Available online at www.sciencedirect.com
ScienceDirect
Procedia - Social and Behavioral Sciences 96 (2013) 2858 – 2866
Procedia
Social and Behavioral Sciences

13th COTA International Conference of Transportation Professionals (CICTP 2013)

Rheological Evaluation of Foamed WMA Modified with Nano Hydrated Lime

Aboelkasim Diab[a] , Zhanping You[b,]*, Hainian Wang[c]

[a,b]*Michigan Technological University, Department of Civil and Environmental Engineering, Houghton, Michigan 49931, USA.*
[c]*Chang'an University, Highway School, Xia'n, Shaanxi, 710064, China.*

Abstract

Although the Warm Mix Asphalt (WMA) is gaining popularity very rapidly and becoming a mainstream technique for producing asphalt mixtures, there are many concerns regarding its long-term performance. Over the years, the Regular Hydrated Lime (RHL) has gained considerable recognition as a common additive to bituminous pavements. However, the Nano Hydrated Lime (NHL) (particle sizes 100 nanometer (nm) or less) has not been used as an additive to the asphalt mixtures before. The rheology properties of foamed WMA were studied since the pavement performance is primarily controlled by the rheological properties of asphalt cement. NHL materials with particle sizes of 50 nm and 100 nm were used in this study along with RHL to investigate the effectiveness of the new generation fabricated NHL modification on the rheological properties of the foamed WMA. NHL was added to the asphalt binder at ratios of 20%, 10%, and 5% (by weight). The foamed WMA was produced by adding Advera® at ratios of 3%, 4.5%, and 6% (by weight). The Dynamic Shear Rheometer (DSR) test was used to evaluate the rutting and fatigue cracking of the binders while the Bending Beam Rheometer (BBR) test was used to evaluate thermal cracking of the binders. The overall results reveal that the binder rheological properties can be enhanced successfully by adding small amounts of NHL. The NHL particle size affects the rheological properties of the binders. The application of the RHL with the normal dose (20% by weight of binder) can be replaced by adding almost 5% (by weight) of NHL (50 nm). The outputs of this study can be interesting from a practical point of view since it was proved that the NHL has interesting functionality on the rheological performance of the binders.

Selection and peer-review under responsibility of Chinese Overseas Transportation Association (COTA).

Key words: Foamed WMA;Nano Hydrated Lime;Rutting;Fatigue Cracking;Thermal Cracking

1. Introduction and Background

Warm Mix Asphalt (WMA), a new paving technology that originated in Europe, has a common purpose of reducing mixing and compaction temperatures of asphalt mixes. There are some benefits behind lowering

---

* Corresponding author. Tel.: (906)487-1059; fax: (906)487-1620.
E-mail address: zyou@mtu.edu

Selection and peer-review under responsibility of Chinese Overseas Transportation Association (COTA).
doi:10.1016/j.sbspro.2013.08.318

mixing and compaction temperatures especially when it comes to environmental and energy savings. Many research works indicate that both emissions and fuel consumption can be reduced significantly when the WMA concept is applied (Button et al. 2007; You and Goh 2008; Goh and You 2009; Hassan 2009). The WMA technologies can be classified into two groups; the first group reduces the asphalt binders' viscosity through the addition of organic or chemical additives, while the second group reduces the viscosity of the asphalt binders using foaming methods. These processes allow for producing asphalt mixtures at temperatures 15 to 30°C lower than typical traditional Hot Mix Asphalt (HMA). Several WMA production processes including WAM-Foam®, Sasobit®, Asphamin®, Advera®, Evotherm®, and others have been developed to reduce the mixing and compaction temperatures of HMA. The foaming process decreases the overall mix viscosity so that the foamed binder is workable during construction and coats the aggregates better (Kristjánsdóttir 2007; Prowell and Hurley 2007; D'Angelo et al. 2008). Advera®, Aspha-min® and WAM Foam® are all examples used to produce foamed WMA. Foaming binder using Advera® is one of the commonly used foaming technologies throughout the U.S. and many countries (D'Angelo et al. 2008; Goh and You 2012; Jamshidi et al. 2012). The foaming processes are based on the fact that when a given volume of water turns into steam it expands by a factor of 1,673 (Middleton and Forfylow 2009); consequently the hot asphalt binder expands and corresponding to reduction in the overall mix viscosity(Hodo et al. 2009; Wayne 2009; Wielinski et al. 2009).

The Synthetic zeolites additives have been used to enhance the coating of aggregates by asphalt at lower production temperatures. Zeolite includes approximately 20% water that is trapped in its structure and upon heating to approximately 100°C, the water is released and then foamed asphalt is produced (Bonaquist 2008).

Laboratory studies and field experiences have been conducted in the past few years on foamed-based WMA. Their result mainly indicated that a foamed WMA would aid compaction, increase moisture damage, and provide comparable or higher rutting potential compared to the HMA mixture (Hurley et al. 2006; Wasiuddin et al. 2007; Goh and You 2008; Wasiuddin et al. 2008). Therefore, in order to assure positive performance of the asphalt pavements, highway agencies stipulate the use of specific materials for highway pavement construction. Among the methods of asphalt concrete mixtures improvement is to use RHL as additive. The RHL has gained considerable recognition as a useful additive for improving the performance of bituminous pavements. Studies regarding RHL modified HMA mixtures have been conducted by a number of researchers, e.g (Peterson 1987; Little and Epps 2001; Sebaaly et al. 2001; Diab et al. 2012). Few researchers studied the applicability and functionality of RHL as additive to WMA mixtures. Xiao et al. (2010) used RHL into Sasobit®-WMA mixtures and the results showed that Sasobit®-WMA mixtures containing 1% or 2% RHL exhibited less rutting susceptibility. Although the effectiveness of hydrated lime is a function of the hydrated lime content and the method of use, the size of the hydrated lime particles is very important as well (Shen et al. 2010). In an attempt by Cheng et al. (2011) he used Los Angeles (LA) abrasion machine to produce smaller sizes of the hydrated lime particles. They used hydrated lime in two sizes (normal size and approximately half normal size). The effect of hydrated lime's size on the moisture susceptibility of Sasobit®-WMA mixtures was investigated. Most of the Sasobit®-WMA mixtures containing fine hydrated lime particles exhibited higher ITS, toughness and flow number in dry and wet conditions than the mixes containing normal-size hydrated lime. However, pavement scientists have not studied the usage of NHL (particle size ≦ 100 nm).

The performance of the asphalt binder controls the behavior of asphalt mixture and the pavement performance is primarily controlled by the rheological properties of asphalt cement (Roque et al. 1987). Rheological measurements can be a powerful tool in the characterization and design of viscoelastic blends (Hofstra and Klomp 1972; Kortschot and Woodhams 1984; Berker et al. 1990; Tasdemir 2009). The main objective of this study was to investigate the rheological properties of the foamed WMA modified with NHL.

2. Research Motivation

Despite the promising benefits of WMA, the asphalt industry has reservations concerning WMA implementation. This is mostly connected with concerns on the long-term performance of WMA pavements. There are concerns from some researchers who report premature rutting and potential moisture damage of the foamed WMA products in laboratory experiments. It is well known that the performance of the asphalt binder controls the behavior of asphalt mixture (Roque et al. 1987) and the pavement performance is primarily controlled by the rheological properties of asphalt itself. However, using newly fabricated materials that have unique effectiveness, functionality and applicability can control the desired rheological properties. Based on the literature, the potential interaction between RHL and bitumen is expected on the basis of its rugose surface and very high specific surface area (Johansson 1998). Fabricating the NHL particles from the RHL could be an effective way to increase the surface area of particles and this will help increasing the interaction between NHL particles and bitumen. The fabricated NHL was used as an additive to the foamed WMA and the rheological properties based on rutting, fatigue cracking and thermal cracking were evaluated through the DSR and BBR tests. The research outcomes can be a fundamental basis for using this new material (NHL) in asphalt pavement industries, especially WMA.

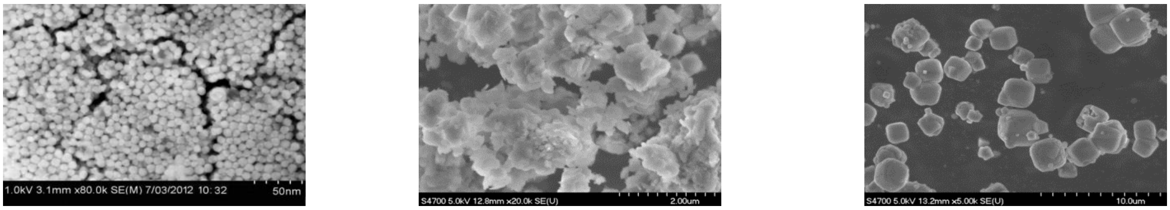
3. Materials

The experimental work in this study includes the use of NHL materials with two particle sizes (50 nm and 100 nm). A sample of the NHL particles (50nm) SEM image is shown in **Fig.1a**. The RHL also was used in this study along with the NHL. The SEM image of the RHL is shown in **Fig.1b**. It is quite clear from **Figs 1a and 1b**, the RHL has random particle sizes and shapes compared to the NHL. The chemical and physical properties of the hydrated lime additives used in this study are shown in **Table 1**. For easier estimation of the NHL particle size, the number written below **Fig.1a** was calculated to represent the scale division, not the whole scale. The doses of the NHL added were 20%, 10% and 5% (by weight of neat binder), which is approximately 1% (commonly used dose of hydrated lime), 0.5% and 0.25% respectively (by weight of the mixture). One binder grade (PG 58-28) from Gladstone, MI with properties shown in **Table 2** was used throughout the entire study.

Table 1. Chemical and Physical Properties of Hydrated Lime

Property	Value
$Ca(OH)_2$	>90%
CaO(%)	<1.2%
CO_2	< 1.5%
$CaCO_3$	<3 %
Insoluble matter	<1%
SiO_2	<1.5 %
Relative density	2.24
PH	12.4

Advera®, which is used to produce foamed WMA is a synthetic zeolite product available in a very fine white powdered form, passes through a 750mm (No. 200) sieve. It is composed of hydro-thermally crystallized framework silicates with spaces that allow large cations and are perfect for adjusting to moisture levels without damaging the asphalt (Hurley and Prowell 2005). SEM of Advera® particles is shown in **Fig.1c**. The percentage of water held internally by the Advera® zeolite is 21% by mass and is released at temperature approximately 100°C. When the Advera® is added to the binders, it transforms into moisture bubbles and creates a volume expansion of the binder which results in asphalt foam and allows increased workability and aggregate coating at lower production temperatures. The gradual release of water can provide about a 7-hour period of improved workability. Typically, Advera® was added at ratios of 3%, 4.5%, and 6% (by weight of neat binder).



(a) (b) (c)

Fig.1. SEM Images: (a) NHL (50nm), (b) RHL, and (c) Advera®

4. Samples Preparation and Description

The NHL materials were added to the asphalt binder at ratios of 20%, 10%, and 5% by weight of the neat asphalt binder (PG 58-28). The high shear mixing machine was used to mix the NHL and asphalt at 3000 rpm rotational speed and at a temperature of 160°C for two hours. After mixing, the foamed NHL modified binders were produced by mixing the modified asphalts with Advera® at ratios of 3%, 4.5%, and 6% (by weight of neat binder) using the high shear mixer for 20 minutes mixing at the same speed and temperature.

The prepared binders ranged from unfoamed binder (No Foam), and binders foamed with Advera® (AD). The unmodified prepared binders were the neat binder (58-28) and the neat binder foamed with 4.5% of Advera® (AD). The hydrated lime modified binders were labeled as follows: the first part stands for the type of hydrated lime added, RHL or NHL (50 nm or 100 nm). The numbers in the parentheses stand for the percent added of Advera® or hydrated lime (RHL or NHL). The RHL was added at a ratio of 20% (by weight).

Table 2. Binder Properties

Property	Value
Original Binder	
Viscosity, Pa-s (135°C)	0.308
G*/sin(δ), kPa (58°C)	1.86
RTFO Residue	
G*/sin(δ), kPa (58°C)	3.08
PAV Residue	
G*.sin(δ), kPa (19°C)	1956
Stiffness (60), MPa (-18°C)	226
m-value (60) (-18°C)	0.323

5. Research Methodology

5.1 Rutting and Fatigue Cracking

The DSR measures rheological properties of asphalt binder rather than empirical properties such as penetration values or softening point. Measurements can be performed at various temperatures, strain and stress levels, and frequencies. In the Strategic Highway Research Program (SHRP) asphalt binder specifications, the DSR is used to predict the fatigue and rutting potential of the binder (Youtcheff and Jones 1994). The rutting is evaluated by performing the DSR test on virgin and Rolling Thin Film Oven (RTFO) aged binders while the Pressure Aging Vessel (PAV) aged binders are tested to evaluate fatigue cracking of the binders. The RTFO asphalt binders were produced according to AASHTO T240 (AASHTO 2011a) while the long term aging of the asphalt binder specimens with the PAV oven followed the ASTM D6521 specification standard (ASTM 2008). Procedures for the DSR followed the AASHTO 315 specification standard (AASHTO 2011b). All SuperPave^{TM}

dynamic shear binder tests were performed at a frequency of 1.59 Hz. According to the SuperPave^{TM} specifications, the testing temperature for PG 58-28 is 58°C for virgin and RTFO aged binders. The specification defines and places requirements on a rutting parameter, G*/sin (δ) (where, G*, the complex modulus and δ, the phase angle), which represents the high temperature viscous component of overall binder stiffness. G*/sin (δ) must be at least 1.00 kPa for the virgin asphalt binder and a minimum of 2.20 kPa after aging in the RTFO test. G* and δ are also used in the SuperPave^{TM} asphalt specification to help control fatigue cracking in asphalt pavements. Since fatigue cracking occurs at low to moderate pavement temperatures after the pavement has been in service for a period of time, the specification requires that the PAV and RTFO tests be conducted prior to measuring these properties. Therefore, it was decided to use G*.sin (δ) value as specified by SHRP. The specifications suggest that the complex modulus tests be performed on the long-term oven aged (PAV) binders at the temperature depending on the PG grade (19°C for PG 58-28). A value of G*.sinδ greater than 5,000 kPa indicates that the asphalt binder is prone to fatigue cracking.

5.2 Thermal Cracking

The BBR test provides a measure of low temperature stiffness and relaxation properties of asphalt binders. These parameters give an indication of an asphalt binder's ability to resist low temperature cracking. The PAV aged binders were tested using the BBR for asphalt binder low temperature testing. The AASHTO T 313-09 standard specification was followed for the BBR testing in this investigation(AASHTO 2011c). The low temperature cracking potential can be quantified through the creep stiffness and m-value. It should be noted that creep stiffness is desired at the minimum pavement design temperature after two hours of load. However, SHRP researchers discovered that by raising the test temperature 10°C**,** an equal stiffness is obtained after a 60 second loading. According to PG 58-28 used in this investigation, -18°C was used for all BBR testing. The obvious benefit is that a test result can be measured in a much shorter period of time. The second parameter needed from the BBR test is the m-value. The m-value represents the rate of change of the stiffness, S (t), versus time. The bending beam computer also calculates this value automatically. The calculation of the creep stiffness is based on the classic beam analysis theory (Equation 1). It is expected that 300 MPa is the maximum value for asphalt binder creep stiffness and m-value is expected to be at least 0.3 for BBR testing. The asphalt binder should pass both criteria to pass the SuperPave ^{TM} specifications.

$$S(t) = PL^3/4bh^3\ \delta(t) \tag{1}$$

Where,
S(t) = creep stiffness at time, t = 60 seconds;
P = applied constant load, 100gm (980 mN);
L = distance between beam supports, 102 mm;
b = beam width, 12.70±0.05 mm;
h = beam thickness, 6.35±0.05 mm; and
δ (t) = deflection at time, t = 60 seconds loading.

6. Results and Discussion

Fig.2 shows the G*/sin (δ) for virgin binders (control (58-28), foamed and unfoamed NHL modified and foamed RHL modified binders). It is clear from this figure that the AD (neat binder foamed with 4.5% of Advera®) has less capability to resist the rutting among all other binders. It seems the addition of Advera® to the control binder by 4.5% (by weight) lowers the resistance to permanent deformation (rutting) of the neat binder. However, it is quite clear from the figure that the addition of NHL to the control binder stiffens the binder consequently, increasing the rutting resistivity. Despite the addition of Advera® to control binder reduced G*/sin (δ), the foamed NHL modified binder increased the G*/sin (δ) compared to that the unfoamed NHL modified binder. This emphasizes that there is compatibility between Advera® and NHL to enhance the virgin binder properties. From the figure it can also be seen that as the NHL percent increases, the G*/sin (δ) increases (rutting decreases). The foamed RHL modified binder also was studied along with the foamed NHL modified binder. It is clear that the RHL is not competitive compared to the NHL. Different percentages of Advera® also were added to the NHL modified binders. Generally from the studied percentages (3%, 4.5%, and 6%), the 4.5% seems the optimum content of Advera® when considering rutting.

The G*/sin (δ) values for the RTFO binders also were calculated and plotted in **Fig.3**. The general trend of the foamed hydrated lime (NHL and RHL) modified binders is similar as that for the virgin binders shown in **Fig.2**. Interestingly, it can be seen that the rutting resistance of RTFO foamed control binder (AD) is higher than for the control binder (58-28). However, for the neat and Advera® foamed binders, there is contradiction between virgin and RTFO rutting behavior. Therefore, different tests, such as creep and recovery testing, will be conducted in the future for rutting evaluation of foamed asphalt binders.

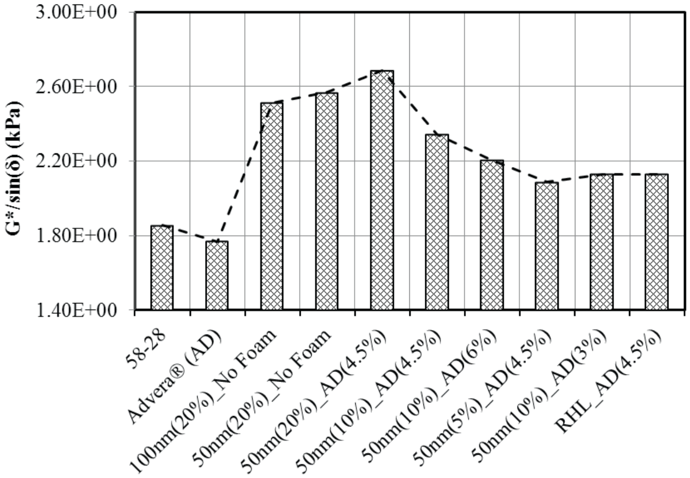


Fig.2. Rutting Parameter (G*/sin (δ)) of Virgin Asphalt Binders

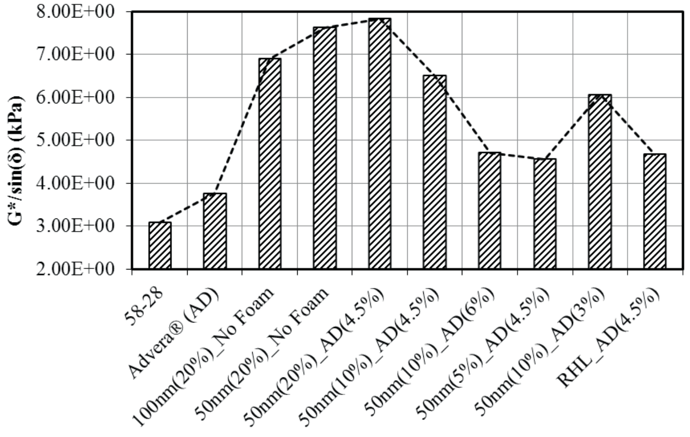


Fig.3. Rutting Parameter (G*/sin (δ)) of RTFO Aged Asphalt Binders

The fatigue cracking parameter G*.sin (δ) was calculated for the PAV aged binders as shown in **Fig. 4**. It can be seen that the addition of Advera® increases the fatigue cracking prone for the neat control and NHL modified binders. The more NHL added to the binder, the more prone to the fatigue cracking. Smaller particle size of NHL (50nm) increases the fatigue cracking of the binder compared to the bigger sizes (100nm). It can also be seen that all virgin, RTFO and PAV binders passed the SuperPave ^{TM} rutting and fatigue cracking specifications.

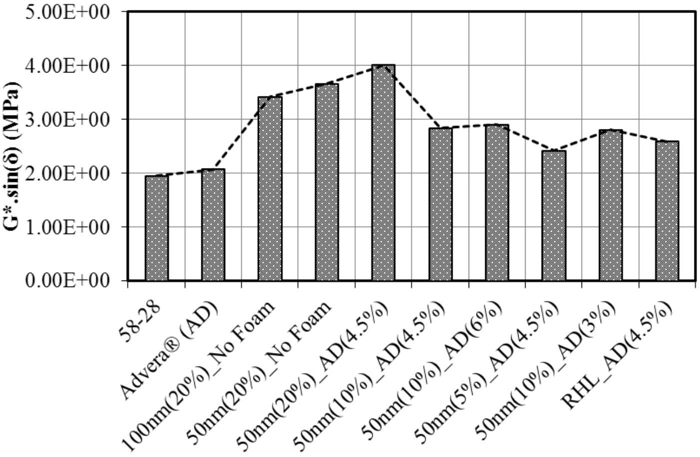


Fig.4. Fatigue Cracking Parameter (G*.sin (δ)) of Asphalt Binders

The effectiveness of the NHL modification on the creep stiffness of binders is shown in **Fig.5**. It is quite clear that the addition of Advera® increases the creep stiffness of the binder. For the studied percentages of NHL and Advera®, the binders did not violate the specifications (creep stiffness<300 MPa). The smaller particle NHL (50nm) has creep stiffness higher than that for bigger sizes NHL (100nm). The m-value for the binders is shown in **Fig.6**. The m-values of all binders is higher than 0.30 therfore met the specifications requirements. From rutting, fatigue cracking, and thermal cracking results, it can be seen that the RHL results were close to that for 5% of NHL (50nm).

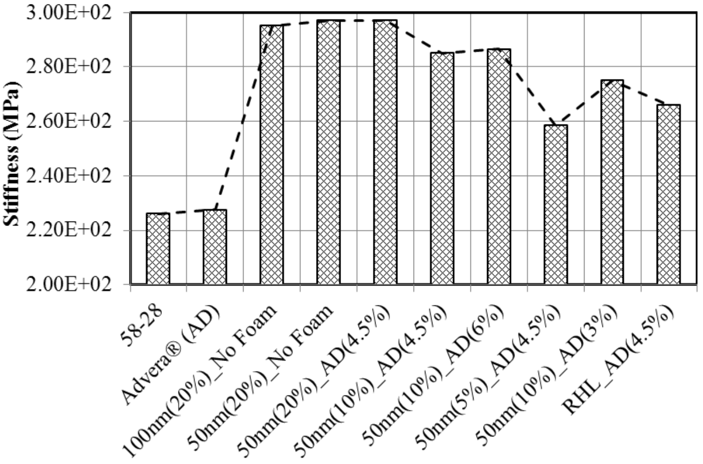


Fig.5. Creep Stiffness of Asphalt Binders

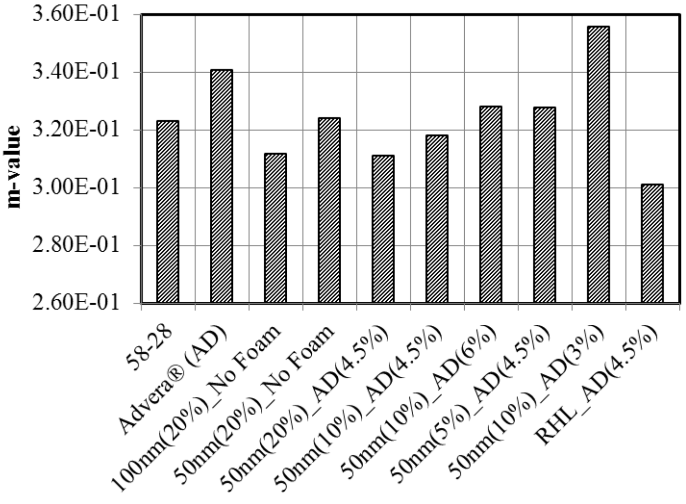


Fig.6. M-value of Asphalt Binders

7. Conclusions

Based on the analysis of the results obtained in this study, the concluding remarks follow:

- The addition of Advera® slightly decreased the rutting resistivity for virgin binders. On the contrary it was increased for the RTFO aged binders.
- The addition of the RHL with its normal dose (20% by weight) can be replaced by adding almost 5% of NHL (50nm) because rutting, fatigue cracking and thermal cracking results changed minimally.
- Rutting resistance, fatigue cracking, and creep stiffness increase with the decrease of NHL particle size and with the increase of NHL dose.
- Higher compatibility between NHL and Advera® since the rutting resistance of foamed NHL modified binder is higher than that for the unfoamed NHL modified binder.
- The 4.5% of Advera® was the optimum content between the studied percentages (3%, 4.5%, and 6%). However, the smaller and the excessive amounts of Advera® negatively affected the rutting resistance of the binder.
- The results of foamed RHL modified binder seemed less competitive than NHL modified binder.
- The creep stiffness of the foamed NHL modified binders is higher than that for the RHL modified binders.

References

AASHTO, A. T.-. (2011a). "Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test)." in AASHTO *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*. American Association of State Highway and Transportation Officials: Washington D.C.

AASHTO, A. T.-. (2011b). "Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)." in AASHTO *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*. American Association of State Highway and Transportation Officials: Washington D.C.

AASHTO, A. T.-. (2011c). "Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR)." in AASHTO *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*. American Association of State Highway and Transportation Officials: Washington D.C.

ASTM (2008). ASTM D 6521: Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV). West Conshohocken, PA, *American Society Testing & Materials*. **4**.

Berker, A., Bouldin, M. G. and Collins, J. H. (1990). "Rheological rationale for rutting resistance." *Tech. Bull.*, Shell Chemical Co., Houston, Tex.

Bonaquist, R. (2008). "Mix Design Practices for Warm Mix Asphalt." NCHRP 9-43, Interim Report. Washington D.C.: *National Cooperation Highway Research Program*.

Button, J. W., Estakhri, C. and Wimsatt, A. (2007). "A Synthesis of Warm-Mix Asphalt." Report 0-5597-1, Texas Transportation Institute, Austin, Texas.

Cheng, J., Shen, J. and Xiao, F. (2011). "Moisture susceptibility of warm mix asphalt mixtures containing nanosized hydrated lime." *Journal of Material in Civil Engeering*, p. 265.

D'Angelo, J., Harm, E., et al. (2008). "Warm Mix Asphalt: European Practice." *FHWA report* no: FHWA-PL-08-007. 68p.

Diab, A., You, Z., Othman, A. M. and Ahmed, H. Y. (2012). "Fatigue characteristics of Hydrated Lime Modified HMA." *International Journal of Pavement Research and Technology* (IJPRT).

Goh, S. W. and You, Z. (2008). "Resilient Modulus and Dynamic Modulus of Warm Mix Asphalt." GeoCongress 2008, *Geosustainability and Geohazard Mitigation, Geotechnical Special Publication* (GSP 178), American Society of Civil Engineers, 1000-1007.

Goh, S. W. and You, Z. (2009). "Preliminary Study of Evaluating Asphalt Pavement Rutting Performance Using The Mechanistic-Empirical Pavement Design Guide." *Proceedings of the 14th Conference on Cold Regions Engineering*, American Society of Civil Engineers, Duluth, Minnesota, 366-373.

Goh, S. W. and You, Z. (2012). "Mechanical Properties of Porous Asphalt Pavement Materials with Warm Mix Asphalt and RAP." *ASCE Journal of Transportation Engineering*. 138(1): p. 90-97.

Hassan, M. M. (2009). "Life-Cycle Assessment of Warm-Mix Asphalt: Environmental and Economic Perspectives." *Transportation Research Board*.

Hodo, W., Kvasnak, A. and Brown, E. R. (2009). "Investigation of foamed asphalt (warm mix asphalt) with high reclaimed asphalt pavement (RAP) content for sustainment and rehabilitation of asphalt pavement." *TRB 88th Annual Meeting, Transportation Research Board*, Washington, D.C.

Hofstra, A. and Klomp, A. J. G. (1972). "Permanent Deformation of Flexible Pavements under Simulated Road Traffic Conditions." *Third International Conference on the Structural Design of Asphalt Pavements*, Vol 1., 613-621.

Hurley, G. C. and Prowell, B. D. (2005). "Evaluation of Aspha-Min Zeolite for Use in Warm Mix Asphalt." *National Center for Asphalt Technology*.

Hurley, G. C., Prowell, B. D., et al. (2006). "Evaluation of Potential Processes For Use In Warm Mix Asphalt." *Association of Asphalt Paving Technologist*, White Bear Lake, MN 55110, United States, Savannah, GA, United States, 41-90.

Jamshidi, A., Hamzah, M. O. and You, Z. (2012). "Performance of Warm Mix Asphalt containing Sasobit®: State-of-the-art." *Construction and Building Materials*. 38: p. 530-553.

Johansson, L. S. (1998). "Bitumen aging and hydrated lime." *Rep. TRITA-IP FR* 98-38, Royal Institute of Technology, Stockholm, Sweden.

Kortschot, M. and Woodhams, R. T. (1984). "Torsional braid analysis of bitumen-liquid rubber mixtures." *Polymer Engrg and SeL*, 24(4), 252-258.

Kristjánsdóttir, O. (2007). "Warm Mix Asphalt Technology Adoption." *NVF 33 Annual Meeting*, Trondheim, Norway.

Little, D. N. and Epps, J. (2001). "The benefits of hydrated lime in hot mix asphalt." *Report for national lime association*.

Middleton, B. and Forfylow, R. W. (2009). "Evaluation of warm-mix asphalt produced with the double barrel green process." *Transp. Res. Rec*., 2126, 19–26.

Peterson, J. C. (1987). "Lime treatment of asphalt to reduce age hardening and improve flow properties." *Presentation at the Annul meeting of AAPT*, Reno,Nevada, pp. 23-25.

Prowell, B. and Hurley, C. (2007). "Warm-Mix Asphalt: Best Practices." *Presentation at 53rd NAPA Annual Meeting*.

Roque, R., Tia, M. and Ruth, B. E. (1987). "Asphalt rheology to define the properties of asphalt concrete mixtures and the performance of pavement." Asphalt rheology; relationship 10 mixture, ASTM STP 941. O. E. Briscoe, cd., ASTM, Philadelphia, Pa., 3-27.

Sebaaly, P. E., Hilty, E. and Weizel, D. (2001). "Effectiveness of lime in hot mix asphalt pavement." University of Nevada,. Reno, http://www.wrscunt.edu/WRSCMoisture_files/repor.pdf.

Shen, J., Huang, B., Shu, X. and Tang, B. (2010). "Influence of nano-sized hydrated lime (HL) on selected properties of hot-mix asphalt (HMA)." *Int J Pavement Res Technol*, 4 (4) (2010), pp. 252–257.

Tasdemir, Y. (2009). "High temperature properties of wax modified binders and asphalt mixtures." *Construction and Building Materials*, vol. 23, no. 10, pp. 3220–3224.

Wasiuddin, N. M., Selvamohan, S., Zaman, M. M. and Guegan, M. L. T. A. (2007). "A Comparative Laboratory Study of Sasobit® and Aspha-min® in Warm-Mix Asphalt." *Transportation Research Board 86th Annual Meeting*, Washington DC, United States.

Wasiuddin, N. M., Zaman, M. M. and Rear, E. A. (2008). "Effect of Sasobit and Asphamin on Wettability and Adhesion Between Asphalt Binders and Aggregates." *Transportation Research Board.*

Wayne, H. (2009). "Field and laboratory investigation of foamed asphalt (warm-mix asphalt) with high recycled asphalt pavement content for sustainment and rehabilitation of asphalt pavement." *TRB 88th Annual Meeting, Transportation Research Board*, Washington, D.C.

Wielinski, J., Hand, A. and Rausch, D. M. (2009). "Laboratory and field evaluations of foamed warm-mix asphalt projects." *Transp. Res. Rec.*, 2126, 125–131.

Xiao, F., Amirkhanian, S. N. and Putman, B. J. (2010). "Evaluation of rutting resistance in warm-mix asphalts containing moist aggregate." *Transport Res Rec: J Transport Res Board*, 2180 (2010), pp. 75–84 http://dx.doi.org/10.3141/2180-09.

You, Z. and Goh, S. W. (2008). "Laboratory Evaluation of Warm Mix Asphalt: A Preliminary Study." *International Journal of Pavement Research and Technology*, 1(1): p. 34-40.

Youtcheff, J. S. and Jones, D. (1994). "Guideline for Asphalt Refiners and Suppliers." *Strategic Highway Research Program*, SHRP-A-686, Washington, D.C.