UNIVERSITI PUTRA MALAYSIA

AGING DEFORMATION RESISTANCE OF NANOCLAY-MODIFIED STONE MASTIC ASPHALT MIXTURE

LAMYA M. J. MAHDI

AGING DEFORMATION RESISTANCE OF NANOCLAY-MODIFIED STONE MASTIC ASPHALT MIXTURE

By

LAMYA M. J. MAHDI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirement for the Degree of Doctor of Philosophy

March 2015

DEDICATION

Dedicated to my beloved husband Dr. Ali Radi Mahdi, who gave me a chance to figure out myself and being with me hand in hand, I will always owe him for his love, support and patience and for sacrificing all so that I can achieve my Ph.D.

To my beloved mother, sisters: Dr. Aida, Dr. Thana, Engineer Alaa and Methal and brothers: Jamal and Engineer Mahdi for their love, and encouragements towards the success of this study.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

AGING DEFORMATION RESISTANCE OF NANOCLAY- MODIFIED STONE MASTIC ASPHALT MIXTURE

By

LAMYA M. J. MAHDI

March 2015

Chairman: Professor Ratnasamy Muniandy, PhD
Faculty: Engineering

Many modifiers have been used to modify bitumen such as fiber, polymer, and filler which cost the road authorities a lot of money in addition to their side effects on the environment and their limited advantage. Aging have limited the service life of pavement and accelerated its premature failures. The problem of asphalt aging still exists in spite of the extensive use of the above mentioned modifiers.

Montmorillonite nanoclay is one of the hybrid materials having a favored layer structure distinguish it from other materials in ability to disperse on a nanometer scale. It is a natural source material with a relatively low cost and more importantly environmentally friendly. The successfully intercalation chemistry of the layered silicates with polymers has been widely studied for a long time, and properties such as thermal, mechanical showed superior enhancement.

Based on these findings, this study presents a laboratory investigation into the performance of asphalt binder and Stone Mastic Asphalt mixture modified with different type and concentration of nanoclay.

The Rolling Thin Film Oven method was used to simulate the short term aging of the base and nanoclay modified asphalt binder, while the Stone Mastic Asphalt mixture was aged according to the asphalt mixture specification. The Dynamic Shear Rheometer was performed to characterize the rheological properties of asphalt binder at different temperatures and frequencies. The effect of nanoclay on the performance of the Stone Mastic Asphalt mixture was also investigated by means of the Indirect Tension Test and the Repeated Load Axial Test.

The microscopic images indicated a homogenous dispersion of the layered silicate in asphalt medium while the spectroscopic technique showed the incorporation of the nanoclay in the asphalt binder matrix via new functional groups. Nanoclay was found to have a significant influence on asphalt binder and mixture properties. The higher nanoclay concentration showed better performance. The asphalt binder physical, rheological properties and rutting resistance were positively improved after the addition of nanoclay.

The permanent deformation resistance of the Stone Mastic Asphalt mixture was found to be enhanced due to the stiffening effect of the nanoclay. Meanwhile, inconsistent trend was observed among the concentrations and types of nanoclay especially with permanent deformation test results, however, both of nanoclay types showed remarkable improvement as compared with the control mixture. The reason can be contributed to the complicated asphalt mixture failure mechanism since different variables having heterogeneous characters contributed in construction the Stone Mastic Asphalt mixture while using very close nanoclay concentration from each others can be a another reason.

The short term aging resistance of modified binder was found to be improved which indicated the ability of layered nanoclay to act as a barrier that restricted and delayed the penetration of oxygen and played an important role to reduce the volatilization of the bitumen's oily components and as consequence improved the asphalt binder resistance to rutting while enhanced the engineering properties of SMA mixtures as providing resistance against permanent deformation.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

KESAN PENUAAN BAGI RINTANGAN BAGI NANOCLAY CAMPURAN STONE MASTIC ASPHALT YANG DIUBAHSUAI

Oleh

LAMYA M. J. MAHDI

Mac 2015

Pengerusi: Professor Ratnasamy Muniandy, PhD
Fakulti: Kejuruteraan

Kebanyakan pengubah telah digunakan untuk mengubah suai bitumen seperti serat, polimer dan pengisi yang menyebabkan pihak berkuasa jalan raya menelan belanja yang banyak di samping kesan sampingan terhadap alam sekitar dan kelebihan yang terhad. Penuaan telah menghadkan jangka hayat perkhidmatan turapan dan mempercepatkan kegagalan pra-matang itu. Masalah penuaan asfalt masih wujud walaupun penggunaan meluas di atas pengubahsuaian tambahan.

Montmorilonit nanoclay adalah salah satu bahan hibrid yang mempunyai struktur lapisan yang disukai membezakannya daripada bahan-bahan lain dalam keupayaan untuk bersurai pada skala nanometer. Ia adalah bahan sumber semulajadi dengan kos yang agak rendah dan lebih penting lagi mesra alam. Kimia interkalasi telah berjaya daripada silikat berlapis dengan polimer telah dikaji secara meluas untuk jangka masa yang lama, dan sifat-sifat seperti haba, mekanikal menunjukkan peningkatan unggul.

Berdasarkan hasil dapatan, kajian ini membentangkan satu kajian makmal ke dalam prestasi pengikat asfalt dan campuran Batuan Mastik Asfalt diubahsuai dengan jenis yang berbeza dan konsentrasi nanoclay.

Kaedah Rolling Thin Film Oven telah digunakan untuk mensimulasikan jangka pendek penuaan daripada asas dan nanoclay diubahsuai asfalt pengikat, manakala campuran Batuan Mastik Asfalt telah berumur mengikut spesifikasi campuran asfalt. Dynamik Ricih Reometer telah dijalankan untuk mencirikan sifat-sifat reologi pengikat asfalt pada suhu yang berbeza dan frekuensi. Kesan daripada

nanoclay kepada prestasi campuran Batuan Mastik Asfalt juga disiasat melalui Ujian Ketegangan Tidak Langsung dan Beban Paksi Berulang Ujian.

Imej-imej mikroskopik menunjukkan penyebaran homogen daripada silikat yang berlapis dalam medium asfalt manakala teknik spektroskopi yang menunjukkan pemerbadanan nanoclay dalam matriks pengikat asfalt melalui kumpulan berfungsi baru. Nanoclay didapati mempunyai pengaruh yang besar ke atas pengikat asfalt dan sifat-sifat campuran. Kepekatan nanoclay yang lebih tinggi menunjukkan prestasi yang lebih baik. Asfalt pengikat fizikal, sifat reologi dan rintangan aluran telah positif bertambah baik setelah penambahan nanoclay.

Ketahanan ubah bentuk kekal daripada campuran Batuan Mastik Asfalt didapati untuk mempertingkatkan oleh pengerasan kesan daripada nanoclay. Sementara itu, trend yang tidak konsisten diperhatikan dalam kalangan kepekatan dan jenis nanoclay terutamanya dengan keputusan ujian ubah bentuk kekal, bagaimanapun, kedua-dua jenis nanoclay menunjukkan peningkatan yang memberangsangkan berbanding dengan campuran kawalan. Alasan boleh menyumbang kepada mekanisme kegagalan campuran asfalt rumit sejak pembolehubah yang berbeza mempunyai heterogen ciri-ciri yang menyumbang dalam pembinaan campuran Batuan Mastik Asfalt semasa menggunakan nanoclay kepekatan yang sangat rapat antara satu sama lain boleh sebab yang lain.

Penuaan rintangan jangka pendek daripada diubahsuai pengikat telah didapati bertambah baik yang menunjukkan keupayaan nanoclay berlapis untuk bertindak sebagai penghalang yang menyekat dan melambatkan penembusan oksigen dan memainkan peranan penting untuk mengurangkan pemeruapan komponen berminyak bitumen dan mengakibatkan peningkatan asfalt rintangan pengikat untuk aluran dan meningkatkan sifat-sifat kejuruteraan campuran Batuan Mastik Asfalt menyediakan rintangan terhadap ubah bentuk kekal.

ACKNOWLEDGEMENTS

In the Name of Allah, Most Gracious, Most Merciful, all praise and thanks are due to Allah, and peace and blessings be upon His Messenger.

First of all, I would like to convey my sincere gratitude and appreciation to my venerable advisor Professor Ratnasamy Muniandy who gave me invaluable and worthwhile advice throughout the course of this research, without his support, guidance and encouragement, this work would not have been accomplished. I would like to thank Associate Professor Salihudin Hashim and Professor Robiah Yunus for being on my advisory committee. Their cooperation, encouragement, mastery advice, keen interest, constructive criticisms have been invaluable during my research work.

Special thanks to Dr. Eltaher Aburkaba and all other faculty members for their cooperation with this study. Deep thanks to our beautiful university (UPM) for the encouragement and support.

The biggest thanks go to my husband for his guidance, supports, love and encouragement.

Last but not least, I would like to express my gratitude to all my family: mother, brothers and sisters, for their love and encouragement.

I certify that a Thesis Examination Committee has met on 31 March 2015 to conduct the final examination of Lamya M. J. Mahdi on her thesis entitled "Aging Deformation Resistance of Nanoclay-Modified Stone Mastic Asphalt Mixture" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

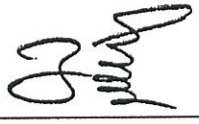
Members of the Thesis Examination Committee were as follows:

Thamer Ahmad Mohammad Ali, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Hussain bin Hamid, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Abang Abdullah bin Abang Mohamad Ali, PhD
Professor Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Vernon Ray Schaefer, PhD
Professor
Iowa State University
United States
(External Examiner)



ZULKARNAIN ZAINAL, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 15 April 2015

This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment on the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Ratnasamy Muniandy, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Robiah Yunus, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Salihudin Hassim, PhD
Associate Professor Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Member)

_____
BUJANG KIM HUAT, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by Graduate Student

I hereby confirm that:

- x this thesis is my original work;
- x quotations, illustrations and citations have been duly referenced;
- x this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- x intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- x written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- x there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: _____ Date: _____

Name and Matric No.: Lamya M. J. Mahdi/ GS28400

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: _____

Name of
Chairman of
Supervisory
Committee: Prof. Dr. Ratnasamy Muniandy

Signature: _____

Name of
Member of
Supervisory
Committee: Prof. Dr. Robiah Yunus

Signature: _____

Name of
Member of
Supervisory
Committee: Assoc. Prof. Ir Salihudin Hassim

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
BET	Brunauer Emmett Teller
BS	British Standard
BT	Bentonite Clay
CAPA	Colorado Asphalt Pavement Association
CEC	Cation Exchange Capacity
COPF	Cellulose Oil Palm Fiber
DLS	Dynamic Light Scattering
DSR	Dynamic Shear Rheometer
EPDM	Ethylene Propylene Diene Monomer
EVA	Ethyl Vinyl Acetate
FHWA	Federal Highway Administration
FN	Flow Number
FTIR	Fourier Transform Infrared Spectroscopy
GEL	Gelatinous
H/C	Hydrogen to Carbon Ratio
HMA	Hot Mix Asphalt
Hz	Hertz
Ic	Index of Colloidal Instability
ISP	Increment in Softening Point
ITT	Indirect Tension Test
KC	Kaolinite Clay
KRIP	Kajang Rocks Innopave Premix Company
LA	Los Angeles Abrasion
LL	Lower Limit
LVDT	Linear Variable Differential Transducer
LVE	Linear Viscoelastic
MATTA	Material Testing Apparatus
MMT	Montmorillonite
MS	Measurement Systems
Na-MMT	Sodium Montmorillonite
NAPA	National Asphalt Pavement Association
NCHRP	National Cooperative Highway Research Program
NMAS	Nominal Maximum Aggregate Size

OAC	Optimum Asphalt Content
OBT	Organic Modified Bentonite
OMMT	Organic Montmorillonite
OSU	Oregon State University
PAV	Pressure Aging Vessel
PG	Performance Grade
PI	Penetration Index
PVC	Polyvinyl Chloride
R&B	Ring and Ball
RLAT	Repeated Load Axial Test
RMP	Refinery Mechanical Pulping
RP	Retained Penetration
RPM	Revolutions per Minute
RTFO	Rolling Thin Film Oven
RV	Rotational Viscometer
SABITA	Southern African Bitumen Association
SBR	Styrene Butadiene Rubber
SBS	Styrene Butadiene Styrene
SHRP	Strategic Highway Research Program
SIS	Styrene Isoprene Styrene
SMA	Stone Matrix Asphalt
SOL	Solution
SSD	Saturated Surface Dry
STA	Short Term Aging
SUPERPAVE	Superior Performing Asphalt Pavement
TEM	Transmission Electron Microscopy
TMD	Theoretical Maximum Density
TR	Crumb Rubber
TSR	Tensile Strength Ratio
UKM	Universiti Kebangsaan Malaysia
UL	Upper Limit
UPM	Universiti Putra Malaysia
UTM	Universal Testing Machine
UV	Ultraviolet
VAI	Viscosity Aging Index
VCA	Voids in Coarse Aggregate
VFA	Voids filled with Asphalt
VMA	Voids in Mineral Aggregates
VTM	Voids in Total Mix
VTS	Viscosity Temperature Susceptibility

Wc	Work Dissipated per Loading Cycle
WDXRF	Wavelength Dispersive X-Ray Fluorescence
WPE	Waste Packaging Polyethylene
WSDOT	Washington State Department of Transportation
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence

CHAPTER 1

INTRODUCTION

1.1 Background

The nanotechnology research has attracted great interest from researcher throughout the world due to the various interesting functions of materials on nanoscale dimensions and having relatively larger surface-area-to-mass ratio which make them more chemically reactive and positively change their strength or other important properties and thus increase their potential to use in a wide range of applications.

Nanoscale materials which is a material having at least one dimension sized from 1 to 100 nanometers, have been adopted by many of the industries and academics and showed unexpected reaction by the community, announcing a new industrial revolution. One of the most attractive nanomaterials is nanoclay which is a natural occurring material widely used by researcher from long time because of its availability, relatively low cost, environmentally friendly and the most important property which is its favorable and unique structure make it more compatible to create nanocomposite. Montmorillonite nanoclay which is the most commonly used layered silicates has been successfully used to reinforce polymers (Ray and Okamoto, 2003). Montmorillonite nanoclay is anisotropy filler which has large aspect ratio (length to thickness ratio) make it especially favorable in matrix reinforcement (Patel et al., 2006).

Montmorillonite from smectite group clays has a 2:1 phyllosilicates layer structure which composed of a shared octahedral sheet sandwiched between two tetrahedral sheets (Okada and Usuki, 2006). In order to provide more compatible nanocomposite with various polymer types, montmorillonite is treated with special types of surfactants such as quaternary ammonium salt through an ion exchange reaction (Giannelis, 1996). Many of polymer properties can successfully enhanced with the addition of few amount of nanoclay (Alexandre and Dubois, 2000).

Recently nanoclay attracted the attention of the asphalt pavement researchers and with the expected of more significant result, small amount of nanoclay was added as a third part to enhance the compatibility between the polymer and asphalt binder, the results showed remarkable improvement in modified binder's properties comparing with the unmodified one (Yu et al., 2007; Polacco et al., 2008; Zhang et al., 2009; Sureshkumar et al., 2010; Galooyak et al., 2010).

The positive results that gained from adding nanoclay to polymer asphalt nanocomposite gave the pavement researchers motivation to adopt this material which enables them to study the asphalt binder behavior at nano scale level.

A lot of studies have been done on nanoclay modified polymers and other materials but the research studies on this promising material to modified asphalt binder is still unclear due to lack of published research on this aspect. Also, very little information is available regarding the effect of nano materials on the characteristics, rheological properties, and viscoelastic behavior of nano material modified asphalt (nanocomposite) and very rare research concerning the effect of nanoclay on asphalt mixture. However, the characteristics of this material can significantly influence the properties of the nanocomposite, and thus can have a significant effect on mixture performance. To better understand and characterize the interaction of nanoclay with the asphalt binder, more effort and studies need to be carried out on nanoclay modified asphalt binder to determine its performance. It is believed that the focus on the asphalt binder rheological properties can have a significant effect in the practical application of nanoclay modified asphalt. Thus, beside the physical properties, this study will focus on the investigation of rheological and deformation properties of unaged and aged bituminous binders and Stone Mastic Asphalt (SMA) mixture, which is considered to be an effective and common approach to obtain the desired purpose mentioned above.

The type and quantity of nanoclay used to modify bitumen are especially important in particularly mixes like Stone Mastic Asphalt (SMA) mixtures where the properties of the mortar consisting of bitumen, fine aggregates, filler, and fiber and acts as a real glue in the asphalt mixture to stabilize the stone aggregate skeleton in an asphalt pavement and thus contributes significantly to compatibility impermeability, adhesion, and in-service pavement performance. Nanoclay varies depending on their groups, sources and the type of surfactant that used to modify them; as a consequence each nanoclay has different performance from others when they use as the reinforcement phase in various matrices.

1.2 Problem Statement

One of the most important issues facing asphalt pavement researchers as a consequence to the increasing traffic loads, traffic volumes, number of vehicle axle load, and environmental factors, is the kind of modifier that need it to improve the properties of the existing bituminous material to ensure provide longer service life, less maintenance, cheaper, and environmental friendly asphalt pavements. During its service life, asphalt pavement experience premature failures such as fatigue, rutting, thermal cracking, and moisture induced damage, this lead to urgent resolution to limit or at least delay this kind of failure which cost the road authority a lot of money with the ever increasing of crude oil prices.

On the other hand, due to the high-temperature, aging has been limited the service life of pavement. The problem of asphalt aging still exists in spite of the extensive

use of modification additives like polymer, filler and fiber in addition of their high cost and possible environmental concerns. At high service temperatures, and relatively low frequency of loading, bitumen because of it viscoelastic properties can become soft with a low stiffness and more susceptible to permanent deformation. Bitumen can easily get aged when exposure to elevated temperature and air due to the diffusion of oxygen and UV radiation.

Due to the relatively new technology introduced on pavement sector and the lack of the published research concerning this aspect; the stiffness and deformation resistance of the asphalt binder modified with nanoclay needs to be explored to provide insight into the performance of asphalt mixture. Based on the promising characteristics of the nanoclay that significantly influence the properties of the asphalt binder (Ghile, 2006), as a consequence their effect on the mixture performance need to be investigated.

The performance of nanoclay in asphalt mixture is unclear due to the few researches available concerning the interaction effects of nanoclay with asphalt mixture. The importance of nanoclay has been more over looked in the asphalt binder than mixture.

1.3 Objectives of the Study

The primary aim of this research is to investigate the possibility of using montmorillonite nanoclay with different types and concentrations to enhance the characteristics of the base bitumen and consequently to examine their potential effect on Stone Mastic Asphalt (SMA) mixtures performance. In order to achieve these aims, the following objectives were defined:

1. To evaluate the effects of nanoclay type and content on physical and rheological properties of asphalt binder before and after aging process.

2. To determine the effect of nanoclay modified binder on Stone Mastic Asphalt (SMA) mixture in terms of their permanent deformation properties before and after aging process.

1.4 Significance of the Study

The knowledge produced by this research can give contribution to develop a superior performing pavements by introducing new binder has the characteristics of lower temperature susceptibility and aging effect and thus can mitigate high temperature rutting throughout naturally occurring material that can reduce the cost of highway construction and maintenance as well as contribute to resolve one of the environmental problems. Nanoclay in this study tends to be economical, environmentally sound and effective to improve the pavement performance.

In addition, results of this research will contribute to a better characterize the interaction of nanoclay with the bitumen and give insight to their significant effects on the performance properties of binder and particularly Stone Mastic Asphalt (SMA) mixtures.

Furthermore, results of this study will give insight about the significance of the use of nanoclay in asphalt pavements particularly SMA mixtures to prevent or at least delay the premature pavement failure and consequently save life cycle cost. Results of this study will enable road authority to make proper judgment regarding the use of nanoclay in asphalt mixtures as a consequence can save a lot of money on maintenance and rehabilitation work of the roads.

1.5 Scope and Limitation

The main goal of this research is to investigate the effect of different montmorillonite nanoclay types and concentrations on the physical and rheological properties and viscoelastic behavior of asphalt binder and consequently on the performance of Stone Mastic Asphalt (SMA) mixture. This research test results are limited best on the following:

- Only two types of montmorillonite nanoclay were used in this study which prepared from the same origin montmorillonite clay but modified using two different types of surfactant in order to convert it to organic montmorillonite.

- This study focused only on the effects of short term aging and how it performs on asphalt binder and Stone Mastic Asphalt (SMA) mixture.

1.6 Thesis Layout

According to the objectives, the layout of the thesis is as follows:

Chapter 1 presents the introduction, research problem, objectives, significance of the study, and scope and limitation. Chapter 2 elaborates the literature review concerning subjects related to the structure, properties, and applications of nanoclay as well as bitumen origin, application, constitution, structure, and properties. Other works related to the nanoclay modified asphalt binder and mixture. In addition to the aging process of both modified asphalt binder and mixture. Description of DSR procedure and test performed. SMA Mix design and failure mechanisms were also explored in this chapter. Chapter 3 describes the methodology used and research approach; experimental procedure and setup. Chapter 4 explores the test results and explains these results with analysis and discussion of whole experimental work. Chapter 5 summarizes the conclusion from this work and provides recommendations for future work.

REFERENCES

AASHTO MP8-01 (2001). *Standard Specification for Designing Stone Matrix Asphalt (SMA)*. American Association of State Highway and Transportation Official (AASHTO). Washington DC, USA.

AASHTO R 30 (2002). *Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA)*. American Association of State Highway and Transportation Officials (AASHTO). Washington DC, USA.

AASHTO R 35 (2010). *Practice for Superpave Volumetric Design for Hot Mix Asphalt (HMA)*. American Association of State Highway and Transportation Officials, Washington DC, USA.

AASHTO T 19 (2008). *Bulk Density (Unit Weight) and Voids in Aggregate. Standard Specifications for Transportation and Methods of Sampling and Testing, 28th Edition.* American Association of State Highway and Transportation Officials (AASHTO). Washington DC, USA.

AASHTO T 27 (2008). *Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates. Standard Specifications for Transportation and Methods of Sampling and Testing, 28th Edition.* American Association of State Highway and Transportation Officials (AASHTO). Washington DC, USA.

AASHTO T 85 (1999). *Standard Test Method for the Specific Gravity and Absorption of Coarse Aggregate*. AASHTO Standard Specifications for Transportation Materials, Part II, Washington, D.C.

AASHTO T 209 (1999). *Standard Test Method for Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures.* AASHTO Standard Specifications for Transportation Materials, Part II, Washington, D.C.

AASHTO T-240 (1995). *Standard Test Method for Determining the Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test) RTFO.* American Association of State Highway and Transportation Officials, Washington DC, USA.

AASHTO T-305 (2009). *Determination of Draindown Characteristics in Uncompacted Asphalt Mixtures.* American Association of State Highway and Transportation Officials, Washington DC, USA.

AASHTO T-316 (2008). *Standard Method of Test for Viscosity: Determination of Asphalt Binder Using Rotational Viscometer*. American Association of State Highway and Transportation Officials (AASHTO), Washington DC, USA.

AASHTO TP5-93 (1995). *Provisional Standard Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheomete.* American Association of State Highway and Transportation Officials, Washington DC, USA.

AASHTO TP31 (1996). *Standard Test Method for Determining the Resilient Modulus of Bituminous Mixtures by Indirect Tension.* American Association of State Highway and Transportation Officials, Washington DC, USA.

Abduljauwad, S. N., Al-Sulaimani, G. J. (1993). Determination of Swell Potential of Al-Qatif Clay. *Geotechnical Testing Journal, ASTM, 16*(4): 469-484.

Adedimila, A. S. (2000). *Bitumen: Nigeria's Other Black Gold?*. Inaugural Lecture Series, University of Lagos.

Airey, G. D. (2002). Rheological Evaluation of Ethylene Vinyl Acetate Polymer Modified Bitumens. *Construction and Building Materials, 16*(8): 473-487.

Airey, G. D., Rahimzadeh, B., Collop, A. C. (2002). Linear Viscoelastic Limits of Bituminous Binders. *Journal of the Association of Asphalt Paving Technologists, 71*: 89-115.

Airey, G. D. (2003). Rheological Properties of Styrene Butadiene Styrene Polymer Modified Road Bitumens. *Fuel, 82*(14): 1709-1719.

Airey, G. D., Mohammed, M. H., Fichter, C. (2008). Rheological Characteristics of Synthetic Road Binders. *Fuel 87*(10-11): 1763-1775.

Airey, G. D., Mohammed, M. H., Collop, A. C., Parry, A., Hayes, C. J. (2008). Linear Viscoelastic Behaviour of Polyacrylate Binders and Bitumen Blends. *Journal of Road Materials and Pavement Design*: S*pecial Issue EATA, 9*: 13-35.

Alexandre, M., Dubois, P. (2000). Polymer-Layered Silicate Nanocomposites: Preparation, Properties and Uses of a New Class of Materials. *Materials Science and Engineering 28*: 1-63.

Anderson, D. A. (1991). *Guidelines on the Use of Baghouse Fines.* National Asphalt Pavement Association. NAPA Info Series 101/87.

Anderson, D. A., Christensen, D. W., Bahia, H. U., Dongre, R., Sharma, M. G., Button, J. (1994). *Binder Characterization and Evaluation, Volume 3: Physical Characterization.* Strategic Highway Research Program, Report No. SHRP-A-369, National Research Council, Washington, D.C.

Anderson, D. A. (1996). *Influence of Fines on Performance on Asphalt Concrete Mixtures*. Fines on Asphalt Concrete Performance, ICAR 4th Annual Symposium.

Anjum, N., Prasad, S. L. A., Suresha, B. (2013). Role of Silicon Dioxide Filler on Mechanical and Dry Sliding Wear Behaviour of Glass-Epoxy Composites. *Advances in Tribology, Volume 2013*, Article ID 324952.

ASTM C 88 (1998). *Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate.* Annual Book of ASTM Standards, American Society for Testing and Material (ASTM), Philadelphia, USA.

ASTM C127 (1998). *Test Method for Specific Gravity and Absorption of Coarse Aggregate, Volume 04.03.* Annual Book of ASTM Standards, American Society for Testing and Material (ASTM), Philadelphia, USA.

ASTM C128 (1997). *Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate.* American Society for Testing and Material (ASTM), Philadelphia, USA.

ASTM C131 (1996), *Standard Test Method for Resistance to Degradation of Small Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine.* Annual Book of ASTM Standards, Vol. 04.08. American Society for Testing and Material (ASTM), Philadelphia, USA.

ASTM C136 (1981). *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates, Volume 04.02.* Annual Book of ASTM Standards, American Society for Testing and Material (ASTM), Philadelphia, USA.

ASTM C188 (1999). *Standard Test Method for Density of Hydraulic Cement.* Annual Book of ASTM Standards, Vol 04.01, American Society for Testing and Material (ASTM), Philadelphia, USA.

ASTM C 1252 (1993). *Standard Specification for Uncompacted Void Content of Fine Aggregate (As Influenced by Particle Shape, Surface Texture, and Grading.)* Philadelphia, PA: American Society for Testing and Materials.

ASTM D5 (1986). *Test Method for Penetration of Bituminous Material, Volume 04.03.* Annual Book of ASTM Standards, American Society for Testing and Material (ASTM), Philadelphia, USA.

ASTM D8-02 (2002). *Standard Terminology Relating to Materials for Roads and Pavements.* American Society for Testing and Materials, USA.

ASTM D36 (1986). *Test Method for Softening Point of Bituminous Material, Volume 04.03.* Annual Book of ASTM Standards, American Society for Testing and Material (ASTM), Philadelphia, USA.

ASTM D70 (1986). *Standard Test Method for Density of Semi-Solid Bituminous Materials (Pycnometer Method), Volume 04.03.* Annual Book of ASTM Standards, American Society for Testing and Material (ASTM), Philadelphia, USA.

ASTM D113 (1999). *Standard Test Method for Ductility of Bituminous Materials.* United States: American Society for Testing and Materials. (ASTM), USA.

ASTM D1559 (1982). *Test Method for Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus, Volume 04.03.* Annual Book of ASTM Standards, American Society for Testing and Material (ASTM), Philadelphia, USA.

ASTM D2041 (1992). *Standard Test Method for Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures.* American Society for Testing and Material (ASTM), Philadelphia, USA.

ASTM D2726 (1988). *Test Method for Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface Dry Specimen, Volume 04.03.* Annual Book of ASTM Standards, American Society for Testing and Material (ASTM), Philadelphia, USA.

ASTM D2872 (1997). *Standard Test Method for Effect of Heat and Air on a moving Film of Asphalt (Rooling Thin-Film Oven Test).* United States: American Society for Testing and Materials.

ASTM D3279 (1990). *Standard Test Method for n-Heptane Insoluble.* American Society for Testing and Materials.

ASTM D4123 (2002). *Standard Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures.* American Society for Testing and Materials, USA.

ASTM D4123-82 (1995). *Standard Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures, Volume 04.03.* Annual Book of ASTM Standards, American Society for Testing and Material (ASTM), Philadelphia, USA.

ASTM D4402 (1987). *Test Method for Viscosity Determinations of Unfilled Asphalts Using the Brookfield Thermo sell Apparatus, Volume 04.03.* Annual Book of ASTM Standards, American Society for Testing and Material (ASTM), Philadelphia, USA.

ASTM D4791 (1986). *Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate, Volume 04.03,* Annual Book of ASTM Standards, American Society for Testing and Material (ASTM), Philadelphia, USA.

ASTM D5821 (1996 d). *Standard Test Method for Determining the Percentage of Fractured Particles in Coarse Aggregate.* Annual Book of ASTM Standards, Vol. 04.08, American Society for Testing and Materials, USA.

ASTM D6390 (2005). *Standard Test Method for Determination of Drain down Characteristics in Uncompacted Asphalt Mixtures.* American Society for Testing and Materials, USA.

ASTM D6857 (2003). *Test Method for Maximum Specific Gravity and Density of Bituminous Paving Mixtures Using Automatic Vacuum Sealing Method.* American Society for Testing and Materials, USA.

Bahia, H. U., Anderson, D. A. (1995). *The Strategic Highway Research Program (SHRP) Binder Rheological Parameters: Why are They Required and How Do They Compare To Conventional Properties.* Transportation Research Board (TRB), pp 1-27.

Bahia, H. U., Zhai, H., Zeng, M., Hu, Y., Turner, P. (2001). Development of Binder Specification Parameters Based on Characterization of Damage Behavior. *Journal of the Association of Asphalt Paving Technologists, 70*: 442-470.

Becker, Y., Méndez, M. P., Rodríguez, Y. (2001). Polymer Modified Asphalt. *Vision Tecnologica, 9* (1): 39-50.

Beyer, G. (2002). Nanocomposites: A New Class of Flame Retardants for Polymers. *Plastics Additives and Compounding, 4*(10): 22-28.

Biswas, M., Ray S. S. (2001). Recent Progress in Synthesis and Evaluation of Polymer Montmorillonite Nanocomposites. *Adv Polym Sci; 155*: 167-221.

Blazejowski, K. (2010). *Stone Matrix Asphalt: Theory and Practice*. CRC Press; Book 1 Edition.

Blumstein, A. (1965). Polymerization of Adsorbed Monolayers. I. Preparation of the Clay-Polymer Complex. *Journal of Polymer Science Part A: General Papers 3*(7): 2653-2664.

Boyer, R. E. (1995). *Slurry and Mirco Surfacing Performance and Experiences*. Asphalt Institute Research Center, Thirty-Third Annual Conference of the International Slurry Surfacing Association.

Brown, E. R., Haddock, J. E. (1997). *A Method to Ensure Stone-on-Stone Contact in Stone Matrix Asphalt Paving Mixtures*. National Center for Asphalt Technology, NCAT Report No. 97-2.

Brown, E. R., Kandhal, P. S., Zhang, J. (2001). *Performance Testing for Hot-Mix Asphalt.* National Center for Asphalt Technology, NCAT Report 01-05.

Brown, E. R., Mallick, R. B. (1995). *Evaluation of Stone-on-Stone Contact in Stone-Matrix Asphalt.* Transportation Research Record 1492, TRB, National Research Council, Washington, DC, pp. 208-219.

Brown, E. R., McRae, J. L., Crawley, A. B. (1989). Effect of Aggregates on Performance of Bituminous Concrete. *American Society of Testing and Materials STP 1016*, Philadelphia, PA.

BS-EN 12697-25 (2005). *Standard Test Method for Determination of Resistance of Bituminous Mixtures to Permanent Deformation.* British and European Standard.

BS 3690-2 (1989). *Bitumens for Building and Civil Engineering.* Specification for Bitumens for Industrial Purposes. British Standard.

Bukowski, J. R. (1991). *Stone Mastic Asphalt Test and Evaluation*. Project No. 18. Office of Technology Applications, FHWA.

Bukowski, J. R. (1993). *SMA in America*. Paper Presented at the Annual Meeting of the Transportation Research Board, Washington, DC.

Bushing, H. W., Antrim, J. D. (1968). Fiber Reinforcement of Bituminous Mixtures. *Proceedings of the Association of Asphalt Paving Technologists, 37*, 629-659.

CAPA (2014). *Colorado Asphalt Pavement Association*. ***http://www.co-asphalt.com***.

Campbell, C. (1999). *The Use of Stone Mastic Asphalt on Aircraft Pavements. Research/Professional Practice Projects*, School of Engineering and Technology, Deakin University.

Chipperfield, E. H. (1984). *Bitumen Production properties and Uses in Relation to Occupational Exposures*. IARC Review on Bitumen Carcinogenicity. London, Institute of Petroleum. Report IP 84-006.

Chong, K. P. (2003). *Nano-scale Mechanics Research and Challenges*. Plenary Paper, Study of Matter at Extreme Conditions Conference, Miami Beach, FL.

Cooley, L A., Huner, M. S., James, R. S. (2002). *Micro-Deval Testing of Aggregates in the Southeast.* National Center for Asphalt Technology Auburn University, Alabama, NCAT Report No. 02-09.

Corbett, L. W. (1969). Composition of Asphalt Based on Generic Fractionation Using Solvent Deasphalteneing, Elution-Adsorption Chromatography and Densiometric Characterization. *Analytical Chemistry, 41*: 576-579.

CoreLok Operator's Guide (2011). InstroTek Incorporated, a Versatile Density System with Many Different Applications from U.S.

Cortizo, M. S., Larsen, D. O., Bianchetto, H., Alessandrini, J. L. (2004). Effect of the Thermal Degradation of SBS Copolymers during the Ageing of Modified Asphalts. *Polymer Degradation and Stability, vol. 86*, no. 2, pp. 275-282

Daly, W. H., Qiu, Z., Youngblood, J., Negulescu, I. (1994). Enhancing Reinforcement Effects of Polymers in Asphalt: An Applied Approach to Solid Waste Disposal. *Progress in Pacific Polymer Science 3*: 381-399.

Domone, P., Illston, J. (2010). *Construction Materials: Their Nature and Behaviour*. The Fourth Edition Book.

Eaton, R. A., Roberts, R. J., Blackburn, R. R. (1991). *Use of Scrap Rubber in Asphalt Pavement Surfaces.* Special Report 91-27, U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory.

Fang, C., Zhang, Y., Yu, R., Liu, X., Hu, J., Zhang, M. (2014). Effect of Organic Montmorillonite on the Hot Storage Stability of Asphalt Modified by Waste Packaging Polyethylene. *Journal of Vinyl and Additive Technology*, doi: 10.1002, vnl.21376.

FHWA (2000). *Superpave Fundamental Reference Manual.* Federal Highway Administration Research (FHWA), NHI Course No.131053, USA.

Gaestel, C., Smadja R., Lamminan, K. A. (1971). Contribution á la Connaissance des Propriétés des Bitumes Routiers, *Revue Générale des Routes et Aérodromes, 466*: 85-97.

Galooyak, S. S., Dabir, B., Nazarbeygi, A. E., Moeini, A. (2010). Rheological Properties and Storage Stability of Bitumen/SBS/Montmorillonite Composites. C*onstruction and Building Materials, 24*(3): 300-307.

Galooyak, S. S., Dabir, B., Nazarbeygi, A. E., Moeini, A., Berahman, B. (2011). The Effect of Nanoclay on Rheological Properties and Storage Stability of SBS-Modified Bitumen. *Petroleum Science and Technology, 29*: 850-859.

Gao, G., Zhang, Y., Zhang, Y., Sun, K., Fan, Y. (2002). Improved Storage Stability of LDPE/SBS Blends Modified Asphalts. *Polymer and Polymer Composites; 10*(3): 229-236.

Ghile, D. B. (2006). *Effects of Nanoclay Modification on Rheology of Bitumen and on Performance of Asphalt Mixtures*. Master Thesis. Delft University of Technology, Netherlands.

Giannelis, E. P. (1996). Polymer Layered Silicate Nanocomposites. *Advanced Materials, 8*(1): 29-35.

Giannelis, E. P., Krishnamoorti, R., Manias, E. (1999). Polymer-Silicate Nanocomposites: Model Systems for Confined Polymers and Polymer Brushes. *Advances in Polymer Science, Vol.138*. Springer-Verlag Berlin Heidelberg.

Giavarini, C. (1998). Polymer-Modified Bitumen, Asphaltenes and Asphalts. *Association of Asphalt Paving Technologists, Report number, 381*, pp 57-73.

Gilby, G. W. (1985). Ethylene Vinyl Acetate (EVA) Copolymers as Modifyers for Bitumen Binders. *Institute of Asphalt Technology*. p. 37-41.

Gilman, J. W. (1999). Flammability and Thermal Stability Studies of Polymer Layered-Silicate (Clay) Nanocomposites. *Applied Clay Science 15* (1999): 31-49.

Gilman, J. W., Kashiwagi, T., Brown, J. E. T., Lomakin, S. (1998). Flammability Studies of Polymer-Layered Silicate Nanocomposites. *The 43rd International Society for the Advancement of Material and Process Engineering (SAMPE) Symposium, 43*(1): 1053-1066.

Girdler, R. B. (1965). Constitution of Asphaltenes and Related Studies. *Proceeding of Association of Asphalt Paving Technologists, Vol 34*: 45-79.

Goh, S. W., Akin, M., You, Z., Shi, X. (2011). Effect of Deicing Solutions on the Tensile Strength of Micro- or Nano-Modified Asphalt Mixture. *Construction and Building Materials, 25*(1): 195-200.

Golestani, B., Nejad, F. M., Galooyak, S. S. (2012). Performance Evaluation of Linear and Nonlinear Nanocomposite Modified Asphalts. *Construction and Building Materials 35*: 197-203.

Goodrich, J. L., Goodrich, J. E., Kari, W. J., (1986). Asphalt Composition Tests: Their Application and Relation to Field Performance. *Transportation Research Record 1096*, pp 146-167.

Gul, W. A. (2008). *Effect of Recycled Cement Concrete Content on Rutting Behavior of Asphalt Concrete*. Master Thesis. Middle East Technical University.

HAAKE RheoStress Manual (2011). *The Versatile Rheometer Concept of HAAKE*, RheoStress RS1, Thermo Electron Corporation.

Hamzah, M. O., Puzi, M. A. A., Azizli, K. A. M. (2008). Properties of Geometrically Cubical Aggregates and its Mixture Design. *Journal of Radiation Research and Applied Sciences, JRRAS 3* (3).

Hamzah, M. O., Yi, T. C. (2008). Effects of Temperature on Resilient Modulus of Dense Asphalt Mixtures Incorporating Steel Slag Subjected to Short Term Oven Ageing. *World Academy of Science, Engineering and Technology Vol.2*.

Hansen, K. R., McGennis, R. B., Prowell, B., Stonex, A. (2000). Current and Future Uses of Non-Bituminous Components of Bituminous Paving Mixtures. *Transportation in the New Millennium TRB A2D02*, Washington, DC, USA.

Hanson, D. I., Graves, R. E., Brown, E. R. (1994). Laboratory Evaluation of the Addition of Lime Treated Sand to Hot-Mix Asphalt. *Transportation Research Record 1469*, pp.34-42

Heukelom, W. (1965). The Role of Filler in Bituminous Mixes. Proceedings, *Association of Asphalt Paving Technologists, Volume 34*, pp 396-429.

Heukelom W., Wijga, P. W. O. (1971). Viscosity of Dispersions as Governed by Concentration and Rate of Shear. *Journal of Technologists. Vol. 40.*

Hicks, R. G., Scholz, T. V. (2003). Life Cycle Costs for Lime in Hot Mix Asphalt. *Arlington, Virginia, USA: National Lime Association, Vol. 2.*

Hindustan Petroleum (2013). *HP Bitumen Handbook.* A Government of India Enterprise.

Huang, Y. H. (1993). *Pavement Analysis and Design.* Englewood Cliffs, New Jersey, Prentice Hall. First Edition Book.

Huber, G. A. (1999). *Methods to Achieve Rut-resistant Durable Pavements.* The National Cooperative Highway Research Program (NCHRP). Transportation Research Board, Pavements, Asphalt - 61 pages.

Hussain, F., Hojjati, M., Okamoto, M., Gorga, R. E. (2006). Review article: Polymer-matrix Nanocomposites, Processing, Manufacturing, and Application: An Overview. *Journal of Composite Materials, Vol. 40*, No. 17, 1511-1575.

Ibrahim, K., Yasreen, S. G., Madzlan, N. B. (2010). *The Effect of Fine Aggregate Properties on the Fatigue Behavior of the Conventional and Polymer Modified Bituminous Mixtures Using Two Types of Sand as Fine Aggregate.* Proceeding of Malaysian Universities Transportation Research Forum and Conferences, (MUTRFC2010).

Isacsson, U., Lu, X. (1999). Characterization of Bitumens Modified with SEBS, EVA and EBA Polymers. *Journal of Materials Science 34:* 3737-3745.

Isacsson, U., Lu, X. (1995). Testing and Appraisal of Polymer Modified Road Bitumens-State of Art. *Materials and Structures, 28*: 139-159.

Jahromi, S. G., Andalibizade, B., Vossough, S. (2010). Engineering Properties of Nanoclay Modified Asphalt Concrete Mixtures. *The Arabian Journal for Science and Engineering, Volume 35*, Number 1B.

Jahromi, S. G., Khodaii, A. (2008). Carbon Fiber Reinforced Asphalt Concrete. *The Arabian Journal for Science and Engineering, Volume 33*, Number 2B.

Jahromi, S. G., Khodaii, A. (2009). Effects of Nanoclay on Rheological Properties of Bitumen Binder. *Construction and Building Materials, 23*(8): 2894-2904.

- D Q N D X V N D L W ¡ 9 ä X N L H Q ¡ Thermoplastic Polyurethane/ Montmorillonite Nanocomposites. *Polymery i kompozyty konstrukcyjne: Monografia Cieszyn*, pp. 193-199.

Jasso, M., Bakos, D., Stastna, J., Zanzotto, L. (2012). Conventional Asphalt Modified by Physical Mixtures of Linear SBS and Montmorillonite. *Applied Clay Science 70*: 37-44.

Jia, Q. M., Zheng, M., Chen, H. X., Shen, R. J. (2005). Synthesis and Characterization of Polyurethane/ Epoxy Interpenetrating Network Nanocomposites with Organoclays. *Polymer Bulletin 54*(1-2): 65-73.

Jones, D. R. (1992). *An Asphalt Primer: Understanding How the Origin and Composition of Paving-Grade Asphalt Cements Affect Their Performance.* SHRP Asphalt Research Program Technical Memorandum No. 4. Strategic Highway Research Program. The University of Texas Austin, Texas.

Kamal, M. A., Shazib, F., Yasin, B. (2005). Resilient Behaviour of Asphalt Concrete under Repeated Loading and Effects of Temperature. *Journal of the Eastern Asia Society for Transportation Studies, Vol. 6*, pp. 1329-1343.

Kandahl, P. S. (1981). Evaluation of Baghouse Fines in Bituminous Paving Mixtures. *Proceedings of the Association of Asphalt Paving Technologists, Volume 50*: 150-210.

Kandhal, P. S. (2005). Selection of Bitumen for Paving Highways in India. *Indian Roads Congress, Indian Highways, 33*(7): 17-27.

Katicha, S. W. (2003). *Development of Laboratory to Field Shift Factors for Hot-Mix Asphalt Resilient Modulus*. Master Thesis, Faculty of the Virginia Polytechnic Institute and State University.

Khan, M. B., Khattak, A., Irfan, M., Ahmed, S. (2012). Factorial Design Approach to Investigate the Effect of Different Factors on the Resilient Modulus of Bituminous Paving Mixes. *ARPN Journal of Science and Technology, Vol. 2*, No. 11, pp 1055- 1062.

Kietzman, J. H. (1960). The Effect of Short Asbestos Fibers on Basic Physical Properties of Asphalt Pavement Mixes. *Highway Research Board, Bulletin No. 270*, pp. 1-19.

Kim, J. R., Drescher, A., Newcomb, D. E. (1991). *Rational Test Methods for Predicting Permanent Deformation in Asphalt Concrete Pavement: Final Report*. Department of Transportation. Office of Research Administration, University of Minnesota.

Kim, Y. R. (2009). *Modeling of Asphalt Concrete*. Book of McGraw-Hill Publishers, 1st Edn., The American Society of Civil Engineers (ASCE).

King, G., King, H., Pavlovich, R., Epps, A. L., Kandhal, P. (2001). Additives in Asphalt. *Journal of the Association of Asphalt Paving Technologists*. pp.32-69.

Kojima, Y., Usuki, A., Kawasumi, M., Okada, A., Fukushima, Y., Kurauchi, T., Kamigaito, O. (1993). Mechanical Properties of Nylon 6-Clay Hybrid. J*ournal of Materials Research, 8.* (05): 1185-1189.

Koklas, S. N., Kalfoglou, N. K. (1994). Effect of Block Copolymer Architecture on Compatibility 3. Expoxidized Styrene-Butadiene Block Copolymer with Polystyrene/ Chlorinated Polymer Blends. *Polymer, 35* (7): 1433-1441.

Koo, J. H. (2006). *Polymer Nanocomposites Processing, Characterization, and Applications*. McGraw-Hill Nanoscience and Technology Series.

Krauss, G. (1982). Modification of Asphalt Block Copolymers of Butadiene and Styrene. *Rubber Chem. Tech., vol. 55*: 1389-1402.

Lagaly, G. (1986). Interaction of Alkylamines with Different Types of Layered Compounds. *Solid State Ionics, 22*(1): 43-51.

Lamontagne, J., Dumas, P., Mouillet, V., Kister, J. (2001). Comparison by Fourier Transform Infrared (FTIR) Spectroscopy of Different Ageing Techniques: Application to Road Bitumens. *Science Direct, Fuel, 80*(4): 483-488.

Lan, T., Kaviratna, P. D., Pinnavaia, T. J. (1994). On the Nature of Polyimide-Clay Hybrid Composites. *Chemistry of Materials, 6*(5): 573-575.

Lee, D. C., Jang, L. W. (1996). Preparation and Characterization of PMMA-Clay Hybrid Composite by Emulsion Polymerization. *Journal of Applied Polymer Science, 61*(7): 1117-1122.

Lesueur, D., Little, D. N. (1998). Effect of Hydrated Lime on Rheology, Fracture, and Aging of Bitumen. *Transportation Research Record No. 1661*, pp 93-105.

Levine, D. M. Ramsey, P. P. Smidt, R. K. (2001). Applied Statistics for Engineers and Scientists Using Microsoft Excel and Minitab. *United States of America: Prentice Hall Publishing*.

Lewandowski, L. H. (1994). Polymer Modification of Paving Asphalt Binders. *Rubber Chemistry and Technology, vol.67,* No 3, 447-480.

Little, D. N., Lytton, R. L., Williams, D., Chen, C. W. (1997). *Fundamental Properties of Asphalts and Modified Asphalts*. Volume 1: Interpretive Final Report. FHWA, U.S. Department of Transportation.

Liu, G., van de Ven, M., Wu, S., Yu, J., Molenaar, A. (2011). Influence of Organo-Montmorillonites on Fatigue Properties of Bitumen and Mortar. *International Journal of Fatigue, 33*(12): 1574-1582.

Liu, G., Wu, S., van de Ven, M., Yu, J., Molenaar, A. (2010). Influence of Sodium and Organo-Montmorillonites on the Properties of Bitumen. *Applied Clay Science, 49*(1-2): 69-73.

Lu, X., lsacsson, U. (1998). Chemical and Rheological Evaluation of Ageing Properties of SBS Polymer Modified Bitumens. *Fuel, 77*(9-10): 961-972.

Lu, X., Isacsson, U. (2000). Modification of Road Bitumens with Thermoplastic Polymers. *Journal of Polymer Testing, 20* (1): 77-86.

Madejová, J., Janek, M., Komadel, P., Herbert, H. J., Moog, H. C. (2002). FTIR Analyses of Water in MX-80 Bentonite Compacted from High Salinary Salt Solution Systems. *Appl. Clay Sci, 20*(6): 255-71.

Madejová, J., Komadel P. (2001). Baseline Studies of the Clay Minerals Society Source Clays: Infrared methods. *Clays and Clay Minerals, 49*(5): 410-432.

Mahdi, L. M. J., Muniandy, R., Yunus, R., Hashim S., Aburkaba, E. (2013). Effect of Short Term Aging on Organic Montmorillonite Nanoclay Modified Asphalt. *Indian Journal of Science and Technology, 6*(11): 5434-5442.

Marateanu, M., Anderson, D. (1996). Time-Temperature Dependency of Asphalt Binders-an Improved Model. *Journal of the Association of Asphalt Paving Technology, 65*: 408-448.

Marais, C. P. (1979). *The Use of Asbestos in Trial Sections of Cap-Graded Asphalt and Slurry Seals*. Proceedings of the Third Conference on Asphalt Pavements for South Africa, Durban, pp. 172-175.

Masson, J. F., Pelletier, L., Collins, P. (2001). Rapid FTIR Method for Quantification of Styrene-Butadiene Type Copolymers in Bitumen. J*ournal of Applied Polymer Science, 79*(6): 1034-1041.

Mathew, T. V., Rao, K. V. K. (2006). *Introduction to Transportation Engineering*. Chapter 23, Pavement Materials: Bitumen. NPTEL.

McGennis, R. B., Anderson, R. M., Kennerdy, T. W., Solaimanian, M. (1995). *Background of SUPERPAVE Asphalt Mixture Design and Analysis.* U.S. Department of Transportation, Federal Highway Administration, Report No. FHWA-SA-95-003.

McGennis, R. B., Shuler, S., Bahia, H. U. (1994). *Background of Superpave Asphalt Binder Test Methods.* National Asphalt Training Center Demonstration Project 101. FHWA-SA-94-069.

Mehta, P. K. (1987). Natural Pozzolans: Supplementary Cementing Materials in Concrete. *CANMET Special Publication 86*: 1-33.

Merusi, F., Giuliani, F., Polacco, G. (2012). *Linear Viscoelastic Behaviour of Asphalt Binders Modified with Polymer/clay Nanocomposites*. SIIV-5th

International Congress-Sustainability of Road Infrastructures. Procedia-Social and Behavioral Sciences 53: 335-345.

Moavenzadeh, F., Soussou, J. E., Findakly, H. K. (1974). *Synthesis for Rational Design*. Volume II, Final Report for Federal Highway Association (FHWA) Contract 7776.

Mohammad, L. N., Negulescu, I. I., Wu, Z., Daranga, C., Daly, W. H., Abadie, C. (2003). Investigation of the Use of Recycled Polymer Modified Asphalt Binder in Asphalt Concrete Pavements. *Journal of the Association of Asphalt Paving Technologists 72*: 551-594.

Monismith, C. L., Epps, J. A., Finn, F. N. (1985). Improved Asphalt Mix Design. *Journal of the Association of Asphalt Paving Technologists, Vol. 54*, pp 347-406.

Monismith, C. L., Tayebeli, A. A. (1988). Permanent Deformation Considerations in Asphalt Pavement Sections. *Journal of the Association of Asphalt Paving Technologists, 57*: 414-463.

Morgen, P., Mulder, A. (1995). *The Shell Bitumen Industrial Handbook.* Shell Bitumen Publications, London.

Muniandy, R., M. J., L., Yunus, R., Hasham, S., and Aburkaba, E. (2013). Effect of Organic Montmorillonite Nanoclay Concentration on the Physical and Rheological Properties of Asphalt Binder. *Australian Journal of Basic and Applied Sciences, 7*(9): 429-437.

Muniandy, R., Mahdi, L. M. J., Yunus, R., Hasham, S., and Aburkaba, E. (2013). Characterization of Organic Montmorillonite Nanoclay Modified Asphalt Binders Using Dynamic Shear Rheometer (DSR). *Australian Journal of Basic and Applied Sciences, 7*(14): 300-310.

Muniandy, R., Mahdi, L. M. J., Yunus, R., Hasham, S., and Aburkaba, E. (2013). Influence of Clay Nanoparticles on the Physical and Rheological Characteristics of Short Term Aged Asphalt Binder. *Australian Journal of Basic and Applied Sciences, 7*(11): 488-498.

NAPA (1994). *Guidelines for Materials, Production, and Placement of Stone Mastic Asphalt.* National Asphalt Pavement Association, Information Series 118, 8/94.

NAPA (1999). *Designing and Constructing SMA Mixtures: State of the Practice.* National Asphalt Pavement Association.

NCHRP Report 465 (2002), *Simple Performance Test for Superpave Mix Design.* National Center for Asphalt Technology.Washington, D.C.

NCHRP Report 285 (2004). *Laboratory Determination of Resilient Modulus for Flexible Pavement Design.* National Center for Asphalt Technology. Washington, D.C.

Nellensteyn, F. J. (1924). The Constitution of Asphalt. J*ournal of the Institute of Petroleum Technology 10*: 311.

Nien, Y. H., Yeh, P. H., Chen, W. C., Liu, W. T., Chen, J. H. (2008). Investigation of Flow Properties of Asphalt Binders Containing Polymer Modifiers. *Polymer Composites, 29*: 518-524.

Okada, A., Kawasumi, M., Usuki, A., Kojima, Y., Kurauchi, T., Kamigaito, O. (1990). Nylon 6-Clay Hybrid. *Materials Research Society Symposium Proceedings, 171*: 45-50.

Okada, A., Usuki, A. (2006). Twenty Years of Polymer Clay Nanocomposites. *Macromolecular Materials and Engineering, 291*(12): 1449-1476.

Oscarsson, E. (2007). Prediction of Permanent Deformations in Asphalt Concrete Using the Mechanistic-Empirical Pavement Design Guide. *Transport and Roads, Thesis, Volume Bulletin 236*/3000.

OSU (2014). Oregon State University. College of Engineering (COE) Online Classes. *classes.engr.oregonstate.edu/cce/spring*.

Ouyang, C., Wang, S., Zhang, Y., Zhang, Y. (2005). Preparation and Properties of Styrene Butadiene Styrene Copolymer/Kaolinite Clay Compound and Asphalt Modified with the Compound. *Polymer Degradation and Stability, 87*(2): 309-317.

Papagiannakis, A. T., Masad, E. A. (2007). *Pavement Design and Materials.* Handbook of John Wiley and Sons Publishers, First Edition.

Patel, H. A., Somani, R. S., Bajaj, H. C., Jasra, R. V. (2006). Nanoclays for Polymer Nanocomposites, Paints, Inks, Greases and Cosmetics Formulations, Drug Delivery Vehicle and Waste Water Treatment. Bull. I*ndian Academy of Sciences, Mater. Sci., Vol. 29*, No. 2, pp. 133-145.

Paul, D. R., Robeson, L. M. (2008). Polymer Nanotechnology: Nanocomposites. *Polymer, 49*(15): 3187-3204.

Pavement Interactive (2012). Guidance Pavement-Distress, *Accessed: October 2012. http://www.pavementinteractive.org/article/general.*

Pavement Interactive (2010). Milling to Prepare Existing Surfaces, Prevention of Re-Rutting and/or Cracking. **http://www.pavementinteractive.org**.

Pavlidou, S., Papaspyrides, C. D. (2008). A Review on Polymer–Layered Silicate Nanocomposites. *Progress in Polymer Science, 33*(12): 1119-1198.

Peltonen, P. V. (1991). Characterization and Testing of Fibre-Modified Bitumen Composites. *Journal of Materials Science 26*: 5618-5622.

Petersen, J. C. (1984). Chemical Composition of Asphalt as Related to Asphalt Durability: State of the Art. *Transportation Research Record No. 999*: 13-30.

Petersen, J. C., Robertson, R. E., Branthaver, J. F., Harnsberger, P. M., Duvall, J. J., Kim, S. S., Anderson, D. A., Christiansen, D. W., Bahia, H. U. (1994). *Binder Characterization and Evaluation* Volume 1. SHRP-A-367. Strategic Highway Research Program National Research Council Washington, D.C.

Pfeiffer, J. P., Saal, R. N. J. (1940). Asphaltic Bitumen as Colloidal Systems. *The Journal of Physical Chemistry, 44*(2): 139-149.

3 R O D F F R * . U ß t] ß 3) L O Rheological Properties of Asphalt/SBS/Clay Blends. *European Polymer Journal. 44* (11): 3512-3521.

Polacco, G., Stastna, J., Biondi, D., Zanzotto, L. (2006). Relation between Polymer Architecture and Nonlinear Viscoelastic Behavior of Modified Asphalts. *Current Opinion in Colloid and Interface Science, 11*(4): 230-245.

Qi, Z. G., Shang, W. Y. (2002). Theory and Practice of Polymer/ Layered Silicate Nanocomposites. *Chinese Chemical Industry Press: China. 105*, p. 79.

Raju, B. R., Swamy, R. P., Suresha, B., Bharath, K. N. (2012). The Effect of Silicon Dioxide Filler on the Wear Resistance of Glass Fabric Reinforced Epoxy Composites. Advances in Polymer Science and Technology: *An International Journal; 2*(4): 51-57.

Rasmussen, R. O., Lytton, R. L., Chang, G. K. (2002). Method to Predict Temperature Susceptibility of an Asphalt Binder. *Journal of Materials in Civil Engineering, 14*: 246-252.

Ray, S. S., Okamoto, M. (2003). Polymer/Layered Silicate Nanocomposites: A Review from Preparation to Processing. *Progress in Polymer Science 28*: 1539-1641.

Read, J., Whiteoak, D. (2003). *The Shell Bitumen Handbook*. Fifth Edition. Shell Bitumen UK.

Redelius, P. G. (2006). The Structure of Asphaltenes in Bitumen. *Road Materials and Pavement Design. EATA* 2006, pages 143-162.

Reubush, S. D. (1999). *Effects of Storage on the Linear Viscoelastic Response of Polymer - Modified Asphalt at Intermediate to High Temperatures.* Faculty of the Virginia Polytechnic Institute and State University, Master Thesis.

Roberts, F. L., Kandhal, P. S., Brown, E. R., Lee, D. Y., Kennedy, T. W. (1996). *Hot Mix Asphalt Materials, Mixture Design, and Construction.* NAPA Education Foundation. Lanhan, Maryland. Second Edition.

Roberts, F. L., Mohammad L. N., Wang, L. B. (2002). History of Hot Mix Asphalt Mixture Design in the United States. *Journal of Materials in Civil Engineering, 14*(4): 279-293.

Robertson, R.E. (1991). *Chemical Properties of Asphalts and Their Relationship to Pavement Performance.* Strategic Highway Research Program National Research Council Washington, D. SHRP-A/UWP-91-510.

Robinson, R., Thagesen, B. (2004). *Road Engineering for Development*. Second Edition Book. Taylor and Francis Group.

Rosinger, A. (1914). Beiträge zur Kolloidchemie des Asphalts. *Kolloid-Zeitschrift 15*(5): 177-179.

Salamon, A. W., Courtney P. and Shuttler, I. (2010). A Primer. Nanotechnology and Engineered Nanomaterials. **www.perkinelmer.com**.

Sebaaly, P. E. (2007). Comparison of Lime and Liquid Additives on the Moisture Damage of Hot Mix Asphalt Mixtures. *National Lime Association.*

Serfaas, J. P., Joly, A., Samanos, J. (1992). *SBS-Modified Asphalts for Surface Dressing- A Comparison between Hot-Applied and Emulsified Binders. Polymer Modified Asphalt Binders.* ASTM STP 1108. American Society for Testing Materials, Philadelphia, 281-308.

Serfass, J. P., Samanos, J. (1996). Fiber-Modified Asphalt Concrete Characteristics, Applications and Behavior. *Journal of the Association of Asphalt Paving Technologists, 65*:193-230.

Shahabadi, A. Z., Shokuhfar, A., Nejad, S. E. (2010). Preparation and Rheological Characterization of Asphalt Binders Reinforced with Layered Silicate Nanoparticles. *Construction and Building Materials, 24*(7): 1239-1244.

SHRP-A-341 (1993). *Fundamental Properties of Asphalt-Aggregate Interactions Including Adhesion and Absorption.* Strategic Highway Research Program National Research Council Washington, DC.

SHRP-A-367 (1994). *Binder Characterization and Evaluation, Strategic Highway Research Program.* National Research Council, Washington, D.C, vol 1, 37-38.

SHRP-A-410 (1994). *Superior Performing Asphalt Pavements (Superpave): The Product of the SHRP Asphalt Research Program.* Strategic Highway Research Program, National Research Council, Washington, D.C, 29-33.

Siddiqui, M. N., Ali, M. F. (1999). Studies on the Aging Behaviour of the Arabian Asphalts. *Fuel, 78*(9): 1005-1015.

Sureshkumar, M. S., Filippi, S., Polacco, G., Kazatchkov, I., Stastna, J., Zanzotto, L. (2010). Internal Structure and Linear Viscoelastic Properties of EVA/Asphalt Nanocomposites. *European Polymer Journal, 46*(4): 621-633.

The Asphalt Institute (2007). *The Asphalt Handbook.* Manuel Series No: 4 (MS-4) Seventh Editions. Lexington, KY: The Asphalt Institute.

The Royal Society (2004). *Nanoscience and Nanotechnologies: Opportunities and Uncertainties.* The Royal Society and the Royal Academy of Engineering. *London.* ***http://www.royalsoc.ac.uk***.

The Southern African Bitumen Association (Sabita) (2007). *Bituminous Binders for Road Construction and Maintenance.* Manual 2, Fourth Edition, August 2007.

Theng, B. K. G. (1979). Formation and properties of clay-polymer complexes. *Journal of Plant Nutrition and Soil Science, 143*(3): 359-1980.

Thostenson, E. T., Li, C., Chou, T. W. (2005). Review Nanocomposites in context. *Composites Science and Technology, 65*: 491-516.

Tia, M. (2003). *Bituminous Materials and Mixtures*. Civil Engineering Handbook, Second Edition, Chapter 45, CRC Press, Inc., Boca Raton, Florida, pp. 18.

Tutumluer, E. (2005). *Stress Rotations Due to Moving Wheel Loads and Their Effects on Pavement Materials Characterization.* OMP Brown Bag Seminar Presentation. FAA Center of Excellence for Airport Technology-Advanced Testing and Material Modeling.

Vaia, R. A., Teukolsky, R. K., Giannelis, E. P. (1994). Interlayer Structure and Molecular Environment of Alkyl-Ammonium Layered Silicates. *Chemistry of Materials, 6* (7): 1017-1022.

van de Ven, M. F. C., Molenaar, A. A. A. (2009). Nanoclay for Binder Modification of Asphalt Mixtures. In A. Loizos, M. N. Part l. *Advanced Testing and Characterization of Bituminous Materials*, pp 133-142. *London: Taylor and Francis Group.*

Van der Poel, C. (1954). A General System Describing the Viscoelastic Properties of Bitumen and Its Relation to Routine Test Data. *Journal of Applied Chemistry, Vol. 4*, pp. 221-236.

Wang, K. H., Choi, M. H., Koo, C. M., Choi, Y. S., Chung, I. J. (2001). Synthesis and Characterization of Maleated Polyethylene/Clay Nanocomposites. *Polymer, 42*(24): 9819-9826.

Wang, L., Masad, E. (2006). Analysis of Asphalt Pavement Materials and Systems: Emerging Methods. *Proceedings of the Symposium on the Mechanics of Flexible Pavements, Boulder, Colorado.*

Wang, S., Zhang, Y., Zhang, Y. (2003). SBS/Carbon Black Compounds Give Asphalts with Improved High-Temperature Storage Stability. *Polymer and Polymer Composites, 11*(6): 477-485.

Wardlaw, K. R., Shuler, S. (1992). *Polymer Modified Asphalt Binders.* Issue 1108. ASTM International.Technology and Engineering - 361 pages.

Wen, G., Zhang, Y., Zhang, Y. (2002). Improved Properties of SBS-Modified Asphalt with Dynamic Vulcanization. *Polymer Engineering and Science, Vol. 42*, No. 5.

Whiteoak, D. (1991). *The Shell Bitumen Handbook*. Shell Bitumen UK. Chapter 10.

Witczak, M. W., Kaloush, K. E., Pellinen, T., El-Basyouny, M., Quintus, V. H. (2002). *Simple Performance Test for Superpave Mix Design.* NCHRP Report 465. Transportation Research Board. National Research Council. Washington D.C.

WSDOT (2000). Washington State Department of Transportation. Tech Notes on Stone Matrix Asphalt (SMA). *http://www.wsdot.wa.gov.*

Wu, S., Pang, L., Mo, L., Chen, Y., Zhu, G. (2009). Influence of Aging on the Evolution of Structure, Morphology and Rheology of Base and SBS Modified Bitumen. *Construction and Building Materials, 23*(2): 1005-1010.

Wu, S., Wang, J., Jiesheng, L. (2010). *Preparation and Fatigue Property of Nanoclay Modified Asphalt Binder*. International Conference on Mechanic Automation and Control Engineering (MACE), pp 1595-1598.

Xi, Y., Frost, R., Hongping H. (2007). Modification of the Surfaces of Wyoming Montmorillonite by the Cationic Surfactants Alkyl Trimethyl, Dialkyl Dimethyl and Trialkyl Methyl Ammonium Bromides. *Journal of Colloid and Interface Science 305*: 150-158.

Xie, W., Gao, Z., Liu, K., Pan, W. P., Vaia, R., Hunter, D., Singh, A. (2001). Thermal Characterization of Organically Modified Montmorillonite. Material Characterization by Thermal Analytical Methods. *Thermochimica Acta, Volumes 367-368*, Pages 339-350.

Xu, R., Manias, E., Snyder, A. J., Runt, J. (2001). New Biomedical Poly (Urethane Uera)-Layered Silicate Nanocomposites. *Macromolecules, 34*: 337-339.

Yu, J., Feng, P., Zhang, H., Wu, S. (2009). Effect of Organo-Montmorillonite on Aging Properties of Asphalt. *Construction and Building Materials, 23*(7): 2636-2640.

Yu, J., Wang, L., Zeng, X., Wu, S., Li, B. (2007). Effect of Montmorillonite on Properties of Styrene-Butadiene-Styrene Copolymer Modified Bitumen. *Polymer Engineering and Science. 47*(9): 1289-1295.

Yu, J., Zeng, X., Wu, S., Wang, L., Liu, G. (2007). Preparation and Properties of Montmorillonite Modified Asphalts. *Materials Science and Engineering, 447*(1-2): 233-238.

Yuehong, M., Jianxi, Z., Hongping, H., Peng, Y., Wei, S., Dong, L. (2010). Infrared Investigation of Organo-Montmorillonites Prepared from Different Surfactants. *Spectrochimica Acta Part A 76*(2): 122-129.

Zacharias, M. P., Emery, S. J. (1994). *Application of the Brookfield Viscometer Test Method in South African Road Grade Bitumen Specifications.* 6th Conference on Asphalt Pavements for Southern Africa, Vol. 2, pp. V109-V123, Cape Town.

Zetasizer Nano Series User Manual (2007). Malvern Instruments Ltd. United Kingdom. MAN0317 Issue 3.1.

Zhang, B., Xi, M., Zhang, D., Zhang, H., Zhang, B. (2009). The Effect of Styrene-Butadiene-Rubber/Montmorillonite Modification on the Characteristics and Properties of Asphalt. *Construction and Building Materials. 23*(10): 3112-3117.

Zoorob, S. E., Suparma, L. B. (2000). Laboratory Design and Investigation of the Properties of Continuously Graded Asphaltic Concrete Containing Recycled Plastics Aggregate Replacement (Plastiphalt). *Cement and Concrete Composites, 22*(4): 233-242.