BINDER CHARACTERIZATION AND PERFORMANCE OF WARM STONE MASTIC ASPHALT MIXTURE

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"I dedicated this thesis to my late father, Amb. Suleiman Yero and late mother, Hajia Fatima Babagana, and to my be loved family for their awesome support and patience"

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ABSTRACT

The conventional stone mastic asphalt (SMA) is normally produced at high temperature (180^{o}C) that consumes fuel, increases cost, and generates heat with emissions of green house gases. This study investigated the potential of producing stone mastic asphalt at lower temperature (130^{o}C) termed as warm stone mastic asphalt (WSMA) against the normal high mixing temperature. Three grades of bitumen 80/100, 60/70 and PG 76-22 were investigated. A long chain aliphatic hydrocarbon Sasobit wax (SW) was used as an additive to reduce the mixing temperature. The Sasobit wax was incorporated at 0.5%, 1%, 1.5%, 2%, 2.5% and 3% of bitumen content. The empirical tests were conducted on 105 samples of the three binder types, which include penetration test at 10^{o}C and 25^{o}C. Softening point test, dynamic viscosity (DV) at 135^{o}C and kinematic viscosity (KV) at 60^{o}C were conducted to determine the penetration index (PI) and penetration viscosity number (PVN). The results indicate the modified bitumen has better resistance to temperature susceptibility with the additive and better resistance to rutting as it decreases the viscosity of the binder at high temperatures and produces high stiffness modulus as compared to the base bitumen. The study also investigated 126 samples for rheology test of the bitumen using the rolling thin film oven test (RTFOT), pressure aging vessel (PAV), and dynamic shear rheometer (DSR). The results from these tests at high test temperature indicate higher complex shear modulus ($G^*/\sin\delta$) with low phase angle (increase stiffness) for aged modified binders indicating better resistance to rutting damage, while at low test temperature they exhibit low complex modulus with high phase angle (decrease stiffness) indicating better resistance to fatigue. The testing on the compatibility and morphology of the modified binders using the scanning electron microscopy test (SEM) were also conducted. The results show the homogeneity of the binder with Sasobit as is completely soluble in the binder with no agglomeration. The study investigated the effect of the warm asphalt additive on the binder aging using Fourier transformation infrared test (FTIR). The results show an insignificant impact on the binder aging. The study prepared and investigated 225 samples of SMA14 and WSMA14 mixtures using the Marshall mix design. The flow and stability tests conducted on the WSMA mixtures show values higher than the minimum JKR/SPJ/2008-S4 specification for SMA in Malaysia with less than 2.5% Sasobit in the three binder sourced investigated. The study recommends up to 2% Sasobit for PEN 80/100, up to 1.5% for PEN 60/70 and 1% for PG 76-22. Based on the penetration test conducted, the two modified PEN bitumen can be categorized as PG 76-22. Also the performance test on the asphalt mix with Sasobit that include rutting and resilient modulus test indicated resistance to rutting damage. Thus, it can be concluded that the Sasobit wax improves bitumen performance, decreases asphalt production temperatures and is feasible to be used in the production of WSMA.

ABSTRAK

Stone mastic asphalt (SMA) konvensional dihasilkan pada suhu campuran yang tinggi iaitu 180^{o}C. Ini akan mengakibatkan peningkatan penggunaan bahan api, penghasilan haba dan pelepasan gas rumah hijau. Kajian ini dijalankan untuk mengkaji potensi penghasilan stone mastic asphalt pada suhu campuran yang lebih rendah berbanding suhu campuran normal iaitu 130^{o}C. Campuran ini dinamakan warm stone mastic asphalt (WSMA). Tiga gred bitumen digunakan dalam kajian ini iaitu gred 80/100, 60/70 dan PG 76-22. Rantaian panjang alifatik hidrokarbon lilin Sasobit wax (SW) digunakan sebagai bahan tambah untuk mengurangkan suhu campuran. Lilin Sasobit dicampukan pada kadar 0.5%, 1%, 1.5%, 2%, 2.5% dan 3% daripada kandungan bitumen. Ujian-ujian empirical telah dijalankan ke atas 105 sampel yang mewakili ketiga-tiga jenis bitumen tersebut. Ujian-ujian yang dijalankan adalah ujian penusukan pada suhu 10^{o}C dan 25^{o}C, ujian titik lembut, ujian kelikatan dinamik (DV) pada suhu 135 ^{o}C dan kelikatan kinematik (KV) pada suhu 60 ^{o}C yang bertujuan untuk mementukan indeks penusukan (PI) dan nombor kelikatan penusukan (PVN). Keputusan menunjukkan bitumen yang diubahsuai dengan bahan tambah mempunyai rintangan yang lebih baik terhadap suhu dan perpalohan. Ini disebabkan bahan tambah tesebut dapat mengurangkan kelikatan pengikat pada suhu tinggi dan menghasilkan modulus kekerasan yang tinggi berbanding bitumen asas. Ujian-ujian reologi turut dijalankan ke atas 126 sampel bitumen yang melibatkan ujian Rolling Thin Film Oven (RTFOT), Pressure Aging Vessel (PAV), dan Dynamic Shear Rheometer (DSR). Keputusan ujian bagi pengikat tua (aged binder) pada suhu tinggi menunjukkan modulus ricih kompleks ($G^*/\sin\delta$) yang tinggi dengan sudut fasa yang rendah (kekerasan meningkat). Ini menunjukkan rintangan yang lebih baik terhadap perpalohan. Manakala, ujian pada suhu rendah mencatatkan modulus ricih kompleks yang rendah dengan sudut fasa yang tinggi (kekerasan menurun). Ini menunjukkan rintangan yang lebih baik terhadap kelesuan (fatigue). Ujian kesesuaian dan morfologi ke atas pengikat diubahsuai turut dijalankan dengan menggunakan ujian pengimbasan mikroskopi electron (SEM). Keputusan ujian menunjukkan keseragaman pengikat dan Sasobit di mana Sasobit larut di dalam pengikat tanpa ada penggumpalan. Selain itu, kajian kesan penuaan pengikat terhadap bahan tambah asfal sederhana panas (warm asphalt) dengan menggunakan ujian transformasi inframerah fourier (FTIR). Keputusan ujian menunjukkan kesan yang tidak ketara pada penuaan pengikat. Kajian terhadap 225 sampel SMA14 dan WSMA14 menggunakan rekabentuk Marshall turut dijalan. Keputusan ujian aliran dan kestabilan menunjukkan campuran WSMA diubahsuai bagi ketiga-tiga jenis bitumen dengan 2.5% Sasobit masing-masing mematuhi spesifikasi JKR/SPJ/2008-S4. Kajian ini mencadangkan 2% Sasobit untuk bitumen 80/100 PEN, 1.5% untuk bitumen 60/70 PEN dan 1% untuk bitumen PG 76-22. Ujian prestasi terhadap perpalohan dan resilient modulus bagi campuran diubahsuai ini menunjukkan campuran ini mematuhi spesifikasi yang telah ditetapkan. Kesimpulan dari kajian ini membuktikan lilin Sasobit dapat meningkatkan prestasi bitumen, mengurangkan suhu campuran asphalt dan boleh dipraktikkan dalam penghasilan WSMA.

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LIST OF SYMBOLS AND ABBREVIATION

AAPA	Australian Asphalt Pavement Association
AASHTO	American Association of State Highway and Transport Officials
AC	Asphaltic concrete
ASTM	American Society for Testing and Material
BBR	Bending Beam Rheometer
BS	British Standard
^{o}C	Celsius, Centigrade
Cc	Coeffient of confidence
cm	centi metre
Cp	centi poise
Cst	centi stokes
dmm	decimillimetre
DGA	Dense graded asphalt mix
DSR	Dynamic Shear Rheometer
$G^{*}.\sin\delta$	fatigue factor
g	gram
HMA	Hot-Mix Asphalt
GHz	Giga hertz
G_{mb}	Bulk specific gravity
G_{mm}	Maximum theoretical specific gravity
G*	Complex shear modulus
JKR	Jabatan Kerja Raya (Public Works Department)
km	kilometre

kN	kilo Newton
kPa	kilo Pascal
m	meter
MRD	Mean rut depth
MMS	Mean Marshall stability
mg	milligram
min	minutes
ml	millilitre
MPa	Mega Pascal
mN	milli-Newton
M_R	resilient modulus
ms	milli seconds
NAASRA	National Association of Australian State Road Authorities
NCAT	National Center for Asphalt Technology
NAPA	National Asphalt Paving Association
N	Newton
OBC	Optimum bitumen content
P	Pressure
PA	Porous Asphalt
PG	Performance Grade
Pa.s	Pascal seconds
δ	Phase angle
PI	Penetration Index
PVN	Penetration-viscosity number
R	Coefficient of correlation
R^2	R-square = coefficient of determination
rad	radian
rpm	revolution per minute
$G^*/\sin\delta$	rut factor
s	seconds
SW	Sasobit wax

SE	Standard error
SSD	Saturated-surface-dry
SMA14	Stone Mastic Asphalt with nominal maximum aggregate size of 12.5mm
SGcoarse	Bulk specific gravity of coarse aggregate
SGfiller	Bulk specific gravity of mineral filler
SGfine	Bulk specific gravity of fine aggregate
SG	specific gravity
SMA	Stone Mastic Asphalt
TMD	Theoretical maximum density
UTM	Universiti Teknologi Malaysia
UTHM	Universiti Tun Hussein Onn Malaysia
VFB	Voids filled with bitumen
VMA	Voids in mineral aggregate
VTM (Va)	Voids in total mix
WA	Water absorption
WMA	Warm mix aspalt
WSMA	Warm stone mastic asphalt

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CHAPTER I

INTRODUCTION

1.1 Background

The history of transportation, either by land, sea, or air is as old as the human civilization. The road transportation has been the main means of transporting goods and services over years all over the world and can be related to the history of mankind. The Romans started the design and construction of the ancient roads that transform to the current asphalt technology. The pavement transformation from localize concept to the progressive roadway materials and construction procedures practice in countries all over the world to provide travel path. In a developing nation like Malaysia with over 91,620 km roads [1], these roads are the major means of transportation, and they are constructed based on regulated procedures provided by the Public Works Department of Malaysia (PWD). Some developed countries like the United State of America with effective means of transportation, has highway spanning over 4.02 million km of pavement [2].

Basically the road pavement can be divided into flexible and rigid, the flexible pavement comprises layers of sub-base, road base and the wearing course, which are made up of bitumen and aggregate. While the rigid pavement is mostly constructed with reinforced concrete and not widely used in the road transportation system.

In a country like Malaysia only 3,651 km (3.99%) of the paved roads are made of rigid pavement, while the flexible pavements make up to 87,626 km (95.64%)[1]. These flexible pavements are mostly constructed using the conventional hot mix asphalt (HMA) technology at high mixing (160^{o}C) and compaction (140^{o}C) temperatures [3].

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The HMA is mainly used as the paving material, it consists of aggregate and bitumen (binder), which are heated and mixed together. The process of producing the HMA involves heating the binder to a high temperature before mixing with the aggregate, hot mix asphalt concrete composed of two components: binder and aggregate. About 94 – 96% by weight of the mix consists of aggregate, and the remaining 4 – 6% by weight consists of binder [3]. Although the percentage of the binder is relatively small, the asphalt binder influences pavement performance more than the aggregate as environmental factors, such as high temperature due to solar radiation, affects the binder more than the aggregate.

In Malaysia the adoption of the stone mastic asphalt (SMA) is in its early stage, and is considered to be a pavement with good resistance properties to rutting damage. The SMA pavement is sometimes called Stone Matrix Asphalt in most European countries. SMA is a design pavement developed in the 1980s in Europe as an impervious wearing surface to provide resistance to rut and durable pavement surface. Stone mastic asphalt was introduced to resist studded tires effects rather than other type of hot mix asphalt in most European countries [4].

The design of the SMA surfacing is basically to resist deformation particularly rutting and maximize durability by using a stone-on-stone skeleton. The SMA consists of high stone content and the voids of the structural matrix filled with viscous bitumen matrix. SMA has high stone content of at least 70%, with good stone-on-stone contact after compaction. The required degree of matrix stiffness is achieved through the addition of crushed sand [4]. The SMA stone-on-stone contact skeleton significantly reduces rutting. The aggregate skeleton in SMA is all in contact, and hence the resistance to rut damage by the pavement depends on the aggregate interlock properties rather than the binder properties. Since under loading the bitumen deform more than the aggregate [4].

There are several types of polymers used in asphalt binders today, currently, the most commonly used polymer for bitumen modification is the styrene butadiene styrene (SBS) followed by other polymers such as crumb rubber, styrene butadiene rubber (SBR), ethylene vinyl acetate (EVA) and polyethylene [4]. SBS behaves like elastic rubbers at ambient temperature and it can be processed like plastics when heated (thermoplastic elastomer).

The various studies conducted on the use of polymer modification in bitumen (PMB) used in paving indicated great improvement in the performance of the modified binders, though possible problems can occur during paving operations. In general, asphalt mixtures produced with PMB binders are normally mixed and compacted at a higher temperature (180^0C), because of their high viscosity properties, than conventional mixtures. Furthermore, the polymers can be destroyed by the temperature being too high during mixing or by being held at an elevated temperature for a long period of time after mixing [5].

However, with lower mixing and compaction temperatures, the PMB mixtures might result in several problems such as inadequate volumetric properties (i.e., high air voids) and poor short-term and long-term performance. The high mixing temperature could result to health problems described by some road crews in Australia, presumably caused by the fumes, included vomiting, nausea, headaches, sore throats and sore eyes. Most of the problems were observed to be experienced when the SBS was used as a modifier [6].

The HMA mixture is classified into dense graded mixes such as asphalt concrete wearing (ACW), gap graded stone mastic asphalt, and open graded mixes include porous asphalt (PA). The SMA mixtures in Malaysia are produced using the conventional HMA process but at a higher mixing and compaction temperatures of 180^0C and 150^0C respectively, based on the Public Works Department of Malaysia (PWD).

The conventional process of producing SMA generates heat, emission and the primary source of emission in asphalt process is the mixers, dryers and hot bins that emit particulate matter such as dust, smoke, and exhaust vapour and other gaseous pollutant. The emissions contain substances such as reactive organic gases (ROGs) and particulate matter (PM). The ROGs emitted involve a wide cross section of contaminants including volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOC's) including polynuclear aromatic hydrocarbons (PAHs), aromatics and aliphatic. They (ROGs) also play a key role in smog formation and visibility degradation [7]. Particulate matters (PM) often referred to as aerosols, are of particle sizes fewer than 2.5 to 10 microns and are often adhered to by ROGs. These particles affect air quality because they can be irreversibly trapped in the pulmonary tract, and also a source of pollution.

The sustainability, of the environment is of major concern these days, and it involves the creation and maintenance of conditions under which humans and nature can exist harmoniously, while fulfilling social and economical requirements. These requirements include the reduction of emissions and the alleviation of its effects on human health and the environment. The modification of bitumen and different asphalt mixing procedures has been studied and practiced for ages but the current environmental policies renewed interest in proffering for green and sustainable pavements [8], and this could be attributed to the following;

- Reduction of emission in green house gases
- Reduction in the release of particulate dust
- Increasing a better performance of pavement
- High cost of fuel globally
- Improve workability
- Longer haulage distance opportunities
- Conducive working environment

1.2 Problem Statement

The SMA mixtures are normally designed to provide pavement with good resistance to rutting, with high coarse aggregate content, fines and modified binder. The stone mastic asphalt is normally produced using the conventional HMA procedure at high temperature (180^0C) and also compacted at high temperature (150^0C). This generates heat, consumes fuel, emits greenhouse gases that affects the environment and also makes the working environment very unfriendly. As the production of SMA consist of the use of polymer modified binders such as PG 76-22 that arise from the high temperature demands and fume emissions during operations (i.e., mixing and compaction). These issues involve possible effects on human health, a negative environmental impact and the increased fuel costs. Recently, the new warm mix asphalt (WMA) technology has been used to alleviate some of these problems. Previous researches conducted reviewed SMA mixtures using the HMA process. Hence there is a need to study and investigate a more sustainable process for SMA using the WMA technology at a relatively low temperature with less heat, less emissions and at a relatively low cost without compromising its quality.

1.3 Objective of the research

This study has the following objectives;

(a) To evaluate the rheological and mechanical properties of bitumen modified with and without the additive Sasobit wax.

(b) To investigate the negative effect of aging on the modified binders during mixing.

(c) To investigate stability of the additive with bitumen at storage and the morphology of the mixture.

(d) To determine the performance of warm stone mastic asphalt (WSMA) with respect to resistance to binder fatigue and plastic deformation.

1.4 Scope of the research

This study involved the use of a commercial additive Sasobit wax with bitumen and extensive laboratory testing. The research included empirical tests for the penetration and softening point for both neat and modified bitumen of 80/100 penetration grade, 60/70 penetration grade and PG 76–22. Determination of the effect of temperature on the viscosity of the binder with and without the additive by measuring the viscosity at varying temperatures. The study investigated the rheological properties of the binder with and without the warm mixes additive, and the effect of the increase and reduction of the complex modulus and phase angle. The study also evaluated the effect of aging on the binder by using the rolling thin film test (RTFOT) and pressure-aging vessel (PAV) tests were with, a total of 505 no. binder samples investigated.

The study utilized Fourier transform infrared spectroscopy test (FTIR), to evaluate the WMA binders and their aging properties. The study involved the production of warm stone mastic asphalt (WSMA) at a lower temperature of 135^{o}C compared with the SMA at 180^{o}C. The warm stone mastic asphalt samples with nominal maximum aggregate size (NMAS) of 12.5 mm (designated as SMA14) were studied.

In designing mixtures, the total of 225 specimens were prepared using Marshall compaction method with three specimens for each of bitumen content of 5.0%, 5.5%, 6.0%, 6.5%, and 7.0% with Sasobit wax content of 0%, 0.5%, 1%, 1.5%, 2%, 2.5% and 3% by Marshall hammer at compaction efforts of 50 blows per face including nine specimens designed for binder drain down test purpose. The indirect tensile resilient modulus of the asphalt concrete was tested. The study investigated 12 SMA14 and WSMA14 samples using the WESSEX wheel tracker to determine the rutting potential of the WMA at high temperatures. All the data obtained from the study were analyzed and presented accordingly. All the testing was performed at the UTM Transportation Laboratory except for the dynamic shear rheometer test, which was conducted at the Highway Laboratory of Universiti Tun Hussein Malaysia (UTHM).

1.5 Significance of the research

This research shall improve on the industrial process of SMA mixtures, laying and compaction at a relatively lower temperature. The study is expected to improve three areas of pavement performance, namely, controlling rutting, fatigue cracking and aging. The study shall also provide a better environmental friendly method of producing asphalt mixture, which complies with the 1997, Kyoto protocol on stemming global warming and depletion of the Ozone layer. The study could provide valuable information towards understanding the WMA technology to agencies that desire to construct SMA pavements using the WMA technology in developing countries like Malaysia.

REFERENCES

1. Ahmad, J., (2010). *A study on moisture induced damage and rutting of hot mix asphalt*. Ph.D Thesis, Universiti Teknologi MARA, pp. 5-10.
2. Huang, Y.H. University of Kentucky (2004). 2nd Edition. *Pavement Analysis and Design*. Published by Pearson Prentice Hall, pp. 1-11.
3. Warm mix asphalt-*A state of the Art review*, advisory note #17, Australian Asphalt Pavement Association, 2001 (retrieved 25/05/2009 from www.aapa.asn.au)
4. Robert, F.L., Kandhal, P.S., Brown, E.R., Dah, Y. L., and Kennedy, T.W. (1996). *Hot Mix Asphalt – Materials, Mixture Design and Construction.* 2nd edition. NAPA Education Foundation, Lanham, Maryland, pp. 248-485
5. Xiaohu, L. and Ulf, I. (1997). Rheological characterization of styrene-buta-diene-styrene copolymer modified bitumens. *Journal for construction and building materials,* Vol. 11, No. 1, pp.23-32.
6. Kim, H., (2010). *Performance evaluation of SBS modified asphalt mixtures using warm mix asphalt technologies*. Ph.D Thesis, Clemson University, U.S.A. pp. 16-43.
7. Gandhi, T. and S. Amirkhanian, (2008). *Effect of warm asphalt additives on asphalt binder and mixture properties.* Ph.D Thesis, Clemson University, U.S.A. pp 10-75.
8. Biro, S., Tejash, G., and Serji, A. (2009). Midrange temperature rheological propertiesof warm asphalt binders. *Journal of materials in Civil engineering.* ISSN 0899- 1561/7-316-323, Vol. 21, No.7, pp.316-323.
9. Mallick, R. B., and El-korchi, T. (2009). *Pavement engineering principles and practice*. ISBN 13: 978-1-4200-6029-4,pp. 163-165.
10. Read, J and Whiteoak, D. (2003) *The Shell Bitumen Handbook*. Fifth Edition. Thomas Telford Publishing, Thomas Telford Ltd, 1 Heron Quay, London E14 4JD, pp 62 – 136.

11. Roberts, L.F., Louay Mohammad, N. and Wang, L.B. (2002) "History of hot mix asphalt mixture design in the United States" *Journal of Materials in Civil Engineering*, pp. 279-293.
12. Jabatan Kerja Raya Malaysia. *Standard Specification for Road Works, Section 4: Flexible Pavement.* No. JKR/SPJ/2008-S4, pp. S4-58 – S4-69.
13. Chen, J.S., Liao, M.C., and Shiah, M.S. (2002). Asphalt Modified by Styrene-butadiene- styrene Triblock Copolymer: Morphology and Model. *Journal of Materials in Civil Engineer.* Vol. 14, pp.224 – 229.
14. Yildirim, Y. (2007). Polymer modified asphalt binders. *Journal of Construction and Building Materials,* Volume 21, pp. 66-72.
15. Hurley, G., and Prowell, B., (2005). *Evaluation of Sasobit for use in warm mix asphalt.* NCAT Report 05-06,pp. 2-24.
16. Borleo, M., Kanitpong, K., and Charoentham, N. (2008). Performance evaluation of warm mix asphalt produced with Sasobit additive. Proceedings of 6th ICPT, Sapporo, Japan, pp. 177-184.
17. Hurley, G., and Prowell, B., (2006). Evaluation of potential process for use in warm mix asphalt, *Journal of the Association of Asphalt Paving Technologist*, Vol. 75, pp.41-90.
18. World Whether report (2009) retrieved 23/09/09 from www.globalwarming.com.
19. Maccorone et al. 1994. *Warm mix asphalt for cold wheather paving,* pp. 1-2 (retrieved from www.swutc.tamu.edu/pub).
20. Olof. K., (2006). *Warm mix asphalt for cold weather paving.* Masters Thesis, Clemson University, U.S.A. pp 3-55.
21. Prowell, B., (2007). *Warm mix asphalt summary report*. The International Technology scanning program at National Center for Asphalt Technology (NCAT) Auburn, U.S.A.
22. Kuennen, T. (2004). *Warm mixes are a hot topic*. Better roads magazine (retrieved 15/09/09 from www.betterroads.com)
23. Edwards, Y. and U. Issacsson, 2007. Rheological effect of commercial waxes and polyphosphoric acid in bitumen 160-220-high and medium temperature performance.*Journal of construction and building materials, Vol.*21: pp.1899-1908.

24. Edwards, Y. and Redelius, P. (2009). Rheological effects of waxes in bitumen. *Journal of energy and fuels*. ISSN: 10.1021/ef020202b.

25. Sasol wax international (2006). Sasobit product information, *The bitumen additicve for highly stable easily compactible asphalt*, (retrieved 25/09/09 fromwww.sasolwax.com).

26. Sasol international product (2008). *The impact of Sasobit on the adhesion between bitumen and aggregate,* Newsletter 06/08.

27. Moavenzadeh, F. and Goetz, W.H. (1963). Aggregate degradation in bituminous mixtures. *Highway Research Record 24*. National Research Council.Washington D.C.

28. Damm, K. W., (2004). *Sasobit as asphalt flow improver*, Sasol international product information Vol.145, pp. 1-29.

29. Kanitpong, K., Nam, K., Martono, W., and Bahia, H., (2008). Evaluation of warm mix asphalt additive. *Proceedings of the institution of civil engineers construction materials*, DOI: 10.1680, 161: pp. 1-8.

30. Edwards, Y., Tasdemir, Y., and Issacsson, U., (2006). Effect of commercial waxes on asphalt concrete mixtures performance at low and medium temperatures. *Journal of cold Regions Science and Technology* Vol. 45: pp. 32-41.

31. Edwards, Y. and U. Issacsson, 2006. Rheological effect of commercial waxes and polyphosphoric acid in bitumen 160-220-low temperature performance. *Journal of Fuel*. 85: pp. 989-997.

32. Warm mix asphalt technologies and research, (2007). *Potential to reduce fuel consumption and emissions* (retieved from www.govengr.com).

33. Meor, O.H., Ali, J. and Zulkurnain, S. (2010). Evaluation of the potential of Sasobit to reduce required heat energy and CO_2 emission in the asphalt industry. *Journal of Cleaner production,* Vol. 18, pp. 1859-1865.

34. Frag Ahmed, K., Kamil, A. and Yusuf, M. (2010). Development of warm mix asphalt and compliance with the requirements set by specifications. *European journal of Scientific research*. ISSN 1450-216X Vol. 48 No.1, pp.118-128.

35. Rusbintardjo, G., (2010). Bitumen modification using oil palm fruit ash for Stone mastic asphalt. Ph.D Thesis, Universiti Teknologi Malaysia, pp. 1-28.

36. Bahia, H.U., and Anderson, D.A. (1994). The Pressure Aging Vessel (PAV): A Test to Simulate Rheological Changes Due to Field Aging. *ASTM Special Technical Publication 1241, 1994.*

37. Kandhal, P.S. and Parker, F. (1998) "Aggregate tests related to asphalt concrete performance in pavements" NCHRP Report 405, Transportation Research Board National Research Council, Washington D.C.

38. Lavin, P.G. (2003). *Asphalt Pavements A Practical Guide to Design, Production, and Maintenance for Engineers and Architects.* First Edition Spon Press, 11 New Fetter Lane, London EC4P 4EE, pp. 1.

39. Chen, J.S., Liao, M.C., and Shiah, M.S. (2002). Asphalt Modified by Styrenebutadiene styrene Triblock Copolymer: Morphology and Model. *Journal of Materials in Civil Engineering.* Vol. 14. pp 224 – 229.

40. Mohd, N. (2006). The aggregate degradation Characteristics of stone mastic asphalt (SMA) mixtures. Thesis, Universiti Teknologi Malaysia, pp. 5-18.

41. Kandhal, P.S. and Koehler, W.S. (1985) "Marshall mix design method: current practices" *Proceedings, Association of Asphalt Pavement Technologists*, Vol. 54, pp. 284-303.

42. Hunter, N.R., (2000). Asphalt in road construction, ISBN: 072772780X, pp. 332-365.

43. American Society for Testing and Materials (ASTM) (2006). *ASTM D 3515: Standard specification forHot –mixed, Hot-laid bituminous paving mixtures.* Philadelphia U.S.: ASTM International.

44. National Asphalt Pavement Association (NAPA). (1999). *Designing and Constructing SMA Mixtures: State-of-the-Practice*, QIP 122.

45. Schimiedlin, R. B. and Bischoff, D. L. (2002). *Stone Matrix Asphalt The Wisconsin Experience*. Wisconsin Department of Transportation. Madison, United States of America.

46. Keunnen, T. (2003). Better Roads Magazine. *Stone Matrix Asphalt is Catching on in the U.S.* United States of America.

47. Watson, D. E. and Jared, D. (1995). *Stone Matrix Asphalt: Georgia's Experience* Georgia Department of Transportation. Georgia, United States of America.

48. Mangan, D. and Butcher, M. (2004). Technical Note 16 Stone Mastic Asphalt. *Australian Roads Research Board*. Australia.

49. Pierce, L. M. (2000). Stone Matrix Asphalt. *WSDOT Report No. SR-524*. Washington State, United States of America.

50. Superpave asphalt technology program, (2008). Superpave mix design (retrieved from 4/10/09 www.utexas.edu.reserach).

51. Bahia, H.U., and Anderson, D.A. (1995). *The SHRP Binder Rheological Parameters*: Why Are They Required and How Do They Compare to Conventional Properties. Transportation.

52. McGennis, R.B., Anderson, R.M., Kennedy, T.W., and Solaimanian, M. (1995) *Background of Superpave Asphalt Mixture Design and Analysis.* Federal Highway Administration (FHWA), Report No. FHWA-SA-95-003, July 1995,pp. 1-3.

53. American Society for Testing and Materials (ASTM) (2004). *ASTM D 2872: Standard Test Method for Effect and Heat and Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test).* Philadelphia U.S.: ASTM International.

54. American Society for Testing and Materials (ASTM) (2000). *ASTM D 6521: Standard Test Method for pressure aging vessel test.* Philadelphia U.S.: ASTM International

55. American Society for Testing and Materials (ASTM) (2006). *ASTM D440: Standard test method for Viscosity Determination of Asphalt at Elevated Temperatures Using a Rotational Viscometer*. Philadelphia U.S.: ASTM International.

56. Gonzalez, O., Munoz, M.E., and Garcia, M. (2004). Rheology and stability of bitumen blends. *European polymer journal*, Vol. 40 pp.2365-2372.

57. Perraton, D., Di Benedetto, H., Sawzéat, C., De La Roeche, C. Bankowski, W.,Parte, M., and Grenfell, J. (2010). Rutting of bituminous mixtures: wheel racking tests campaign analysis. *Journal of Materials and Structures.* RILEM TC 206 ATC “Advanced Testing of Bituminous Materials”. Published online November 2010.

58. American Society for Testing and Materials (ASTM) (1987). *ASTM D 4123-82: Standard test method for Indirect tension test for resilient modulus of bituminous mixtures.*

59. American Society for Testing and Materials (ASTM) (2004). *ASTM D 2041: Standard test method for Theoretical maximum specific gravity and density of bituminous paving mixtures.* Philadelphia U.S.: ASTM International

60. American Society for Testing and Materials (ASTM) (1992). *ASTM D 1559: Standard Test Method for Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus.* Philadelphia U.S.: ASTM International.

61. American Society for Testing and Materials (ASTM) (1992). *ASTM D 2726: Standard Test Method for Bulk Specific Gravity and Density of non Absorptive Compacted Bituminous Mixtures.* Philadelphia U.S.: ASTM International.

62. American Society for Testing and Materials (ASTM) (2006). *ASTM C 136: Standard test method for mineral aggregate sieve analysis,* Philadelphia U.S.: ASTM International.

63. American Society for Testing and Materials (ASTM) (2006). *ASTM C 117: Standard test method for materials finer than No.200 sieve in mineral aggregate by washing,* Philadelphia U.S.: ASTM International.

64. American Society for Testing and Materials (ASTM) (2006). *ASTM C 127: Standard test method for Coarse aggregate sieve analysis,* Philadelphia U.S.: ASTM International.

65. American Society for Testing and Materials (ASTM) (2006). *ASTM C 128: Standard test method for Fine aggregate sieve analysis*, Philadelphia U.S.: ASTM International.

66. American Society for Testing and Materials (ASTM) (1992). *ASTM C 88-90: Standard test method for soundness of aggregates by use of sodium sulfate,* Philadelphia U.S.:ASTM International.

67. American Society for Testing and Materials (ASTM) (2004). *ASTM D 5-97: Standard test method for penetration of bituminous materials*, Philadelphia U.S.: ASTM International.

68. American Society for Testing and Materials (ASTM) (2009). *ASTM D36 – 2009: Standard Test Method for Softening Point of Bitumen (Ring-and-Ball Apparatus).*Philadelphia U.S.: ASTM International.

69. Bahia, H.U., and Anderson, D.A. (1994). The Pressure Aging Vessel (PAV): A Test to Simulate Rheological Changes Due to Field Aging. *ASTM Special Technical Publication 1241, 1994.*

70. European Standard Nederland Norm NEN-EN 14770 (2005). *Bitumen and Bituminous binders – Determination of complex shear modulus and phase angle- Dynamic Shear Rheometer (DSR)* ICS 75.140; 91.100.50, November 2005.

71. American Society for Testing and Materials (ASTM). *ASTM D5892 Standard Test Method for Storage Stability Determination of Bitumen Modifier*. Philadelphia U.S.: ASTM International.

72. WESSEX wheel tracker manual, BS 598 part 110 1998.

73. American Association of State Highway and Transportation Officials (AASHTO) AASHTO M92 SC-T-90: *Method for determining drain-down characteristics in an uncompacted bituminous mixture* using.

74. Dogan and Bayramli (2002). Effect of polymer additives and process temperature, *Journal of applied polymer science*. DOI:10.1002/app, pp.2333-2336.

75. Dowdy, S., Weardon, S., and Chilko, D. (2003). Statistics for research, third edition pp. 431-484.

76. American Society for Testing and Materials (ASTM) (1992). *ASTM D 3203: Standard test method for percentage air voids in compacted dense and open bituminous paving mixtures,* Philadelphia U.S.:ASTM International.

77. American Society for Testing and Materials (ASTM) (1992). *ASTM D 2041: Standard test method for Theoretical maximum specific gravity and density of bituminous paving mixtures,* Philadelphia U.S.:ASTM International.