

5-2014

The Characterization of Foamed Asphalt Binders Using a Rotational Viscometer

John William Ryan

University of Arkansas, Fayetteville

Follow this and additional works at: <http://scholarworks.uark.edu/etd>



Part of the [Civil Engineering Commons](#)

Recommended Citation

Ryan, John William, "The Characterization of Foamed Asphalt Binders Using a Rotational Viscometer" (2014). *Theses and Dissertations*. 2316.

<http://scholarworks.uark.edu/etd/2316>

The Characterization of Foamed Asphalt Binders Using a Rotational Viscometer

The Characterization of Foamed Asphalt Binders Using a Rotational Viscometer

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Civil Engineering

by

John Ryan
University of Arkansas
Bachelor of Science in Civil Engineering, 2012

May 2014
University of Arkansas

This thesis is approved for recommendation to the Graduate Council.

Dr. Andrew Braham
Thesis Director

Dr. Kevin D. Hall
Committee Member

Dr. Micah Hale
Committee Member

ABSTRACT

Foamed asphalt is a popular technic of vaporizing water into asphalt binder that falls under the umbrella term of warm-mix asphalt. In order to understand how to adjust mix designs for the use foamed asphalt, methods must be developed for characterizing different foamed asphalt binders. One way to characterize the asphalt binder is through viscosity testing using a rotational viscometer. The standard method of using a viscometer to measure the viscosity of asphalt binder is insufficient when dealing with foamed asphalts, so a new method has been created along with 4 metrics to analyze the data to characterize foamed asphalt binders.

ACKNOWLEDGEMENTS

I would like to give special thanks to the Arkansas State Highway and Transportation Department for the funding of this project. I would like to acknowledge Cory Bramlett, Erica Yeung, Kaisha Plambeck, and Alex Jackson for their help with the lab work as well. I would like to thank Dr. Stacy Williams for all of her technical support for my research in this project. Finally, a huge thank you goes out to Dr. Andrew Braham for the time and effort he invested into me and my graduate career.

DEDICATION

I would like to dedicate this paper to my father and the rest of my family for their continued support throughout my college career.

TABLE OF CONTENTS

I. INTRODUCTION.....	1
II. METHODS.....	4
III. RESULTS AND DISCUSSION	11
IV. SUMMARY AND CONCLUSIONS.....	18
V. REFERENCES	20

I. INTRODUCTION

Warm Mix Asphalt (WMA) is becoming a very popular alternative to traditional Hot Mix Asphalt in the United States. WMA additives as an alternative to HMA is a topic that has been thoroughly researched and developed for designing mixtures but foamed asphalt is still a relatively undiscovered area of WMA (1) - (2). NCHRP report 691 recommends the use of lab foamers when doing mix design work in the lab; however a study by NCAT found no difference in the field between an HMA pavement and a foamed pavement using the same design as the HMA pavement (3) - (4). The information supporting both sides suggests that more work is needed to determine the value to using lab foamers for mix design use. There are a three lab foaming machines (Wirtgen's WLB 10s, PTI's "The Foamer", Instrotek's AccuFoamer) that have been produced that claim to mimic field foaming machines, such as the AQUABlack WMA System, the AquaFoam System, and the Double Barrel Green System, but there is not much data to defend these claims. There are several ways that foamed asphalt could be characterized for mix design use. One such way is via the viscosity of the foamed asphalt binder itself. Here four metrics [FVf/OBV (final foamed viscosity/original binder viscosity), AAOB (area above original binder viscosity and below foamed binder viscosity), ABOB (area above foamed binder viscosity and below original binder viscosity), and TTI (time to intersection of foamed asphalt binder viscosity and original binder viscosity)] were created solely for the purpose of characterizing foamed asphalt binder.

The most observed method for characterizing foamed asphalt is via the expansion ratio (ER) and half-life (HL) of the foamed asphalt. The expansion ratio of foamed asphalt is the initial volume of a sample of asphalt binder after foaming divided by the final volume of that sample of

binder(or the initial volume before foaming) (5). Half-life is a measure of the time required for a sample of foamed asphalt to reach half of its maximum volume. Some recommendations are that the HL be at least 6 seconds and that the ER be at least 8:1 for foamed warm-mix (5). This method of optimizing half-life and expansion ratio requires testing a whole matrix of possible water contents, binder temperatures, and air/water pressures (6). This could require up to 96(4 water contents, 4 air pressures, 3 temperatures, 2 replicates (6)) 500g samples of binder to be tested that would take hours to complete. Some research has shown that these parameters can be dependent on the operator (5), so research is being done on how to use lasers or video cameras to measure these parameters more accurately (5). Another way to try to characterize foamed asphalt binder is to use liquid nitrogen to freeze foamed asphalt samples and use x-ray imaging to characterize the foam thru bubble count and bubble diameter classification (7). At least two different research groups followed the standard ASTM D4402 to measure the viscosity of foamed asphalt and saw no change or an insignificant change in the viscosity of foamed binder vs. original binder (8) - (9). These groups examined the final viscosity of the foamed asphalt at higher temperatures around 160°C. Most of these methods require extra equipment that can become very expensive. The attempt in this research is to use standard asphalt lab equipment already readily available to characterize foamed asphalt.

The current method for measuring the viscosity of asphalt binder is to follow ASTM D4402 using a Brookfield rotational viscometer. The viscosity given by the rotational viscometer is the ratio between the applied shear stress and the rate of shear and can be calculated from Equation 1 (10). Typically the RV measures torque in a percent (0 to 100), divides this torque by the RPM, and multiplies it by a series of constants based on the spindle used (11).

Equation 1

$$\eta = \frac{\tau}{\gamma} \quad \tau = \frac{T}{2\pi R_s^2 L} \quad \gamma = \frac{2\omega R_c^2 R_s^2}{x^2(R_c^2 - R_s^2)}$$

Where:

η = dynamic viscosity (Pa * s)

τ = shear stress (N / cm²)

γ = shear rate (s⁻¹)

T = torque (N * m)

L = effective spindle length (m)

R_s = spindle radius (m)

R_c = container radius (m)

ω = rotational speed(radians / second)

x = radial location where shear rate is being calculated

The SI unit of viscosity is the Pascal second (Pa*s) and the centimeter gram second unit of viscosity is the poise frequently reported in cP where 1 cP is equal to 0.1 Pa*s. An important note when using the Brookfield viscometer is that the viscometer assumes there are no air bubbles inside the liquid being tested. Using this equipment is straightforward when using unfoamed asphalt binder that has no air bubbles inside of the binder but foamed asphalt does have air inside it and is an unstable substance, meaning that the volume of a sample of foamed asphalt is constantly changing from the instant the water starts to mix with the asphalt binder until such a time that all the water/air has escaped the binder. There are several observations about foamed asphalt that can be recorded in relation to trying to obtain a viscosity measurement:

- After the foaming process stops, there may be a slight continued increase in volume until the maximum expansion is reached and the foam starts to collapse

- If any heat is added to the foam, such as inserting a sample into a temperature controlled thermo-cell, the foam can continue to expand as the air bubbles inside the foam are heated and air pressures in the bubbles build
- If the foamed asphalt is introduced to the thermo-cell at the same temperature as the foaming process was set, then the asphalt could expand outside of its sample chamber and possibly not leaving enough material inside the chamber to test
- At higher temperatures, the viscosity value of a binder both foamed and unfoamed can be very similar if using the typical testing procedure

All of these observations lead to the creation of a new testing procedure that will allow foamed asphalt to be easily tested in a viscometer at a wide range of temperatures. This testing procedure will record the observed viscosity over time so that the influence of the bubbles over time can be observed.

II. METHODS

The first task is to create a testing method that allows differences to be recorded for foamed asphalt vs. original binder while using a rotational viscometer. Typically two temperatures such as 135°C and 160°C are used to test asphalt binders for Superpave testing (12). Asphalt binder must have a viscosity of less than 3 Pa*s at 135°C. The viscosity at these two temperatures is used to create a line to find the mixing and compacting temperature zones on a temperature-viscosity chart. The spindle, sample chamber, and thermo-cell are preheated to the testing temperature and asphalt is poured in at that temperature. If this procedure is followed with foamed asphalt, two things would occur. First, the foamed asphalt would expand in the thermo-cell overflow out of the sample chamber and thermo-cell. The remaining sample would not be

large enough to perform a proper viscosity test. Second, the foamed nature of the sample would not be observed through the data if the sample is allowed to cool off to a lower temperature and allow the sample to stabilize.

Since foamed asphalt isn't a stable substance, a new method was established to measure viscosity over a period of time instead of at a single data point at one time such as in ASTM D4402. In this method, viscosity data points were recorded at 1 minute intervals until three measurements in a row recorded the same viscosity value. This allows for a viscosity vs. time curve to be constructed for each foam sample. An example of these curves can be seen in Fig. 1. The viscosity measurements taken for the foamed asphalt is called "observed viscosity" as an effort to point out that the measurement isn't a true viscosity of the asphalt binder but a reading that the Brookfield is outputting based on the combination of binder and air bubbles inside the sample. Fig. 1 shows three PG grade binders in a foamed and un-foamed (original binder) condition. The un-foamed viscosities were obtained at one point in time but extended graphically across the figure to provide a better reference baseline with which to analyze the foamed observed viscosity. The whiskers shown are a 95% confidence interval based on 3 replicates. It was observed that there was a wider distribution of data in the first portion of the test and as the test progressed, the variability decreased.

The first testing phase shown in Table 1 was carried out to determine what might be the best way to approach foamed asphalt. It was decided to only use the Wirtgen WLB 10s and PG 64-22 binder to test foaming temperatures and thermo-cell temperatures. The four foaming temperatures tested were 160°C, 145°C, 130°C and 115°C. These temperatures were chosen to

observe a large range of temperatures that could resemble possible foamed warm-mix mixing temperatures. The thermo-cell temperatures are listed as “foam temp – XX” such that if the foaming temp was 160°C the possible thermo-cell temps would be 130°C, 115°C, and 100°C. Each spindle has a certain viscosity range it is capable of reporting so the spindle was changed a few times in this round of testing due to the viscosity dropping out of the initial spindle’s (spindle 21) testing range.

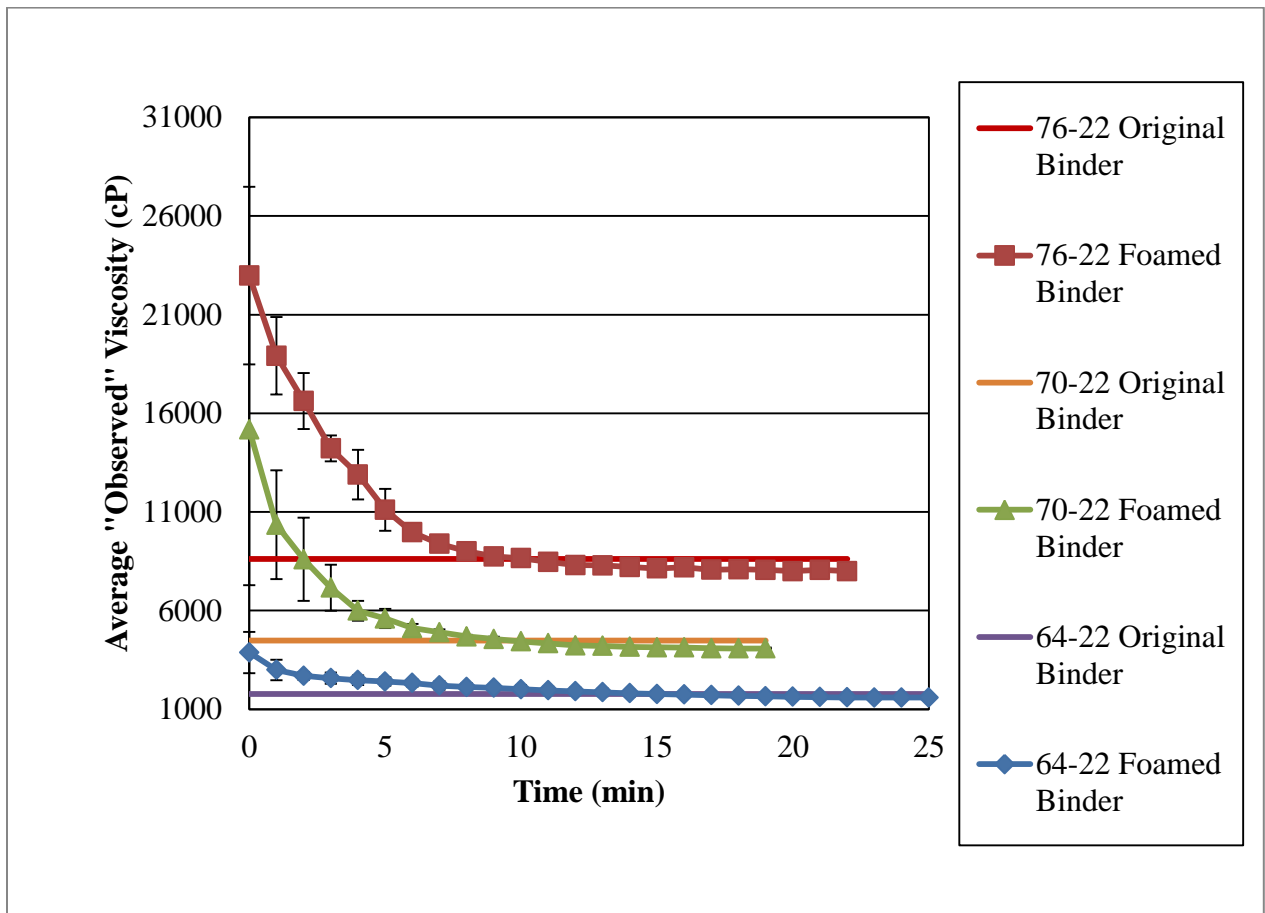


Fig. 1. Example of Viscosity Curves.

Table 1
Phase 1 testing matrix.

Factor	# of levels	Levels
Foaming Temperature	4	160°C 145°C 130°C 115°C
Thermo-cell Temperature	3	Foam Temp - 10°C Foam Temp - 20°C Foam Temp - 30°C
Spindle Number*	3	21 27 28
Binder type	1	Lion Oil 64-22
Foamer type	1	Wirtgen WLB 10S

After looking at the data from this initial round of testing, it was decided to continue testing as many of the foaming temperatures as possible but to only use the maximum thermo-cell temperature drop of -30°C. This was chosen so that the thermo-cell would not warm any of the samples up higher than the temperature that they were placed into the thermo-cell. Foam exiting the Wirtgen foamer ranged anywhere from 5°C to 25°C cooler than the temperature to which the Wirtgen was set. This temperature drop is occurring because the water starts at room temperature but quickly pulls heat from the asphalt as it is mixed together. The change in these temperature drops observed in the different foaming temperatures can be explained by poorer mixing as the foaming temperature goes down. The water isn't distributed as well during the foaming action so it can't absorb as much heat from the foam. This data can be seen in Table 2. The second phase used three binders (PG64-22, PG70-22 polymer modified, and PG76-22 polymer modified) and two foamers (Wirtgen WLB 10s and PTI "The Foamer") but only used 1 spindle

for all the testing because changing the spindle (and thus the spindle geometry) affects how the bubbles are allowed to escape the foam sample during testing. The wider the spindle geometry, the quicker the bubbles were forced out of the sample. Table 3 shows the testing matrix for phase 2. Not all of the temperature/binder/foamer combinations were possible so Table 4 shows which combinations were foamed and tested and which were unable to create foam. If an asphalt binder was not able to foam at certain temperature, “no foam” is indicated on the table. In phase 2 testing, the two foamers were being compared to each other as well as the binder grades being compared to each other.

Table 2
Wirtgen exit foam temperature testing

Sample	Wirtgen set temperature			
	160°C	145°C	130°C	115°C
	Temperature Measured with Probe			
1	134	133	115	109
2	133	121	117	111
3	139	137	115	111
avg.(°C)	135	130	116	110
Change(°C)	25	15	14	5

Table 3
Phase two testing matrix

Factor	# of levels	Levels
Foaming Temperature	1	160°C
Thermo-cell Temperature	1	Foam Temp - 30°C
Spindle Number	1	28
Binder type	3	Lion Oil 64-22 Lion Oil 70-22 PM Lion Oil 76-22 PM
Foamer type	2	Wirtgen WLB 10S PTI “The Foamer”

Table 4
Phase 2 matrix, expanded showing impossible combinations. *means temp raised to 165°C

Foamer & Binder Grade	Foaming temperature			
	160°C	145°C	130°C	115°C
Wirtgen				
PG 76-22	tested	tested	no foam	no foam
PG 70-22	tested	tested	tested	no foam
PG 64-22	tested	tested	tested	tested
PTI	160°C	145°C	130°C	115°C
PG 76-22	tested at 165°C	no foam	no foam	no foam
PG 70-22	tested	no foam	no foam	no foam
PG 64-22	tested	tested	no foam	no foam

In order to make sense of the observed viscosity curves created by the phase 2 testing, four different metrics were created to attempt to characterize the foamed asphalt binder. These metrics are FVf/OBV (final foamed viscosity divided by original binder viscosity), AAOB (area above original binder viscosity and below foamed binder viscosity), ABOB (area above foamed

binder viscosity and below original binder viscosity), and TTI (time to intersection of foamed asphalt binder viscosity and original binder viscosity). FV_f/OBV is the ratio of the final foamed viscosity divided by the original binder viscosity. It is the only metric with no time dependency and is represented graphically in Fig. 2 by the two double ring circles. AAOB represents the area above the original binder line and below the foamed binder curve. It has units of $\text{min} \cdot \text{cP}$ and is represented in Fig. 2 by the double line triangular section. Due to the high variability of the observed viscosity in the first minute, the area bound by time zero minute and time one minute does not count towards the area of AAOB. AAOB is represented by the double line triangular shape in Fig. 2. ABOB represents the area below the original binder line and above the foamed binder curve with the units of $\text{min} \cdot \text{cP}$. The last data point used to create this area is the first of the three matching observed viscosity readings representing the end of the test. ABOB is represented by the dashed line triangular shape in Fig. 2. TTI is the time to intersection of the foamed binder curve and the original binder line. It is calculated by simple line-slope algebra using the first observed foam viscosity data points to either side of the original binder line and is represented by the single ring circle in Fig. 2.

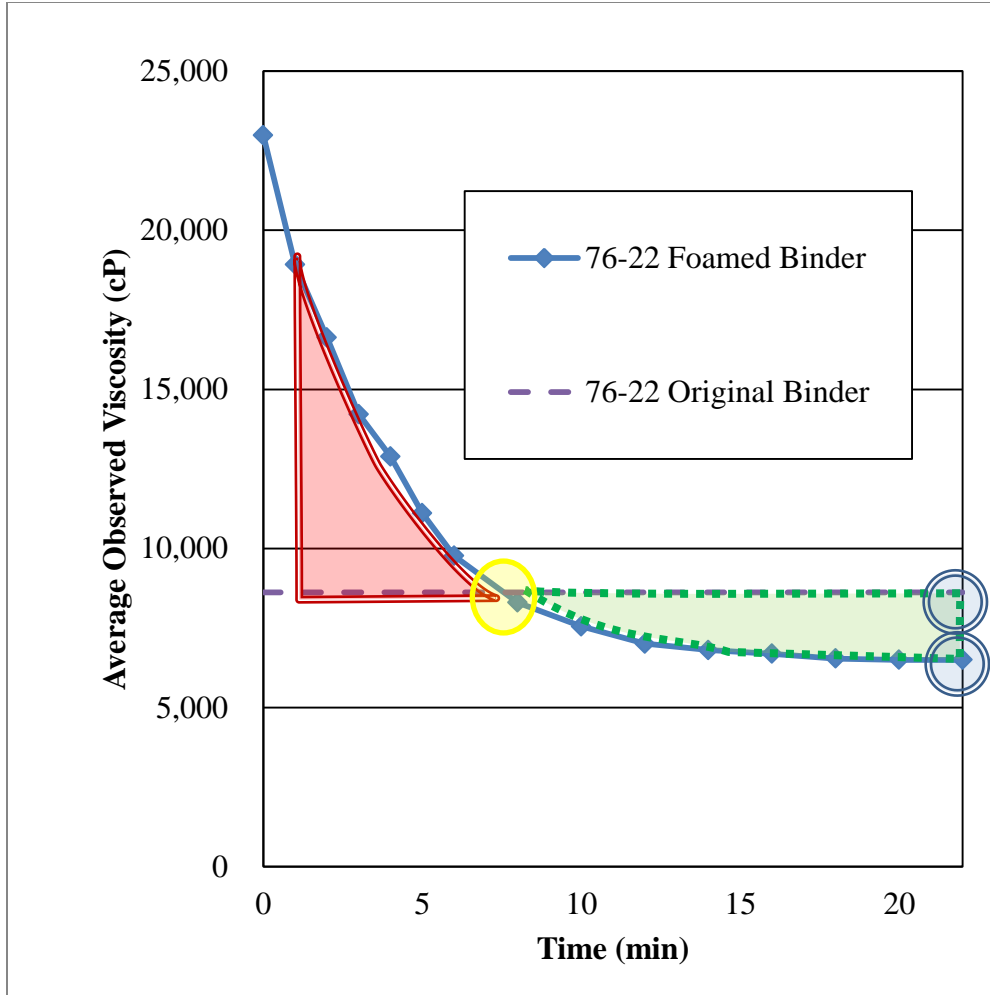


Fig. 2. Example of observed viscosity curve showing where the 4 metrics are found.

III. RESULTS AND DISCUSSION

The Results of the thirteen possible binder/foamer/temperature combinations are shown together in Fig. 3. All the curves start with a relatively high observed viscosity which decreases as the tests progress with all tests finishing by 30 minutes except for 64W115 and 70W130 where the naming is such that the first number designates the PG grade (76-22, 70-22, 64-22), the middle letter represents the foamer (Wirtgen or PTI), and the last number represents the foaming temperature (160°C, 145°C, 130°C, 115°C). The shape of the observed viscosity curve is dependent on the PG grade. PG 64-22 had lower starting points and took longer to level out. PG

70-22 PM had steeper curves and PG 76-22 PM had the steepest curves. The shape of the 64W115 curve can be explained with temperature. Since the initial foaming temperature was lower than the other foaming temperatures used, the water didn't mix thoroughly with the asphalt binder so it didn't cool down as much as the higher foaming temperatures. When this sample was inserted into the thermo-cell, it was still much warmer than the 85°C that the thermo-cell was set. Some sort of lower temperature limit for foaming may be applicable to avoid poor foaming to occur

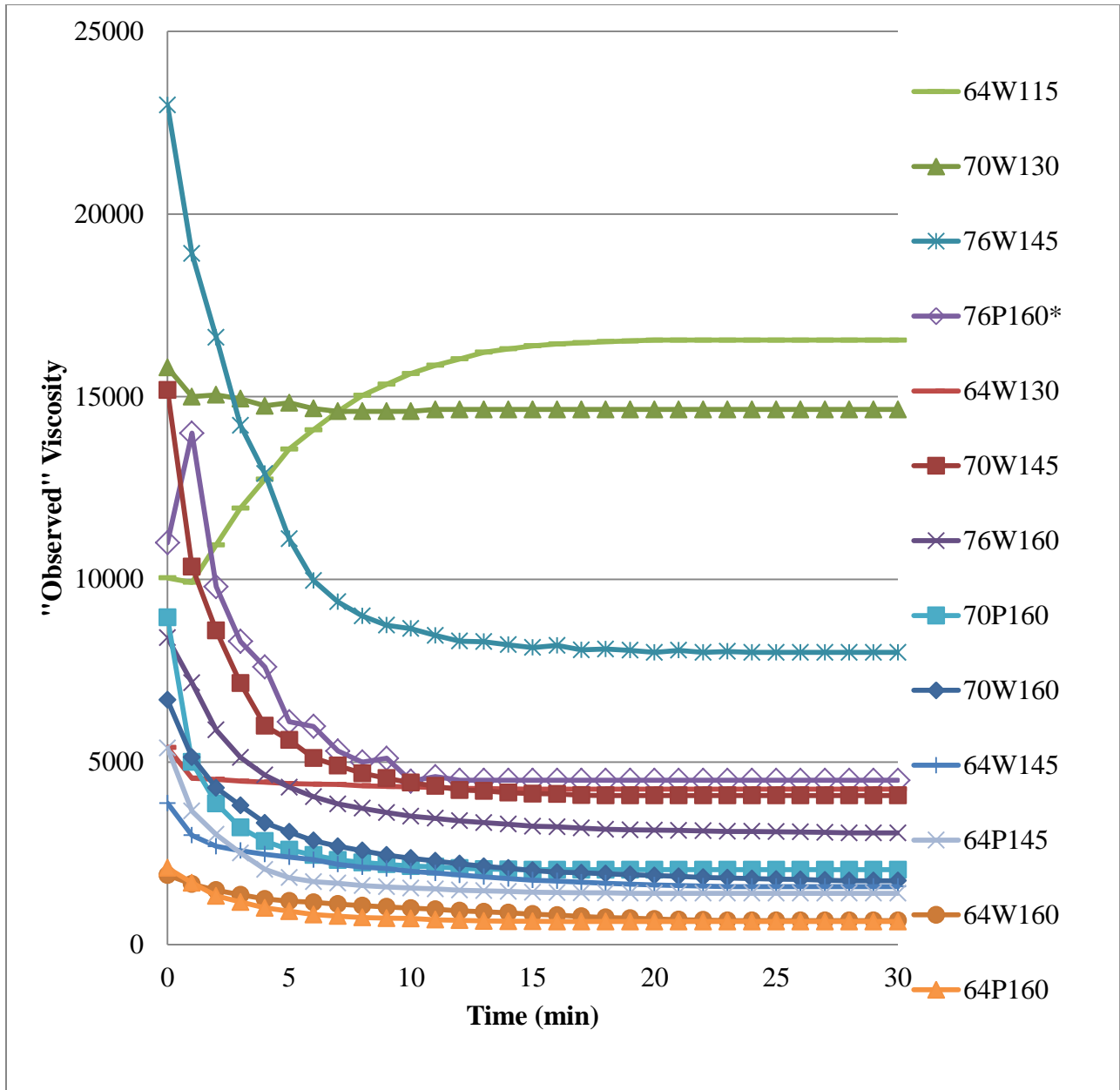


Fig. 3. Phase 2 Data (all 13 curves).

The first foaming metric examined was the FVf/OBV data. Fig. 4 shows the FVf/OBV data. As the foaming temperature decreases, so does this ratio. The ratio decreases as the PG grade decreases at a set temperature. At 160°C the PTI and Wirtgen have similar ratios for all PG grades. The PTI data has a bigger decrease from a foaming temperature of 160°C to 145°C.

When looking at the FVf/OBV data, the lower ratios observed when lowering the foaming temperature are most likely from micro bubbles in the asphalt that are unable to escape from the sample due to the lower temperature but are small enough to not cause friction between the sidewall of the sample chamber and the spindle thus increasing the observed viscosity. A second interesting trend is that the PTI made a more significant drop from 160°C to 145°C (~100% to ~80% as compared to ~98% to ~90% with the Wirtgen). This is probably explained by the different processes of foaming used by each foamer. The Wirtgen pumps the asphalt and water through the system and forces the foam out a nozzle whereas the PTI uses gravity to feed the asphalt binder and lighter pressure to force the water and air to mix with the asphalt binder. This softer foaming process may allow more bubbles to stay immersed in the asphalt binder at lower temperatures. Also the lower the PG grade the lower the ratio which is explained by the smaller bubbles being able to form in the softer asphalt binder.

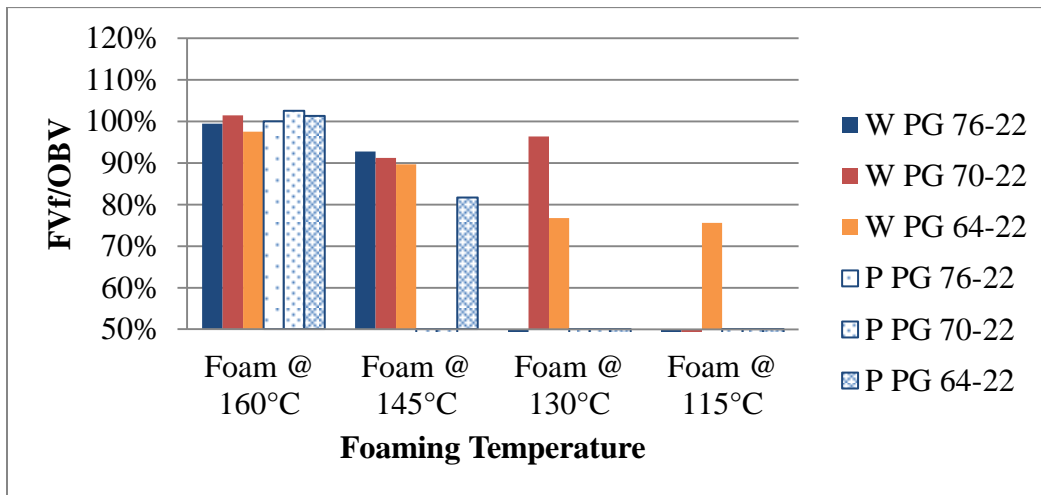


Fig. 4. FVf/OBV data.

The next metric to be considered was the AAOB metric or the area above the original binder and below the foamed viscosity lines. Fig. 5 shows the AAOB data collected. The AAOB area goes

down as the PG grade increases for both foamers. PTI values are generally slightly lower than their Wirtgen counterparts. PG 64-22 has much lower values than both PG 70-22 and PG 76-22.

When the AAOB data is examined, AAOB decreases as the PG grade decreases. This is explained by the softer PG grades allowing the larger bubbles to pop faster. The three data points that are zero for AAOB can be explained by a combination of temperature and poor foaming. The foaming temperature is so low that the foam coming out isn't cooling off as quickly as at the higher temperatures (see Table 2) so the -30°C isn't as close to the actual temperature of the foam as with the higher foaming temperatures and this is affecting the shape of the curve. The foam isn't foaming and mixing as well either because of the lower temperature. The asphalt does not want to mix with the water as readily, so not as many large bubbles are forming to spike up the viscosity reading.

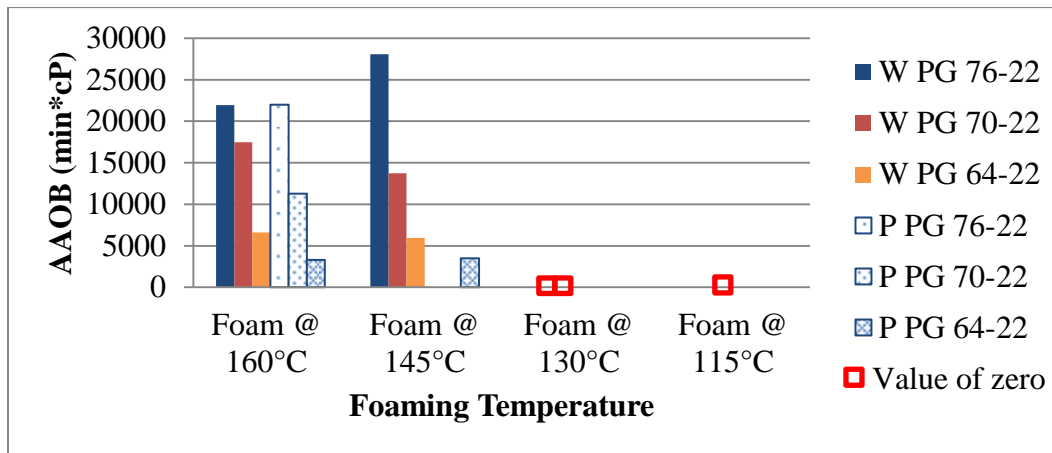


Fig. 5. AAOB data.

The third metric to be analyzed is ABOB, which is similar to AAOB but represents the tail end of the data and is the area below the original binder and above the foamed binder viscosity lines.

Fig. 6 shows the data for ABOB. It is clear that at foaming of 160°C, would not be a reliable metric to characterize foamed asphalt binders because it results in a value of zero for each

foamer/binder tested. The foam's observed viscosity is never able to dip below that of its original binder counterpart. As the temperature of foaming decreases, ABOB starts to show up and at 115°C it is eight times bigger than at 130°C. The polymer modified PG 70-22 is less affected than the unmodified PG 64-22.

The ABOB metric is basically 0 for all of the 160°C tests. At higher temperatures the foamed asphalt starts at a very high observed viscosity due to the large bubbles and because it is at a high temperature, both large and small bubbles are free to escape the asphalt returning the binder back to its original viscosity. For lower temps however, the smaller bubbles can't escape and ABOB starts to rise. At 115°C, again the temperature is affecting the results. ABOB for PG 64-22 jumps by a factor of eight from 130°C to 115°C (16,500 to 132,000). This is because the sample being foamed at 115°C is much warmer than the 85°C at which the thermo-cell is set. This means that the sample takes more time to reach equilibrium and creates a much larger ABOB area than the other combinations.

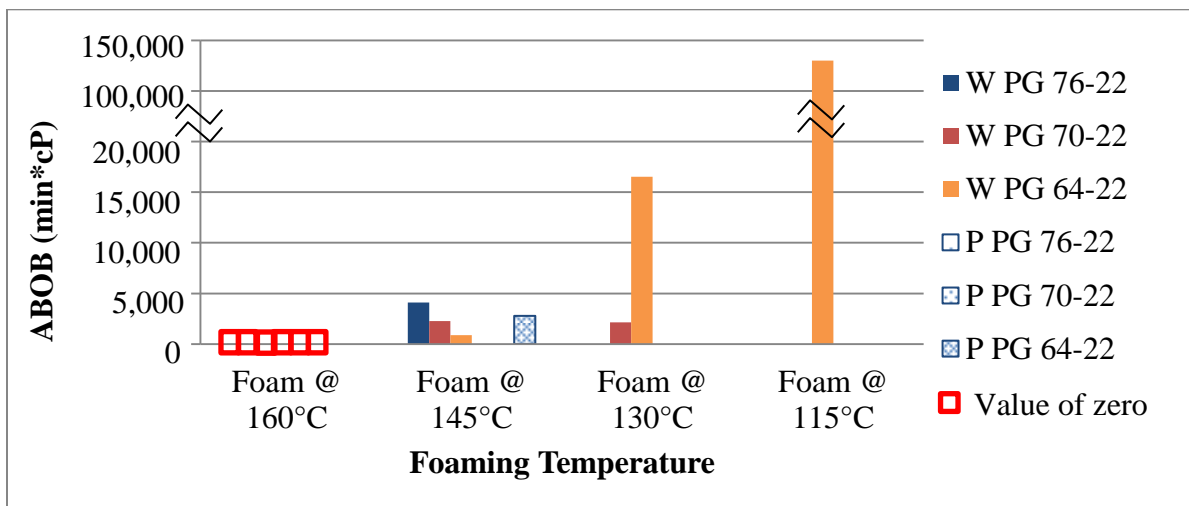


Fig. 6. ABOB Data.

The last metric to be analyzed is TTI, which is the time to intersection of the foamed viscosity and original binder viscosity lines. Fig. 7 shows the data collected for TTI. Lowering the foaming temperature allowed the intersection of foam binder and original binder viscosities to occur more quickly. Values of zero represent samples that started below and never reached their original binder viscosity. Generally, the lower the PG grade, the longer it takes to reach the intersection point.

PG 64-22 took the longest of the PG grades to reach the intersection point. 64-22 is the softest binder so it would seem logical that the opposite trend would hold true. 64-22 had the least AAOB area but took the longest to actually cross the original binder line. This means that the 64-22 binder must be creating more of some midrange bubble size than the higher 70-22 and 76-22 PG grades so that the bigger bubbles pop quickly dropping the observed foam viscosity quickly but keeping the observed viscosity just above the original binder for a longer period of time as those medium bubbles pop. Then when the medium bubbles pop, all that's left are the smallest bubbles which allow the viscosity to drop below the original binder viscosity.

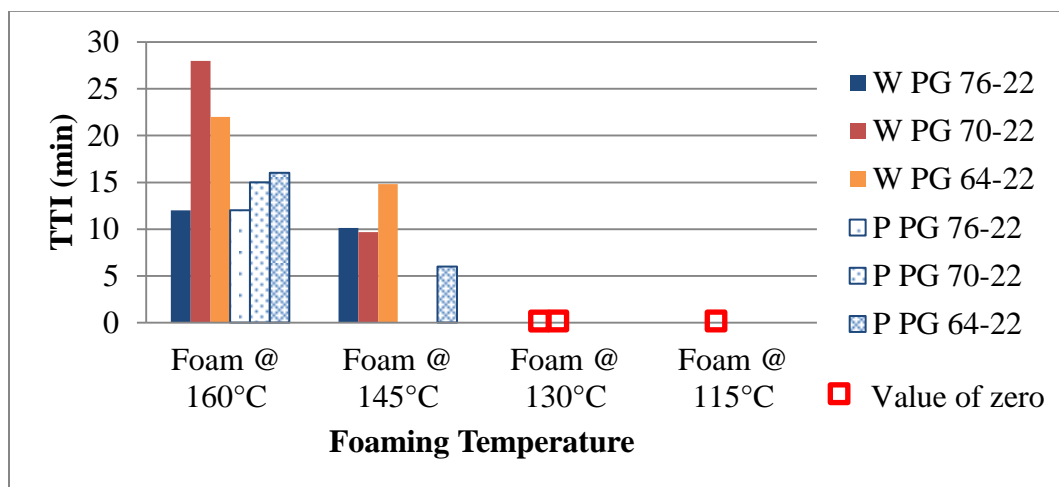


Fig. 7. TTI Data.

So far 4 metrics have been discussed that are hard to relate to current data available for asphalt binders. Another way to try to look at this observed viscosity is to combine AAOB and TTI. AAOB is just a number that relates the size of each curve. When combined with TTI, it can help define the shape of the curve. Fig. 8 shows this data. Higher PG grades observe higher AAOB/TTI values. When able to compare the two foamers, they have relatively similar values. AAOB/TTI provides a better observation of the foamed binder rather than just AAOB because AAOB can give the same value for a foam with a high initial viscosity/ low TTI and a low initial viscosity/long TTI. Those two foams would not act the same way when mixing though so more definition is given to the metric when AAOB is divided by TTI.

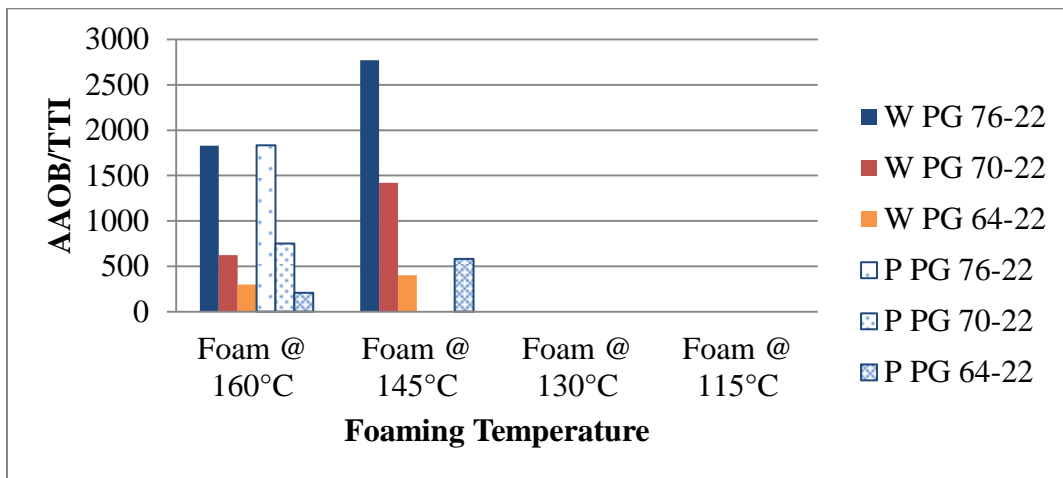


Fig. 8. AAOB/TTI Data

IV. SUMMARY AND CONCLUSIONS

Foamed asphalt is a widely used alternative to HMA in the United States. There is a need to understand and be able to quantify foamed asphalt vs. its HMA counterpart from a mix design perspective. Previous research has been focused on half-life, expansion ratio and trying to count bubble size distributions. The method of testing foamed asphalt in a rotational viscometer outlined in this paper is different and unique in that it uses equipment labs already have and is

simple and reproducible. There are several conclusions about the viscosity of foamed asphalt based on observation and the four metrics designed for foamed asphalt outlined above:

- Higher foaming temperatures tended to have higher initial viscosities and the lower foaming temperatures had lower final viscosities as compared to original binder counterparts.
- ABOB was hard to compare to the other 3 because of the lack of comparable data at 160°C foaming temperature. The other three show trends of becoming smaller as the foaming temperature decreased.
- While FVf/OBV and AAOB decreased with decreasing binder grade, TTI increased with decreasing binder grade.
- When comparing the Wirtgen to the PTI, the PTI generally had lower numbers which is reflected in the visual assessment of the foam created by both foamers. The PTI took longer to create foam and didn't look as mixed as the Wirtgen foamer. The Wirtgen allowed more flexibility when testing different binders and temperatures. The gravity fed design of the PTI limits how well it can foam by how the binder needs to be to flow easily through its system.
- AAOB/TTI gives a good definition of the entire viscosity curve and may prove to be a reliable relationship to move forward with.

Further research with a wider study of binders along with field foamer sampling is essential to prove that one or more of these metrics is useful in characterizing foam asphalts. It may also be worthwhile to try foaming at high temperatures and then setting the thermo-cell much lower to see if any gaps in the viscosity can be seen that way since the lowest FVf/OBV ratios were obtained at the lower foaming/thermo-cell temperatures. When examining this data on its own, without field or mixture data to verify, AAOB and TTI may relate well to current theory on expansion ratio and half-life. Using binders that have higher AAOB and TTI values may prove to have higher expansion ratios and half-lives, which would allow for better mixing and coating. Further research is needed to give a more concrete definition of how foamed asphalt viscosity can be used in mix design for foamed asphalt.

V. REFERENCES

1. **Hurley, Graham C. and Prowell, Brian D.** *Evaluation of Evotherm for use in warm mix asphalt.* s.l. : NCAT, 2006. NCAT REPORT 06-02.
2. **Sheth, Nishant Mukeshkumar.** *Evaluation of selected warm mix asphalt additives.* s.l. : University of Iowa, 2010.
3. **NCHRP.** *Mix Design Practices for Warm Mix Asphalt.* Washington, D.C. : TRB, 2011. NCAT REPORT 691.
4. **NCAT.** *Evaluation of warm mix asphalt in Walla Walla, Washington updated with three year performance data.* s.l. : NCAT, 2011. NCAT Report 11-06.
5. **Ozturk, Hande I.** *Quantification of Quality of Foamed Warm Mix Asphalt Binders and Mixtures.* s.l. : Michigan State University, 2013.
6. **Wirtgen.** *Suitability test procedures of foam bitumen using Wirtgen WLB 10 S.* s.l. : Wirtgen GmbH, 2008.
7. *Investigation of Moisture Dissipation in Foam-Based Warm Mix Asphalt Using Synchrotron-Based X-Ray Microtomography.* **Kutay, M. Emin and Ozturk, Hande I.** s.l. : Journal of Materials in Civil Engineering, 2012.
8. *Measuring Effects of Warm Mix Additives: Use of Newly Developed Asphalt Binder Lubricity Test for the Dynamic Shear Rheometer.* **Hanz, Andrew J., et al., et al.** 2180, Washington, D.C. : Transportation Research Record: Journal of the Transportation Research Board, 210.
9. **Shulga, Olga, Maldonado, Rene and Romagosa, Henry.** *Effect of Foaming on Performance of Asphalt Binders Modified with Polyphosphoric acid.*
10. **ASTM.** *Standard Test Method for Viscosity Determination of Asphalt at Elevated Temperatures Using a Rotational Viscometer.* s.l. : ASTM, 2012. D4402/D4402M - 12.
11. **Pavement Interactive.** Rotational Viscometer. *Pavement Interactive.* [Online] April 21, 2011. [Cited: 3 13, 2014.] <http://www.pavementinteractive.org/article/rotational-viscometer/>.
12. **Harman, Thomas, D'Angelo, John and Bukowski, John.** *Superpave Asphalt Mixture Design Workshop.* s.l. : U.S. Department of Transportation Federal Highway Administration, 1999. Demonstration Project No. 90.
13. **Muthen, K. M.** *Foamed Asphalt Mixes - Mix Design Procedure.* s.l. : SABITA Lrd & CSIR Transportek, 1998. CR-98/077.