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Evaluation of Engineering Properties and Economic Advantages of WMA using Local Materials

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Abstract: Warm Mix Asphalt (WMA) is a technology applied to reduce mixing and compaction temperatures thereby reduces energy consumption and greenhouse gas production in asphalt industries. In this study, the effects of different Sasobit® contents on WMA is investigated using local materials and asphalt mix specifications in Malaysia. The volumetric analysis and mix design results show that Sasobit® contents has no significant effects on the optimum binder content. Statistical analysis showed that the resilient modulus and indirect tensile strength are highly correlated between Sasobit® contents, aging states, test and mixing temperatures. The samples were mixed and compacted at 150 and 145°C incorporating 1.5 and 3% Sasobit® content, respectively, exhibit higher ITS and resilient modulus compared to control samples. In other words, these mixing and compacting temperatures can contribute to energy savings by as much as 8.2 and 12.0%, respectively.

Key words: Sasobit®, saved energy, viscosity, aging, mix performance

INTRODUCTION

Pavement construction requires a significant amount of non-renewable natural resources materials that depleting fast and highly cost especially bitumen. Meanwhile, the Kyoto protocol has encouraged countries around the world to reduce production of greenhouse gases (Angelo *et al*., 2008). In view of these phenomena, it is therefore necessary to develop a clean technology through low-carbon industries coupled with sustainable development. This can be a profitable investment because crude oil production-consumption process from exploitation oil resources, including exploration, extraction, purification, transpiration and distribution, is not only costly but also pollutes the environment. The Asphalt industries are much related to crude oil as they use asphalt to construct and develop infrastructural facilities such as pavements for highways, airfields and ports. Some novel technologies have been developed to reduce carbon emissions and fulfill stringent environmental regulations in the asphalt industries and one of such technologies is Warm Mix Asphalt (WMA). WMA is a new technology in asphalt industries that is able to significantly reduce mixing and compaction temperatures of asphalt mixes as compared to a traditional Hot Mix Asphalt (HMA). This technology has been gaining positive response from policy makers, government road agencies and road builders when some laboratory and field studies showed a promising future in perspective of saving energy and improve performance OF asphalt binder and mixtures. There are a variety of WMA additives added to binder and mixture, one of which is a synthetic wax type called Sasobit®. Laboratory researches have shown that Sasobit® increases aging index, Superpave™ rutting factor and Zero Shear Viscosity (ZSV) (Wasiuddin *et al*., 2007; Biro *et al*., 2009; Akisetty *et al*., 2009). The other experimental investigations revealed that Sasobit reduced rutting and increase dynamic modulus of asphalt mixtures (Wasiuddin *et al*., 2007; Mohammad *et al*., 2008).

Field studies in The United States of America (USA) showed that mixtures modified by Sasobit® extended the paving time by 27 min which would allow a longer hauling distance during construction (Goh and You, 2009).

Another field study in USA demonstrated that the average air voids of the Sasobit® modified mix cores were slightly less than those of the control cores that do not incorporate Sasobit® (Diefenderfer *et al*., 2007).

In Europe, field experiences showed that Sasobit® was used for their stiffening effect at high in-service pavement temperatures (Angelo *et al*., 2008). Incorporating Sasobit® in asphalt binder has reduced viscosity at compaction temperatures, particularly when compared to other types of modifiers.

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In Australia, it was reported from field experiences that HMA containing Sasobit® was hauled up to 9 h and still able to be unloaded (Angelo *et al*., 2008).

In order to use of Sasobit® WMA in large scale production in Malaysia, it is necessary to perform detailed laboratory study on effects of Sasobit® on mixture performance using local aggregate gradation and asphalt binders based on Malaysian specification. The results from the laboratory tests will hopefully be able to show similar advantages of Sasobit® usage in Malaysia.

Currently, Malaysia is a developing and relatively open state-oriented market economy. In 2007, the economy of Malaysia was the 29th largest economy in the world by purchasing power parity with gross domestic product for 2007 was estimated to be $357.9 billion with a growth rate between 5 to 7% since 2007. For continuing this sustained growth rate, it is necessary to find alternatives for more cost-effective development of infrastructures such as pavements without sacrificing quality. Reduction of fuel requirements using Sasobit® to production of asphalt mixture can have significant effect on total cost of pavement construction. Although, researches on renewable sources of energy like palm oil as bio-fuel has started in Malaysia (Shuit *et al*., 2009; Sumathi *et al*., 2008; Yusoff, 2006), there is still a long way to go for large scale production of this fuel type to be accepted as an industrial fuel.

On the other hand, global warming is causing the polar ice caps to melt and it will inevitably raise sea levels resulting in less land for an increasing population. Ecological researches predicted that approximately 1.5°C rise above pre-industrial temperatures would be the onset of complete melting of Greenland ice causing about 7 m of additional sea level rise (Armstrong and Blundell, 2007). Therefore, new methods to promote clean technology development initiatives like Sasobit® can lead to both environmental and engineering benefits. The results of this research can help to accelerate the usage of WMA to develop low carbon asphalt technologies in Malaysia.

In this study, the effects of different Sasobit® contents were evaluated on mix design and volumetric properties of asphalt mixtures for local materials. The mixtures are also evaluated for indirect tensile strength and resilient modulus at different temperatures and ageing conditions. The economic advantages of Sasobit® on pavement construction projects is evaluated in terms of saved fuel requirements to raise aggregate temperature from ambient to mixing point.

MATERIALS AND METHODS

In order to evaluate the potentials of WMA technology in Malaysia, a laboratory study was initiated at the Highway Engineering Laboratory, Universiti Sains Malaysia in 2008. All materials, including aggregate and asphalt binder, are supplied from local sources. The material characteristics and aggregate grading are respectively shown in Table 1 and 2.

Table 1: Rheological properties of AC80/100

Bitumen	Test parameters	Value	Test method
Unaged	Viscosity at 135°C (m.Pa.s)	465	ASTM (2006a)
	G*/Sinδ @ 64°C (kPa)	1.23	ASTM D7175
	Failure temperature (°C)	66.4	
Short term aged	G*/Sinδ @ 64°C (kPa)	2.68	ASTM D7175
	Failure temperature (°C)	66	
Long term aged	G*sinδ at 25°C (kPa)	2958.75	ASTM D7175

Table 2: JKR gradation limit for asphaltic concrete ACW14

Sieve size (mm)	Percent passing
20	100
14	90-100
10	67-86
5	50-62
3.35	40-54
1.18	18-34
0.425	12-24
0.150	6-14
0.075	4-8

Asphalt binder: The asphalt binder used was an 80/100 penetration grade bitumen (AC80/100) from PETRONAS, a Malaysian oil company. Table 1 shows the rheological properties of the asphalt binder.

Aggregate: The aggregate gradation used was an asphaltic concrete mix ACW 14 as shown in Table 2, the gradation specification is in accordance to JKR road specifications. Aggregate and filler types are granite and Portland cement respectively.

Rotational viscometer test: A Brookfield Rotational Viscometer (RV) was used to determine the mixing and compaction temperatures according to the Asphalt Institute recommendations. This test was carried out according to ASTM D4402 (ASTM, 2006a).

Mixture design: Mix type is dense and mix design method is based on Marshall Method according to ASTM D6927 (ASTM, 2006b). Volumetric properties of asphalt mixes were analyzed based on JKR road specification.

Indirect tensile strength: Indirect Tensile Strength (ITS). This test was initially developed for rheology of rocks (Haimson and Tharp, 1974) and, this test is currently used the assess asphalt mixture performance. Test temperatures were 25 and 40°C for both unaged and aged samples according to ASTM D6931 (ASTM, 2006c).

Resilient modulus: The resilient modulus test was carried out accordance with ASTM D4123 (ASTM, 2006d) for asphalt mixtures, test parameters are presented in Table 3.

Table 3: Test parameters of resilient modulus

Test parameters	Value
Temperature	25 and 40°C
Condition pulse period	2000 m sec
Test pulse period	3000 m sec
Pulse width	50 m sec
Poison's ratio	0.35

Mixture conditioning: To simulate aging condition up to field construction and in service, samples were subjected to short and long term aging conditions respectively. For short term aging, the mix samples were put in the conditioning oven for 4 h at 135°C (Asphalt Institute, 2001). The samples were conditioned at 85°C for 5 days for long term ageing simulation according to AASHTO PP2 (AASHTO, 2001).

Statistical analysis: Effects of laboratory treatments on some of engineering characteristics (for instance ITS and resilient modulus) of the asphalt mixes were measured using general linear model through Analysis of Variance (ANOVA). In the statistical analysis, mixing and test temperatures, Sasobit® contents and aging conditions were considered as independent variables and resilient modulus and ITS were considered as responses. The results were compared to statistical analysis with 5% level of significance. In this study, there were 64 combinations of independent variables involved (i.e., 2 Sasobit® contents x 2 ageing conditions x 2 test temperatures x 4 mixing temperatures x 2 replications).

RESULT AND DISCUSSION

Effects of Sasobit® on engineering properties: Mix design and volumetric properties of mixtures: By adding Sasobit®, based on Asphalt Institute guide and rotational viscometer test result, the mixing and compaction temperatures are reduced as shown in Table 4.

Table 4 shows that the mixing and compaction temperatures are reduced as the Sasobit® content increases. Band charts in Fig. 1 shows acceptable ranges of asphalt binder content for control and Sasobit® modified samples. Figure 1a shows that the acceptable binder contents for control samples range from 4.3 to 5.2%. Comparatively, Fig. 1b-e indicate the acceptable binder contents for samples incorporating 1, 2, 3 and 4% Sasobit® contents are respectively 4.4 to 5.3%, 4.5 to 5.4%, 4.4 to 4.9% and 4.6 to 5.2% and do not differ much with the control samples range. It means Sasobit® has no significant effect on acceptable ranges of asphalt binder in the terms of mixture flow, Voids Filled Asphalt (VFA) and air void percentage (P_a). The obtained results are similar to outputs reported by Goh and You (2009) and Hearon and Diefenderfer (2008). On the other hand, by increasing Sasobit® content, the maximum Marshall Stability occurs at lower binder content. Figure 1f indicates that mixes incorporating 4% Sasobit® have the highest Marshall stability with lowest binder content (4.45%) as compared to the other samples. This is because higher Sasobit® content reduces asphalt binder viscosity and increase mixes density. Furthermore, crystalline lattices formed in the binder micro structure increases binder stiffness. Table 5 shows the mix properties of control and samples containing Sasobit® based on ranges prescribed by JKR (2008) for all the samples.

Table 4: Construction temperatures of asphalt binder modified using Sasobit®

	Sasobit® (%)				
Temperature (°C)	0	1	2	3	4
Mixing	160	155	152	150	145
Compaction	150	145	142	140	137

Table 5: Mix properties designed for AC80/100 based on JKR specification

Properties of mix	Value	Prescribed ranges by JKR (2008)
Binder content	4.8%	4-6%
Air void	3.9%	3-5
VFA[1]	75.6%	70-80
VMA[2]	15.37%	-
density	2.38	-
Stability	20.64 kN	More than 8 kN

[1]Void filled asphalt. [2]Void mineral aggregate

It can be seen that the properties of the asphalt mixes modified by Sasobit® are within the limits specified by JKR (2008). On the other hand, the result also indicated that 4% Sasobit® makes asphalt binder susceptible to fatigue whereas 1.5 to 3% is the optimum range. Therefore, this range was used to modify asphalt binder for mix tests.

Indirect tensile strength: General Linear Model (GLM) of Analysis of Variance (ANOVA) was used to analyze the Indirect Tensile Strength test data with ITS as the response variable and Mixing Temperature (MT), Test Temperature (TT), Sasobit® content (S%) and Ageing Type (AT) as factors at 95% of confidence level (α = 0.05). The single and interaction effects of mixes on the ITS values are shown in Table 6; the result shows that all the single factors have significant effect on ITS values of the mixes. Not all interaction factors have significant effect on ITS, such as MT*AT, MT*S%*AT, TT*S%*AT and MT*TT*S%*AT. It explain that the presence of ageing type (AT) influence the three and four interaction factors on the ITS.

The result also signify that the ITS value is a function of the different independent variables as shown in Eq. 1. Effect of each independent variable to each other is quantified using equations in set Eq. 1. Δ_a is introduced to compare short term and long term aged behavior of asphalt mixes in terms of ITS; Δ_s and Δ_T are used to evaluate the effects of Sasobit® and temperature, respectively.

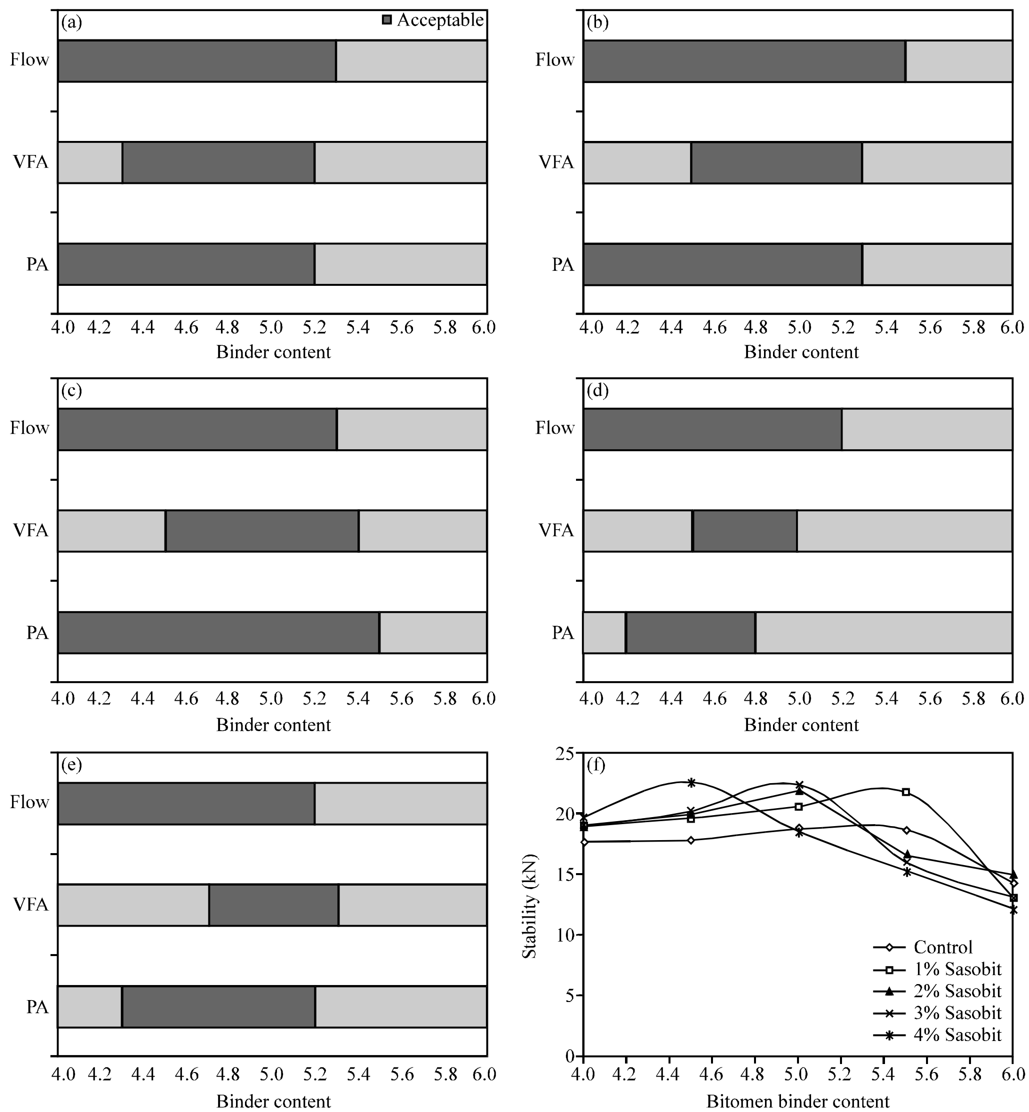

Fig. 1: Volumetric properties and Marshall Stability of asphalt mixture samples. (a) Control condition, (b) 1% Sasobit® (c) 2% Sasobit®, (d) 3% Sasobit®, (e) 4% Sasobit® and (f) Marshal stability

$$ITS = f(MT, TT, S, A) = \begin{cases} \Delta_a = \dfrac{ITS_L - ITS_S}{ITS_S} \\ \Delta_c = \dfrac{ITS_S - ITS_C}{ITS_C} \\ \Delta_T = \dfrac{ITS_{t_2} - ITS_{t_1}}{t_2 - t_1} \end{cases} \quad (1)$$

where, MT,TT,S and A are mixing temperature, test temperature, Sasobit® content and aging conditions respectively; L and S are short term and long term aging conditions; t_2 and t_1 are maximum and minimum test temperatures; and C is control condition (no Sasobit® content). Table 7 shows the ITS results for short and long term aging conditions, respectively.

It is expected that the ITS values are decreased by reducing mixing and compaction temperatures but as indicated in Table 7, Δ_s increases for asphalt samples mixed at 150°C by using Sasobit® and it is just 4.6% lower than the control samples for the mixes prepared at 145°C. At lower mixing temperatures such as 125 and 135°C, ITS reduced drastically and Sasobit® has no considerable effect on ITS for each aging condition and test temperature. The trends obtained are close the results published by Mohammad *et al*. (2008).

There is a 16% difference between ITS of aged and unaged for control samples (Δ_a), while this value is 7.5 and 9.4% for samples incorporating 1.5% Sasobit® and mix at 150 and 145°C. It implies that the samples modified by

Table 6: General linear model on the ITS results

Source	df	Seq SS	Adj SS	Adj MS	F-value	p-Value	Significant
MT	3	1.10194	1.10194	0.36731	553.13	<0.01	Yes
TT	1	8.05850	8.05850	8.05850	12135.16	<0.01	Yes
S%	1	0.12870	0.12870	0.12870	193.81	<0.01	Yes
AT	1	0.51301	0.51301	0.51301	772.54	<0.01	Yes
MT×TT	3	0.15444	0.15444	0.05148	77.52	<0.01	Yes
MT×S%	3	0.00912	0.00912	0.00304	4.58	<0.01	Yes
MT×AT	3	0.00503	0.00503	0.00168	2.52	0.075	No
TT×S%	1	0.02520	0.02520	0.02520	37.95	<0.01	Yes
TT×AT	1	0.01789	0.01789	0.01789	26.94	<0.01	Yes
S%×AT	1	0.00439	0.00439	0.00439	6.61	0.015	Yes
MT×TT×S%	3	0.00744	0.00744	0.00248	3.74	0.021	Yes
MT×TT×AT	3	0.02228	0.02228	0.00743	11.18	<0.01	Yes
MT×S%×AT	3	0.00170	0.00170	0.00057	0.86	0.474	No
TT×S%×AT	1	0.00214	0.00214	0.00214	3.22	0.082	No
MT×TT×S%×AT	3	0.00553	0.00553	0.00184	2.78	0.057	No
Error	32	0.02125	0.02125	0.00066			
Total	63	10.07857					

S: 0.0258; R-Sq: 99.8%; R-Sq(adj): 99.6%

Table 7: Indirect tensile test results for different test temperatures and aging conditions

		Test temperature (°C)											
		25						40					
		Δ_a (%)		Δ_C (%)		Δ_T (%)		Δ_a (%)		Δ_C (%)		Δ_T (%)	
Mixing temperature (°C)	Aging state	1.5	3	1.5	3	1.5	3	1.5	3	1.5	3	1.5	3
		Sasobit® (%)											
150	S	-	-	5.60	16.80	0.60	0.62	-	-	1.60	5.0	-4.8	-5.6
	L	7.50	10.95	2.70	11.72	0.73	0.77	21.7	24.2	2.08	8.5	-5.0	-5.6
145	S	-	-	-6.40	3.20	0.35	0.37	-	-	-40.60	-37.3	-5.5	-6.0
	L	9.40	10.85	-11.70	-1.30	0.61	0.66	74.3	78.4	-14.00	-7.0	-4.5	-5.1
135	S	-	-	-10.40	-8.00	0.34	0.38	-	-	-42.30	-35.6	-5.2	-5.1
	L	6.25	16.52	-17.90	-7.60	0.59	0.63	73.4	65.8	0.00	-11.2	-4.0	-4.7
125	S	-	-	-32.00	-25.60	0.31	0.35	-	-	-47.40	-44.0	-3.6	-3.8
	L	21.17	20.43	-28.90	-22.70	0.50	0.56	61.3	60.0	-29.60	-21.0	-3.5	-3.7

S: Short term aging condition; L: Long term aging condition

Sasobit® experiences less aging. Thermal sensitivity parameters (Δ_T) of asphalt mixes constructed are decreased by reducing construction temperatures at long term aging condition. This parameter lies within -3.5 to -6% for Sasobit® modified samples irrespective aging state.

Resilient modulus: Resilient modulus is an important characteristic of asphalt concrete pavement. It is used in mechanistic pavement design and as one of inputs in the multi-layered elastic methods and finite element to evaluate structural pavement response under traffic loading. Resilient behavior of asphalt mixes depend on the binder type, test temperature, aggregate gradation and ageing type. Figure 2 shows interaction plots of different content of Sasobit® on resilient responses of mixes at various mixing and test temperatures.

Figure 2 shows that resilient modulus increases by increasing mixing temperatures. It take places because higher mixing temperatures lead to more ageing and makes more stiffen asphalt binder. It also shows that resilient modulus increases as Sasobit® content increases irrespective of test and mixing temperatures.

Economic advantages of Sasobit®: The economic advantages of Sasobit® on pavement construction projects is evaluated in terms of saved fuel requirements to heat up aggregate to mixing temperatures. The required heat energy to heat up the asphalt binder is ignored because the quantum is negligible as compared to heating up aggregate. It is assumed that 100,000 ton of granite aggregate is required to heat up to mixing temperature and, fuel type utilized by asphalt plant is heating oil. The price of heating oil for industrial usage is RM2.88 per Liter (IEA, 2010). The required energy and saved costs for different Sasobit® contents are shown in Table 8.

Table 8 shows that Sasobit® has a good potential to save energy using local materials in Malaysia according to literatures (Mallic, 2009; Goh and You, 2009; Hurley and Prowell, 2005).

It also can be seen that by decreasing mixing temperature to 135°C, the cost of required energy to heat

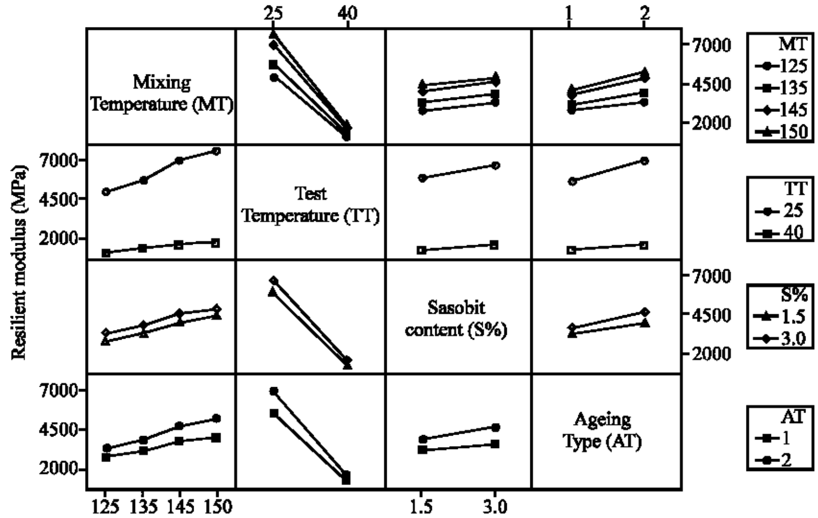

Fig. 2: Interaction plot of the independent variables on resilient modulus

Table 8: Saved cost and energy for mixes incorporated Sasobit®

Mixing temp. (°C)	Sasobit® (%)	ITS (Mpa)	ITS ratio (%)	Resilient modulus (MPa)	Resilient change ratio (%)	Required energy (mmBTU)	Price (RM[1])	Saved energy cost (%)
160	160.0	1.25		6135		11,381.4	370,578	
150	1.5	1.32	+5.6	6623	+8.00			
	3.0	1.46	+16.8	6818	+11.13	10,451	340,284	8.2
145	1.5	1.17	-6.4	5817	-5.20			
	3.0	1.29	+3.2	6477	+5.50	9,983	325,046	12.3
135	1.5	1.12	-10.4	4813	-21.50			
	3.0	1.15	-8.0	5361	-12.60	9,093	296,063	20.0

[1]Malaysia currency

up aggregate decreased by 20% but the resilient modulus and ITS are also decreased significantly. Samples that incorporated 3% Sasobit® and mixed at 145°C exhibit higher resilient modulus and ITS as compared with control samples and the energy saving amount to 12.3%. Under these circumstances, engineers and policy makers of pavement projects should evaluate whether saving energy is more important or to reduce the structural capacity of asphalt concrete pavement. Coming up to final decision in this field depends on engineering judgment and should be made based on life cycle cost analysis of the asphalt pavement, policies of road agency in the field of maintenance and rehabilitation (M and R) and environmental regulations.

CONCLUSIONS

Mix design results showed that different Sasobit® contents have no significant effects on optimum binder content used in this study. The GLM results indicate that there is high interaction between the ITS and all factors due to high coefficient of determination value which is 99.8%. Additionally, by decreasing the mixing temperatures, the ITS and resilient modulus values were decreased however when Sasobit® was added to the mix, the ITS and resilient modulus has significantly increased compared to the control samples. The samples mixed at 150 and 145°C incorporated 1.5 and 3% Sasobit® respectively shows higher ITS and resilient modulus compared to control samples. It was tantamount to energy saving by 8.2 and 12% for 150 and 145°C, respectively.

It is possible to achieve higher energy saving (up to 20%) by reducing mixing temperature to as low as 135°C but the structural capacity of the pavement will decrease. Engineering judgment associated with life cycle cost analysis of pavement can solve this dilemma for road authorities to make the choice whether high quality pavement or more energy saving.

REFERENCES

AASHTO, 2001. AASHTO PP2: Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA). American Association of State Highway and Transportation Officials. http://aec.ihs.com/document/abstract/UEITXAAAAAAAAAAA.

ASTM, 2006a. ASTM D4402: Standard test method for viscosity determination of asphalt at elevated temperatures using a rotational viscometer. http://www.astm.org/Standards/D4402.htm.

ASTM, 2006b. ASTM D6927: Standard Test Method for Marshall Stability and Flow of Bituminous Mixtures. http://www.astm.org/Standards/D6927.htm.

ASTM, 2006c. ASTM D6931: Standard Test Method for Indirect Tensile (IDT) Strength of Bituminous Mixtures. http://www.astm.org/Standards/D6931.htm.

ASTM, 2006d. ASTM D4123: Standard Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures. University of Mexico, West Conshoken, Pa, USA.

Akisetty, C.K., S.J. Lee and S.J. Amirkhanian, 2009. High temperature properties of rubberized binders containing warm asphalt additives. Construction Building Mater., 23: 565-573.

Angelo, J.D., E. Harm, J. Bartoszek, G. Baumgardner and M. Corrigan *et al*., 2008. Warm mix asphalt European practice. National Academy of Sciences, Washington.

Armstrong, F. and K. Blundell, 2007. Energy Beyond Oil. Oxford University Press, London, ISBN-10: 0199209960, pp: 240.

Asphalt Institute, 2001. Superpave Mix Design. Asphalt Institute, 3rd Edn., Lexington, KY.

Biro, S., T. Gandhi and S.J. Amirkhanian, 2009. Determination of zero shear viscosity of warm asphalt binders. Construction Building Mater., 23: 2080-2086.

Diefenderfer S., K. McGhee and B.M. Donaldson, 2007. Installation of warm mix asphalt projects in Virginia. Virginia Transport Research Council, Research Report: FHWA/VTRC07-R25.

Goh, S.W. and Z. You, 2009. Warm mix asphalt using sasobit in cold region. Proceedings of the 14th Conference on Cold Region Engineering, Aug. 31-Sept. 02, Duluth, Minnesota, pp: 288-298.

Haimson, B.C. and T. Tharp, 1974. Stresses around boreholes in bilinear elastic rock. Soc. Petroleum Eng. J., 14: 145-151.

Hearon, A. and S. Diefenderfer, 2008. Laboratory evaluation of warm asphalt properties and performance. Proceedings of the 2008 Conference on Airfield and Highway Pavements, Oct. 15-18, Bellevue, Washington, USA., pp: 182-194.

Hurley, G. and B. Prowell, 2005. Evaluation of Sasobit® for use in warm mix asphalt. NCAT report 05-06, Auburn, USA., pp: 1-30. http://warmmixasphalt.com/submissions/11_20071127_EVALUATION_OF_SASOBIT.pdf.

IEA, 2010. International Energy Agency: End-Use Petroleum Product Prices and Average Crude Oil Import Cost March 2010. International Energy Agency, Italy, Spain, UK., pp: 1-6.

JKR, 2008. Standard Specification for Road Works (Section 4: Flexible Pavement). Public Works Department, Malaysia, Kuala Lumpur.

Mallic, R.B., 2009. A laboratory study on CO_2 emission from asphalt binder and its reduction with the use of warm mix asphalt. Int. J. Sustainable Eng., 2: 275-283.

Mohammad, L., S. Shadi and S. Cooper, 2008. Evaluation of asphalt mixture containing warm mix additive. Proceedings of the 2008 Conference on Airfield and Highway Pavements, Oct. 15-18, Bellevue, Washington, USA., pp: 1016-1023.

Shuit, S.H., K.T. Tan, K.T. Lee and A.H. Kamaruddin, 2009. Oil palm biomass as a sustainable energy source: A Malaysian case study. Energy, 34: 1225-1235.

Sumathi, S., S.P. Chai and A.R. Mohamed, 2008. Utilization of oil palm as a source of renewable energy in Malaysia. Renewable Sustainable Energy Rev., 9: 2404-2421.

Wasiuddin, N.M., S. Selvamohan, M.M. Zaman and M.L.T.A. Guegan, 2007. Comparative laboratory study of sasobit and aspha-min additives in warm mix asphalt. Transportation Res. Rec: J. Transportation Res Board, 1998: 82-88.

Yusoff, S., 2006. Renewable energy from palm oil-innovation effective utilization waste. J. Cleaner Prod., 14: 87-93.