modulus master-  
pp. 2619-2626.

283. Liu, G., Nielsen, E., Komacka, J., Greet, L., & Van de Ven, M.  
Rheological and chemical evaluation on the ageing properties of SBS polymer modified  

284. Liao, M.C. & Chen, J.-S.  

285. Zheng, J. & Huang, T.  

286. Al-Hdabi, A.,  

287. Daranga, C.,  


