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Original Research Paper

Comparative study of ethanol foamed asphalt binders and mixtures prepared via manual injection and laboratory foaming device

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HIGHLIGHTS

- This paper presents the consistency assessment of the foamed binders and mixtures.
- Specimen involved prepared using manual injection and the laboratory foaming device.
- Foamed binders were evaluated based on viscosity, expansion ratio, and thermal cracking.
- Mixture samples were tested for the fracture, thermal cracking, and moisture resistance.
- Foamed binders and mixtures produced via both methods are statistically comparable.

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ABSTRACT

The consistency of the ethanol foamed binders and mixtures prepared using asphalt binders foamed by the manual injection technique and laboratory foaming device were evaluated and compared in this study. The asphalt binders foamed using both methods was prepared at 120 °C, 130 °C and 140 °C. The performance of ethanol-foamed binders was evaluated in terms of rotational viscosity, expansion ratio, and low temperature cracking. Meanwhile, the performance of foamed WMA mixtures was tested using semi-circular bending (SCB), disk-shaped compact tension (DCT), and tensile strength ratio (TSR) tests. In order to conduct the TSR test, the samples were conditioned using the Moisture Induced Stress Tester (MIST) to simulate the pore pressure and scouring effects due to a tire passing over wet pavement. The foamed WMA mixtures were produced using pre-heated aggregates at 80 °C and 100 °C and foamed asphalt binders produced at 130 °C. The nano-hydrated lime was used as the filler and anti-stripping agent. Overall, the properties of ethanol-foamed binders and WMA mixtures produced via both methods are significantly comparable, except the resistance to moisture damage test result. However, the findings indicate that the ethanol-foamed WMA mixtures prepared using both techniques are having good resistance to moisture damage, based on the TSR values more than 0.8. The foamed WMA mixtures also exhibited a better resistance to cracking, as indicated by a higher tensile strength compared to the control HMA. Additionally, the WMA specimen prepared at 100 °C was less susceptible to rutting than the samples produced at 80 °C.

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1. Introduction

Different foaming units and techniques have been invented and made commercially available to produce foamed asphalt binders in the field. The applicability of the foaming process in bituminous materials was discovered in the USA in 1956 (Csanyi, 1956). It was revealed that the foamed asphalt binder can be used as a binding material for different types of soils to enhance its properties. The materials were then used as an alternative to moderate the issue of a shortage of good quality aggregate for road construction (Csanyi, 1956, 1959). Besides water, other foaming agents and gases were also adopted in their research. In 1982, the foamed asphalt binder was implemented in the production of surface layer mixtures and paved on hundreds of miles of road in the United States. In Australia, by 1982, the foamed asphalt mixtures had been widely used as a base or sub-base layer in highway construction. The technology was also widely accepted in other countries such as New Zealand, Japan, Germany, and South Africa (Jenkins, 2000).

Overtime, the benefits of warm mix asphalt (WMA) have been appreciated and accepted by the researchers, engineers, governmental agencies, and the public (Guo et al., 2014; Goh and You, 2011; Hasan et al., 2017a; Wang et al., 2012). Most observations found that the application of WMA significantly reduced the greenhouse gas emissions and energy consumption, especially during the production of asphalt mixtures that consumed at least 60% of the cumulative energy required for the construction and maintenance of a road (Arega et al., 2013; D'Angelo et al., 2008; Diab et al., 2014; Goh, 2012; Harrison and Christodulaki, 2000; McKeon, 2006; Ventura et al., 2007). Jenkins (2000) reported that the use of foamed bitumen over cold mixes and hot mix asphalt reduced the atmospheric pollution, lowered the energy consumptions, as well as the conservation of non-renewable energy resources. Kristjansdottir et al. (2007) specified that the typical reduction in energy consumption as compared to conventional hot mix asphalt (HMA) was about 20%–75% depending on the production temperature. However, the degree of benefit is relatively associated with the type and cost of energy that is utilized in the field. A new method based on the total organic matter (TOM) was developed by the Heritage Research Group to measure the exposure of workers to asphalt fume. In their study, assessments were conducted at two multi-technology plants. The results indicated that the average reduction in TOM for WMA was at least 33% lower compared to worker exposure to asphalt fume associated with HMA production. It was also reported that the TOM reduction was statically significant at a 95% confidence interval ($\alpha = 0.95$) based on a five-sample repetition (West et al., 2014). Some other benefits of WMA also have been identified and experienced in the field, for instance good workability, longer haul distance without having problems in handling, allows cold weather paving due to a low cooling rate of the mixture, permits more road construction and rehabilitation at some restricted (non-attainment) areas, and application of WMA mixtures for overlay has solved the severity of bumps caused by the crack sealant (Chowdhury and Button, 2008; D'Angelo et al., 2008; Diab et al., 2014; Kristjanssdottir et al., 2007; Prowell et al., 2007).

Based on the high demands from researchers, different foaming devices were manufactured and made commercially available by different companies to provide the most convenient and highly repeatable laboratory-scale foaming devices. Table 1 summarizes the types of foaming device, water content, and foaming temperature based on previous studies.

Newcomb et al. (2015) summarized that there are several differences between the specified foaming devices as shown in Table 2. Each foaming device was designed with different types of nozzle to supply the binder and the foaming agent. Additionally, the pressures at which the foaming agent, air, and binder are injected into the reaction chamber, as well as the mass control mode are varies. Basically, the compressed air and foaming agent are injected into the hot bitumen in the WIRTGEN foamer to produce the foamed bitumen. The produced foamed binder is then directly dispensed into a container for the production of asphalt mixture. The AccuFoamer also produced the foamed binder in the same mode in an expansion chamber, before being dispensed through a small diameter nozzle. Meanwhile, the PTI foamer dispensed the foamed binder by gravity, and a small amount

Table 1 – Laboratory foaming device with specific testing conditions in several researches.

Foamer/manufacturer	Water content	Foaming temperature (°C)	References
AccuFoamer by InstroTek Inc. WIRTGEN WLB 10S laboratory foamer	1%–3%	120, 135	You et al. (2018)
Foamer by Pavement Technology Inc.	1%–5%	155	Ozturk and Kutay (2014a, b)
WIRTGEN WLB 10S laboratory foamer	1%–3%	160	Yin et al. (2014)
WIRTGEN WLB 10S laboratory foamer	1%–4%	150, 160, 170, 180	Martinez-Arguelles et al. (2014)
AccuFoamer by InstroTek Inc. WIRTGEN WLB 10S laboratory foamer	1%–5%	160	Arega et al. (2013)
WIRTGEN WLB 10	1%–5%	150, 160, 170, 180	Namutebi et al. (2011)
RW 20 digital overhead mixer with a four blade	1%–3%	160	Arega et al. (2015)
WIRTGEN WLB 10S laboratory foamer	1%–4%	160	Hailesilassie et al. (2014)

Table 2 – Direct comparison of the foaming devices (Newcomb et al., 2015).

Characteristics	WIRTGEN WLB 10S	AccuFoamer by InstroTek Inc.	Foamer by Pavement Technology Inc.
Air flow pressure (kPa)	Min: 100 Max: 1000	Min: 517 Max: 1034	Min: 552 Max: 758
Max foaming agent flow pressure (kPa)	1000	207	230
Binder flow pressure (kPa)	Max: 1000	Max: 413	The binder is dispensed by gravity
Binder temperature (°C)	140–200	160–200	177
Binder chamber size	20 L	150–1800 g	6350 g
Foaming agent temperature	No heat	Up to 82 °C	No heat
Foaming agent dosage (%)	0–5	0–9	1–7
Discharge time (g/s)	100	16–20	14–20
Mass control	Mass flow control	Overhead pressure control	Scale control

of air is used to atomized the water to a fine droplet. The power requirement of the WIRTGEN foamer is found to be the most universal, which is adaptable to various international supplies. Besides that, the volume expansion of foamed binder produced by the WIRTGEN foamer is higher compared to the AccuFoamer and the PTI foamer unit.

At the beginning of the experimental work of this study, the production of foamed binders was carried out through a manual injection due to lack of foaming device. A pharmaceutical syringe was used to inject the foaming agent into the hot bitumen during the production of foamed binders. The machine was purchased and delivered two months before the project ended due to certain circumstances. The purpose of this comparative study is to validate the consistency and repeatability of the collected data for samples prepared using the manual method by comparing with the data of sample produced using foaming device.

The performance of ethanol-foamed asphalt binders and mixtures prepared using both protocols were closely compared. The scope of this study included.

i. Assessments on the behavior of the ethanol-foamed asphalt binders have been carried out in terms of the rotational viscosity test, expansion ratio test, and low temperature cracking test using the Asphalt Binder Cracking Device (ABCD).
ii. Evaluations on the performance of foamed WMA mixtures have been conducted in terms of the resistance to thermal cracking using the disk-shaped compact tension (DCT) test, resistance to fracture using semi-circular bending (SCB) test, and the resistance to moisture damage using the tensile strength ratio (TSR) test. In the TSR test, the samples were formerly conditioned using the Moisture Induced Stress Tester (MIST) to simulate the action of the tire passing over wet pavement that has pressurized and drawn the water within a certain depth of the pavement, creating pore pressure and scouring in asphalt mixture layers.

2. Materials and sample preparations

2.1. Materials

Asphalt binder PG58-28 and aggregates from local sources in Michigan were used as the base materials. To prepare the foamed asphalt binders, ethanol liquid (200 Proof Ethyl Alcohols) was used as foaming agent. The amounts of ethanol adopted were 1% and 3% based on the weight of asphalt binder. The foamed asphalt binders were prepared via manual injection and AccuFoamer foaming device at three different temperatures: 120 °C, 130 °C, and 140 °C. Table 3 shows the aggregate gradation used in this study.

2.2. Foamed asphalt preparation using AccuFoamer

Formerly, as a precaution step, a recommendation from the manufacturer was seek to select the adequate temperatures to produce the foamed binders. A minimum temperature of 120 °C was suggested to avoid blockage in the bitumen's supply nozzle. The preheated temperatures of asphalt binder were selected at 120 °C, 130 °C, and 140 °C, meanwhile the foaming agent chamber was set at the room temperature. Fig. 1 shows the overall steps in producing the foamed binders using AccuFoamer. Before using AccuFoamer, a series of quick calibrations were conducted at various temperatures to select an adequate temperature for producing the foamed asphalt binder. Table 4 shows the quick calibration output of AccuFoamer for ethanol foamed asphalt binder. The calibrated data at each temperature, involving flow rate and pressure for the ethanol and bitumen, was saved prior to use in the production of the foamed asphalt binder. As can be seen from the calibrated data, the flow rate required for the supply of ethanol does not considerably change even though higher bitumen temperatures were used. However, the flow rates for the asphalt binder has shown incremental trends when the calibration was conducted at higher asphalt

Table 3 – Mixture design for Hancock material.

Sieve size (mm)	Percent passing (%)
19.000	100.0
12.500	94.0
9.500	86.3
4.750	68.2
2.360	49.2
1.180	38.4
0.600	27.8
0.300	15.0
0.150	6.7
0.075	4.5
Pan	0.0

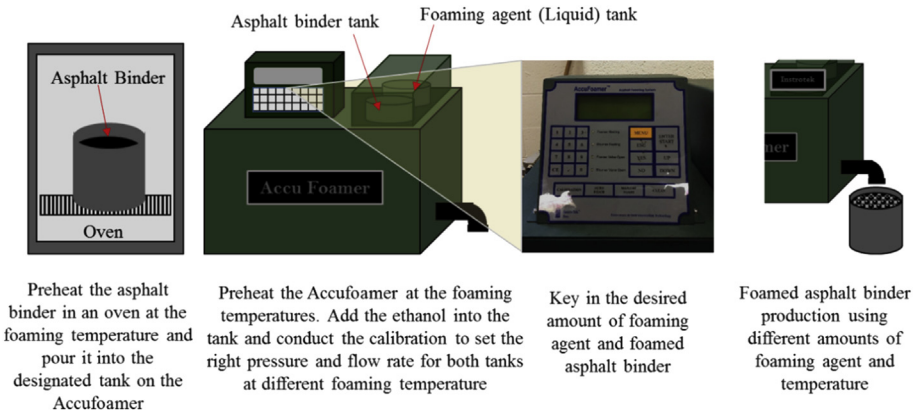

Fig. 1 – Foamed asphalt production using AccuFoamer.

binder temperatures, which resulted from the lower activation energy of asphalt binder (Hasan et al., 2017b; You et al., 2018). Fig. 2 shows the foaming device used in this study.

Based on the quick calibration of data, the foamed binder was produced utilizing 1% and 3% ethanol based on the weight of the asphalt binder. The heating temperature for the asphalt binder tank was set accordingly, depending on the foaming temperatures. The foaming device normally takes at least two hours for the asphalt temperature to reach the pre-set value. Once the desired temperature for the asphalt binder has been reached and stabilized, the calibrated data was selected and production continued. Table 5 shows the interpolated flow rates for the foaming agent and asphalt binder at each production temperature and both ethanol dosage. It was found that the AccuFoamer was not able to produce the foamed binder with 3% ethanol at 120 °C due to insufficient pressure in the asphalt binder tank; therefore, the machine was not able to select a sufficient flow rate within the range of the quick calibration of data. Additionally, the production of foamed binders with 1% ethanol at 120 °C was also found to be insufficient due to incomplete foaming as shown in Fig. 3. Where the ethanol is completely separated from the asphalt binder is represented by yellow spots in the asphalt binder.

2.3. *Manual injection foaming technique*

This manual approach involved four simple steps as depicted in Fig. 4. The process began by pouring the hot binder into an aluminum can, and followed by injecting ethanol into the binder. The asphalt binder was initially preheated at similar temperatures that used to produce the foamed binder using foaming device (120 °C, 130 °C, and 140 °C) for at least two hours. The ethanol stored in an air tide bottle, and remains at the room temperature prior to using for the production of foamed binder to avoid evaporation. Finally, a spatula was used to properly mix the asphalt binder and foaming agents on a hot plate for approximately 30 s.

2.4. *Asphalt mixture preparation*

The aggregate gradation used was based on the specifications for materials from local sources in the Upper Peninsula of Michigan. A bucket mixer was used to blend the aggregates and asphalt binder. The sample was compacted using a gyratory compactor at specified gyrations based on each test requirement. Prior to compaction, the mixture was heated in an oven for two hours to simulate short-term aging that occurs during the preparation of asphalt mixtures in the field. The compacted samples were then let to cool down to room temperature for at least 12 h. Prior to testing, all of the specimens were introduced to a long-term laboratory aging process based on the standard specification AASHTO R30. The specimens were placed in an oven at (85 ± 3) °C for (120 ± 0.5) h. After conditioning, the oven was turned off and the specimens were let to cool to room temperature, waiting for at least 16 h to avoid affecting the structure and shape of the samples.

Table 4 – Quick calibration output of the foaming machine for ethanol-foamed asphalt binders.

Binder temperature (°C)	Foaming agent* (ethanol)				Asphalt binder (PG58-28)			
	Pressure (PSI)		Flow rate (g/s)		Pressure (PSI)		Flow rate (g/s)	
	1	2	1	2	1	2	1	2
120	5.0	30.0	0.2	0.4	5.0	30.2	13.1	52.5
130	4.9	29.9	0.4	1.0	4.9	30.2	15.8	59.8
140	5.0	29.9	0.4	0.9	4.9	30.2	19.3	64.6

Note: *No heat introduce to the foaming agent chamber.

Fig. 2 – Foaming device used in this study.

This aging process was carried out to simulate the effects of aging on bituminous mixtures that occurs over the service life of an asphalt pavement, approximately 7–10 years after the construction.

3. Asphalt binder test methods

3.1. *Rotational viscosity test*

The rotational viscometer was conducted in accordance with the AASHTO T316 to compare the viscosity of foamed asphalt binders prepared using the manual injection technique and a foaming device. The results were recorded at three different temperatures, 80 °C, 100 °C, and 120 °C. In the sample preparation, after the foaming process, about 10.5 g of asphalt binder was immediately poured into the sample chamber, and spindle #27 that was used to measure the viscosity of each specimen. The results were recorded in centipoises (cP) at one-minute intervals for a total of three readings. The test results are presented as mean value based on the average of three readings.

3.2. *Expansion ratio test*

The expansion ratio (ER) test was conducted to compare foamed asphalt binders prepared using both the manual injection approach and the AccuFoamer device by InstroTek Inc. The ER is calculated as the ratio of the volume of the expanded foamed asphalt to the initial volume of asphalt when all of the foam has dissipated, as shown in Eq. (1). Based on previous studies, it is manually measured using a dip-stick or foam ruler (Abel, 1978; Arega et al., 2015; Jenkins et al., 1999; Namutebi et al., 2011; Ozturk and Kutay, 2014b). Some of the recent studies use an X-ray setup (Hailesilassie et al., 2014), and laser-based and ultrasonic sensors (Arega et al., 2013, 2015), as well as an image-based approach, namely the asphalt foam collapse test (AFCT) (Ozturk and Kutay, 2014a) to conduct the measurement. However, in this study a glass beaker and ruler was used to observe the changes in height. Approximately, 100 g of foamed asphalt binder was poured into the beaker and immediately transferred into a preheated oven to allow the foamed asphalt binder to achieve its maximum volume. After three hours, the oven was turned off, and the sample was let to cool down to room temperature for at least two hours before measuring the highest point on the beaker wall. Then, the mean measured height was used to calculate the expanded volume (V_e) of the asphalt binder. The initial volume of asphalt (V_i) was calculated based on the height of the same amount of the control asphalt (unfoamed) binder in a glass beaker of similar size.

$$ER = \frac{V_e}{V_i} \quad (1)$$

where V_e is the expanded volume, and V_i is the initial volume.

3.3. *Thermal cracking resistance test*

Asphalt binders obtained from the expansion ratio test were used for the preparation of ABCD testing samples. This test was carried out to measure the cracking temperatures of a restrained asphalt binder ring introduced to a constant cooling rate. The cracking temperature is determined based on the temperature at the jump in strain on a strain vs. temperature plot (Kim, 2005; Kim et al., 2006). The ABCD system consists of an environmental chamber, a computer control system, an ABCD ring, donut-shaped silicone rubber molds, and a stainless steel syringe set. Fig. 5 shows the ABCD sample, silicone mold, and the stain gauge ring for the ABCD test that was developed by a researcher at the Department of Civil Engineering, Ohio University, Athens, Ohio (Kim, 2007, 2010). The detailed description of the test requirements and procedures can be found in AASHTO TP92.

Table 5 – Ethanol and asphalt binder flow rate for ethanol foamed binder's production at different dosages.

Binder temperature (°C)	Flow rate (g/s)			
	1% ethanol-foamed binder*		3% ethanol-foamed binder*	
	Ethanol	Asphalt binder	Ethanol	Asphalt binder
120	0.36	35.58	3.00	NA***
130	0.60	59.80	0.95	30.82
140	0.65	64.59	0.91	29.30

Note: *Percent of ethanol is based on the weight of the asphalt binder during the foaming process; **No heat introduced to the foaming agent chamber; ***Machine was not able to produce the foamed binder due to improper pressure for asphalt binder.

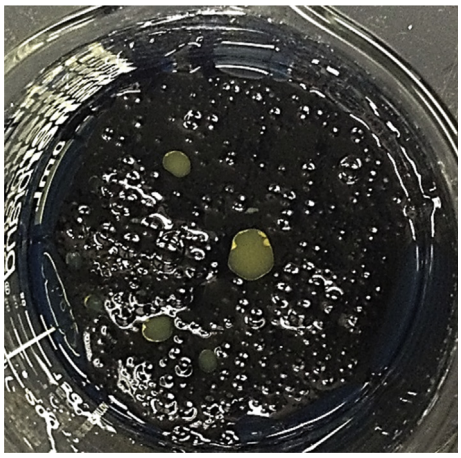

Fig. 3 – Improperly foamed asphalt binder produced at 120 °C with 1% ethanol.

4. Performance evaluation of foamed asphalt mixtures

Several tests were conducted to assess the performance of foamed asphalt mixtures in terms of the moisture susceptibility, rutting potential, fracture resistance, and fracture energy at low temperatures.

4.1. *Moisture susceptibility test*

The moisture susceptibility of asphalt mixtures was evaluated using the TSR test. The ratio is presented based on the indirect tensile strength (ITS) of the conditioned (wet) samples to the ITS of unconditioned (dry) samples. The acceptable TSR value should be greater than 0.8 (80%) according to the MDOT manual (Michigan Department of Transportation, 2008). Before testing, the wet samples were conditioned using the Moisture Induced Stress Tester (MIST) at 50 °C and pressurized to 40 psi for 3500 cycles. This device was used to simulate the pore pressure and scouring at a certain depth in the asphalt pavement layers. After the conditioning process, the sample was transferred into the CoreDry device for drying prior to the ITS test. Both wet and dry specimens were tested at room temperature with a constant loading speed, 0.085 mm/s. The MIST device and ITS test setup are shown in Fig. 6 (a) and (b), respectively.

4.2. *Rutting potential test*

The SmarTracker™ wheel tracking device was used to evaluate the rutting potential of asphalt mixtures according to AASHTO T324. Asphalt mixture samples with a diameter of 150 mm were prepared and cut to a height of approximately (62 ± 2) mm. In this test, repeated wheel loadings of (705 ± 4.5) N was applied to the samples to simulate the repeated traffic loadings. Tap water was used as a medium to control the temperature of the specimen, keeping it at 40 °C, and the sample was loaded for 10,000 cycles with a wheel speed of 52 passes/min. The rut depths were recorded throughout the test in units of mm. Fig. 7(a) shows the wheel tracking device used in this study.

4.3. *Crack resistance test*

The semi-circular bending (SCB) test was conducted to evaluate the fracture resistance of asphalt mixtures at intermediate temperatures. The SCB specimen is a semi-disk shape of a 150 mm diameter cylinder with a height of approximately 50 mm. A (15 ± 0.05) mm (height) notch with thickness of roughly (1.5 ± 0.03) mm was prepared in accordance with AASHTO TP 105 on the sample to create a weak point to initiate crack propagation during the test. The test was conducted at 15 °C using a simple three point bending configuration as presented in Fig. 7(b). Before conducting the test, the notch depth and thickness of the specimen were measured and the sample was conditioned at the testing temperature for at least two hours prior to testing.

5. Foamed asphalt binder test results

The characteristics of foamed asphalt binders produced using manual injection and the AccuFoamer foaming device were evaluated and compared based on the rotational viscosity, expansion ratio, and thermal cracking tests. In the production of the foamed binder, the injection technique was performed

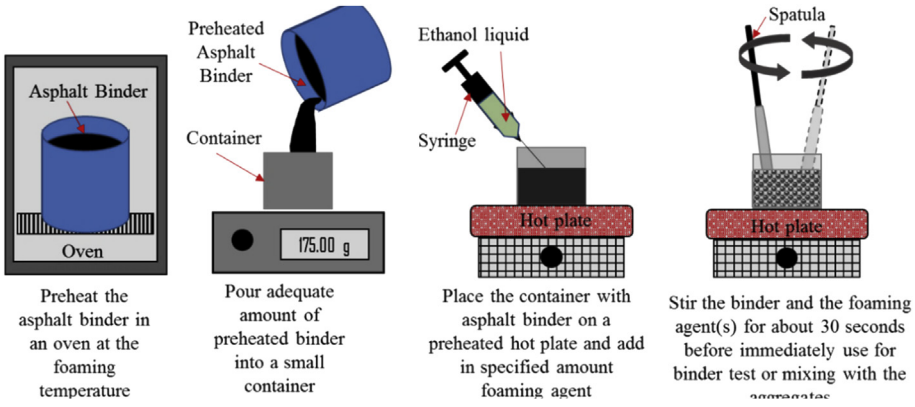

Fig. 4 – Manual injection foaming technique.

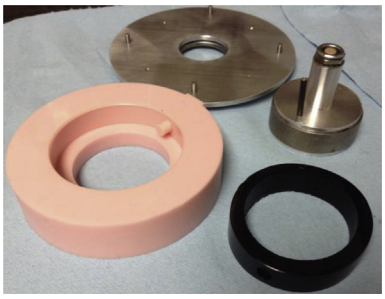

Fig. 5 – ABCD sample mold assembly and the cracked sample.

by injecting the ethanol into the preheated asphalt binder and manually stirred using a spatula for approximately 30 s. Meanwhile, the foamed binder using AccuFoamer was produced via an automatic system that consisted of two nozzles and pressurized tanks for the asphalt binder and foaming agent, as well as a small mixing chamber. Based on the calibrated data and inputs, the foamed binder is dispensed through a quarter inch tube. It is expected that these two production techniques may result in different foamed binder criteria.

5.1. *Viscosity of foamed asphalt binders*

The rotational viscosity test was performed to compare the performance of foamed asphalt binders prepared via manual injection and the AccuFoamer foaming device. The influence of the foaming method was evaluated using two ethanol contents at three testing temperatures. Fig. 8(a) and (b) shows the results of the viscosity test for the control and foamed asphalt binders prepared using 1% and 3% ethanol. Each bar in the figure represents the average of three replicates and, the error bars represent ± one standard deviation from the calculated average value. All of the results have shown good repeatability based on the span of the error bars. There is no appreciable difference between the viscosities of the foamed asphalt binders for the samples prepared using 1% ethanol via both methods regardless of the testing temperature. As mentioned earlier, the 3% ethanol foamed binder prepared using AccuFoamer was not tested since the device was not able to produce the foamed binder due to insufficient pressure for the asphalt binder tank. Hence, the machine was not able to select a sufficient flow rate within the calibrated range as presented in Table 4.

Fig. 8(b) shows the viscosity of 1% and 3% ethanol-foamed binders prepared at 140 °C. The figure indicates that there is no appreciable difference between the viscosities of the foamed asphalt binders for samples prepared using 1% ethanol via both methods at all testing temperatures. However, the viscosities of 3% ethanol-foamed binders prepared using manual injection are much lower compared to the same binder type prepared via AccuFoamer. Additionally, referring to foamed binders produced via foaming device, the viscosity of 3% ethanol-foamed binders only experienced a slight reduction as compared to 1% ethanol-foamed binders. The results point out that the foamed binder produced using the AccuFoamer foaming device with a higher ethanol content does not significantly lower the viscosity of the asphalt binder. This is contrary to the viscosity results of foamed binders' prepared using manual injection. There are two potential reasons that can greatly influence the viscosity of the AccuFoamer's foamed binder. These being: (1) the asphalt binder in the AccuFoamer was continuously preheated in the pressurized tank throughout the calibration and production processes (a higher temperature may cause a higher stiffness), meanwhile, the asphalt binder involved in the foaming process through manual injection was only preheated for about one hour prior to the foaming process, attributing to the difference in stiffness of the asphalt binders using both processes. (2) the temperature of the discharge from the nozzle of the small mixing chamber is typically hot depending on the temperature of the binder tank, which has resulted in the evaporation of ethanol while spraying it into the hot mixing chamber, which can be clearly seen as a fume. These have perhaps influenced the results of 3% ethanol-foamed binders. Based on a study reported in NCHRP report 807 (Newcomb et al., 2015), the variance in the results between tested samples produced using three different foaming devices (WIRTGEN WLB 105, InstroTek Inc. AccuFoamer, and PTI Foamer) was more noticeable for

(a) (b)

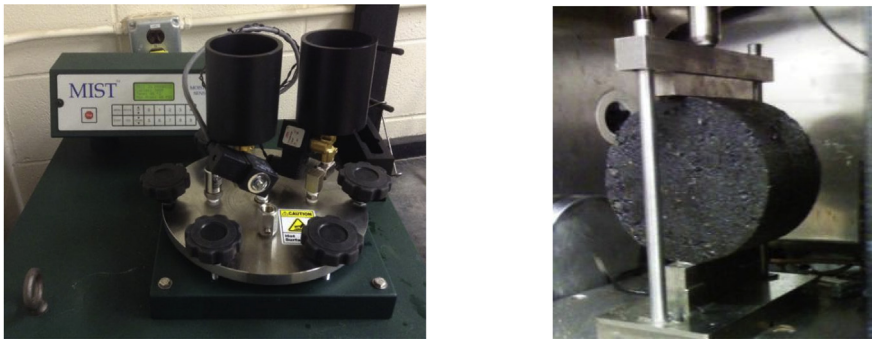

Fig. 6 – Moisture induced stress tester. (a) Conditioning process using MIST in progress. (b) ITS test setup.

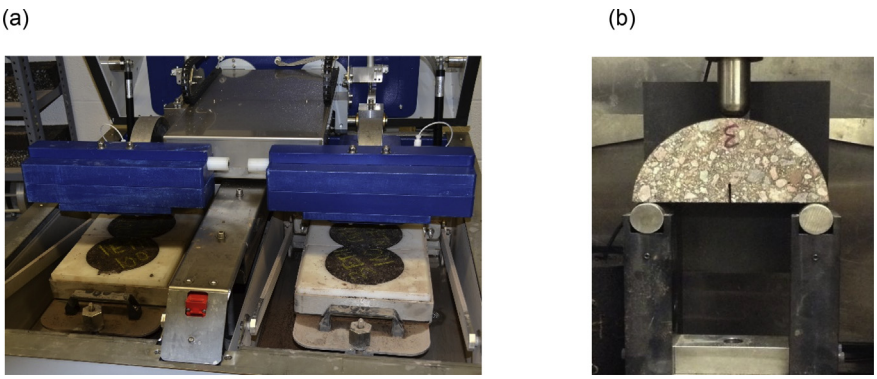

Fig. 7 – Equipment used for the mechanical performance test. (a) SmarTracker™ wheel tracking device. (b) SCB test setup.

the samples produced at a 3% water content than a 1% water content. Additionally, application of asphalt binder with a higher viscosity has resulted in lower workability and aggregate coatability. But, the production of foamed binder at higher temperatures would produce a better characteristics of foamed bitumen, hence improve the performance of asphalt mixture in the field (Newcomb et al., 2015).

5.2. *Expansion ratio of foamed asphalt binder*

The comparison of the foamed binder characteristics was further evaluated based on the expansion ratio. The outcome of the expansion ratio evaluation is shown in Fig. 9. Each bar in the figure represents the average of three replicates, and the error bars represent ± one standard deviation from the calculated average value. All of the results have good repeatability, as shown by the span of the error bars. Based on the bar chart, 1% and 3% ethanol-foamed binders produced using both methods have shown comparable values for the test conducted at 100 °C and 120 °C. However, the expansion ratio results of the sample tested at 140 °C have shown different values between the foamed binders' prepared using manual injection and the AccuFoamer foaming device. The difference seemed to be more pronounced for the 3% ethanol content than the 1% ethanol content. This situation can be explained based on the discussion presented in section 9.6.1. Based on the overall expansion ratio, both production methods in the preparation of foamed binders have exhibited comparable volume expansion criteria. In the lack of a foaming device, a manual production approach can be used for the design purpose within very limited parameters. However, it may only be applicable at certain testing temperatures and a standardized coefficient should be introduced. Based on a previous study performed by Ozturk and Kutay (2014b), air pressure was found to have more influence on the properties of the foamed binder than on the water content (foaming agent), which was not incorporated in the production method through manual injection.

5.3. *Low temperature cracking of foamed asphalt binder*

The ABCD was used to evaluate the low temperature performance of the manually injected foamed binders and the AccuFoamer foamed binders. As specified earlier, asphalt binders obtained from the expansion ratio test were used for the preparation of ABCD testing samples. The main reason is to avoid the presence of bubbles in the ABCD sample that can easily be detected when using a freshly foamed asphalt binder. During the three hour heating period in the expansion ratio test, it allows the ethanol to expel from the foamed binder and the bubbles to collapse. The results of low temperature cracking characteristics are illustrated in Fig. 10. Each bar in the figure represents the average of three replicates, and the error bars represent ± one standard

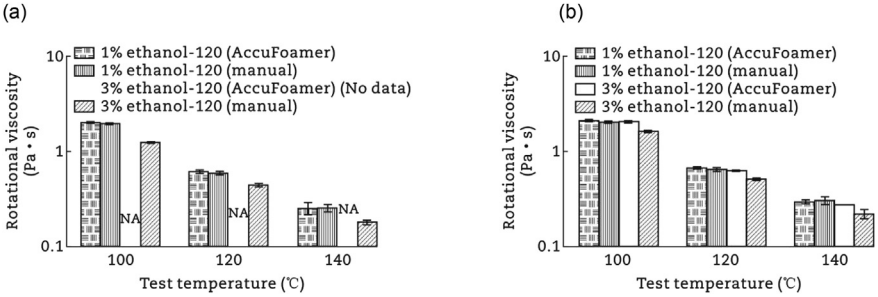

Fig. 8 – Viscosity of ethanol-foamed binders prepared at different temperature. (a) 120 °C. (b) 140 °C.

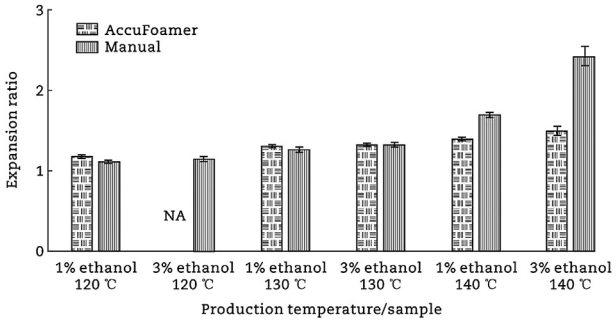

Fig. 9 – Expansion ratio of foamed asphalt binders prepared using AccuFoamer and manual injection.

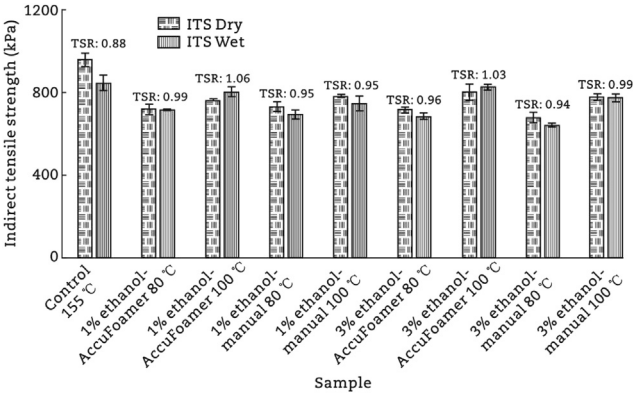

Fig. 11 – ITS and TSR of foamed asphalt mixture samples prepared using manual injection and AccuFoamer device.

deviation from the calculated average value. All of the results have exhibited good repeatability based on the span of the error bars being less than 2 °C. There is no appreciable difference between the thermal cracking performance of the foamed asphalt binder samples prepared using both methods regardless of the testing temperature and ethanol contents as indicated by the mean values and the span of the error bars. Asphalt binders foamed at 120 °C were found to have a higher resistance to thermal cracking versus a foamed binder produced at higher temperatures due to less oxidation and binder stiffness, which resulted from the lower temperature used during preheating prior to foaming via manual injection or AccuFoamer.

6. Asphalt mixtures performance

To evaluate and compare the performance of foamed WMA mixtures to that of the control HMA mixture, the samples were prepared with 1% and 3% ethanol contents. The foamed WMA mixture was mixed with the foamed asphalt binder at 80 °C and 100 °C. Prior to mixing with the aggregates, the foamed binders were produced at 130 °C either using the AccuFoamer foaming device or manual injection, depending on the designation of the sample. After the mixing process, the loose mixture was then short-term aged for 2 h at temperatures similar to those prior to compaction. The control HMA was mixed and compacted at 155 °C and 145 °C, respectively. The control HMA sample was also short-term aged at 145 °C before being compacted with a gyratory compactor. After being compacted and left to cool down to room temperature overnight, all of the specimens were introduced to a secondary aging process. The specimens were placed in an oven at (85 ± 3) °C for (120 ± 0.5) h. After the conditioning process, the oven was turned off and the specimens were let to cool to room temperature and wait for at least 16 h to avoid affecting the structure and shape of the samples. This aging process was carried out to simulate the effects of bituminous-mixture aging that occurs over the service life of an asphalt pavement, approximately 5–7 years after construction. The samples were then tested to determine the resistance to moisture damage, cracking, and rutting.

6.1. *Resistance to moisture damage of foamed asphalt mixture*

The ITS test results for the control HMA and foamed WMA mixtures fabricated using AccuFoamer and manual injection are shown in Fig. 11. The solid bar and pattern-filled bar

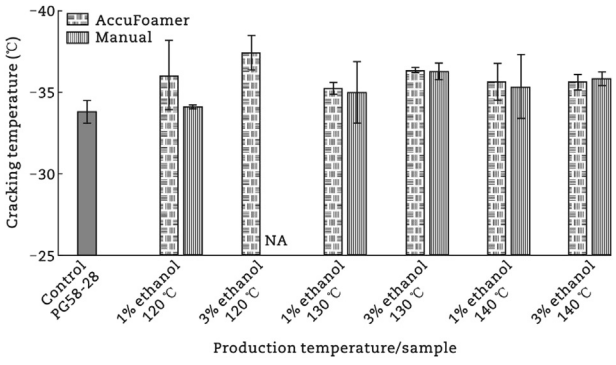

Fig. 10 – Asphalt binder cracking temperature based on the ABCD test.

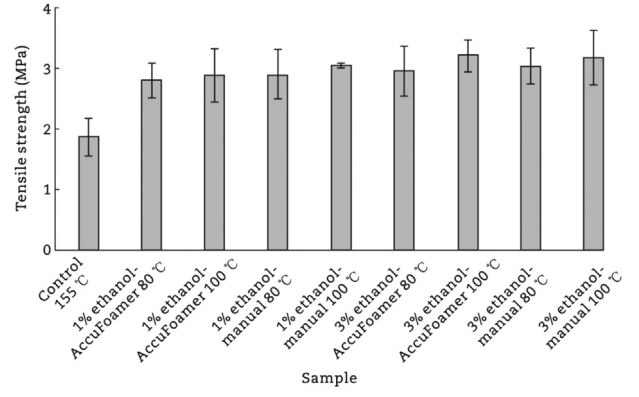

Fig. 12 – Tensile strength of foamed asphalt mixtures using the SCB test.

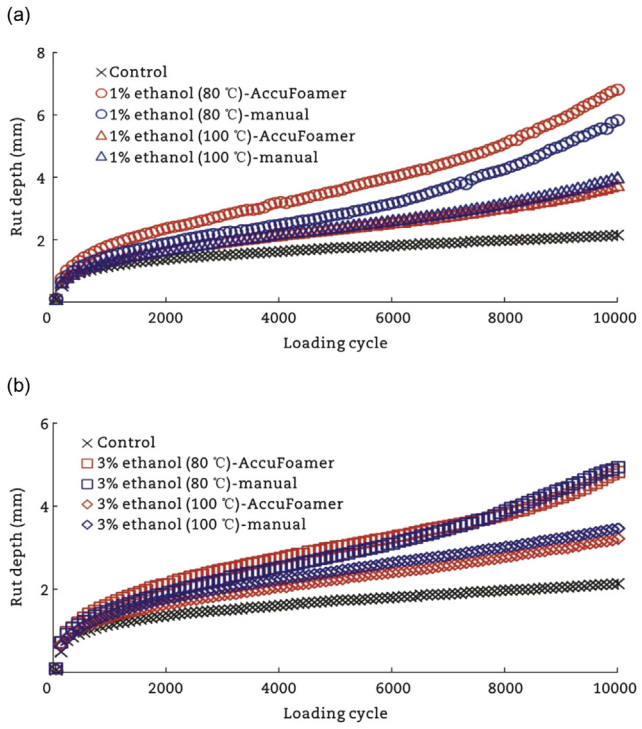

Fig. 13 – Rutting potential. (a) 1% ethanol-foamed asphalt mixtures. (b) 3% ethanol-foamed asphalt mixtures.

represent the average indirect tensile strengths of two replicate measurements for the dry and wet samples, respectively. The error bars represent the ±1 standard deviation from the average value. In general, both production procedures have results of equivalent ITS values for dry and wet samples. A higher temperature used for a sample's fabrication process resulted in significantly higher tensile strength values.

Overall assessments based on Fig. 11, the comparison of wet ITS for the control HMA and foamed WMA mixtures, indicated that wet ITS for the foamed WMA mixtures prepared at 100 °C and the wet ITS of the control HMA mixture are equivalent. However, the dry ITS of the control HMA is significantly higher than the dry ITS for the foamed WMA mixtures. The lower ITS values for dry samples of foamed WMA mixtures as compared to that of the control HMA could be attributed to the lower production temperature involved in preparing the mixture. Meanwhile, all foamed WMA mixtures do not have a significant difference in the ITS values between dry and wet samples. This can be clearly seen based on the calculated tensile strength ratios (TSR) as shown in Fig. 11. The results indicate that the ethanol-foamed WMA mixtures prepared with nano-hydrated lime as filler material have good resistance to moisture damage. A higher production temperature may provide the foamed WMA mixture with a better resistance to moisture damage as indicated by specimens prepared at 100 °C.

6.2. *Cracking resistance of foamed asphalt mixture*

Fig. 12 shows the cracking resistance properties of the control HMA and foamed WMA mixtures tested using the semi-circular bending (SCB) test. The test was conducted at 15 °C, as recommended by the Wisconsin Department of Transportation, for the asphalt mixture prepared using an asphalt binder of grade PG58-28. The result shows that the foamed WMA mixtures are found to have a better resistance to cracking as indicated by a higher tensile strength as compared to the control HMA. This can be due to a higher degree of aging that occurred during the production of HMA. Less binder oxidation (aging), resulting from low production temperatures, can lead to a higher resistance to cracking of asphalt mixtures (Braham et al., 2009; Crews et al., 2012). A study conducted by Braham et al. (2009) reported that the behavior of the asphalt binder in WMA mixtures was more resilient and retained more energy before the failure compared to the HMA mixtures. Additionally, there is no considerable difference in the tensile strength of foamed WMA mixtures prepared at 80 °C and 100 °C, as shown by the span of error bars for each sample. The bars represent the average tensile strengths of four replicate measurements for each sample, and the error bars signify the ±1 standard deviation from the average value.

6.3. *Permanent deformation of foamed asphalt mixture*

The Hamburg wheel tracking test was conducted in accordance with a standard procedure, AASHTO T324, at 40 °C. The results of the control HMA and the foamed WMA mixtures prepared using AccuFoamer and manual injection were presented in terms of rut depth, in millimeter, versus loading cycles. The result was presented based on the mean values of a repetition of two samples. Fig. 13(a) shows the rut depth of the control and foamed WMA specimen's prepared using 1% ethanol. Meanwhile, Fig. 13(b) presents the rut depth versus loading cycle curves of the control HMA and foamed WMA samples produced with a 3% ethanol content. The results show that both approaches in the production of foamed WMA samples exhibited a comparable rut depth, except for the foamed WMA specimen prepared using 1% ethanol at 80 °C, as shown in Fig. 13(a). Higher production temperature

Table 6 – One-way ANOVA comparison between the ethanol-foamed binders produced using manual injection and the AccuFoamer foaming device.

Test	Variable	*p*-value	Tukey pairwise comparison
Expansion ratio	Production method	0.228	No significant difference
ABCD	Production method	0.097	No significant difference
Rotational viscosity	Production method	0.287	No significant difference

Table 7 – One-way ANOVA comparison between the ethanol-foamed WMA mixtures produced using manual injection and the AccuFoamer foaming device.

Test	Variable	p-value	Tukey pairwise comparison
HWTD	Production method	0.841	No significant difference
Moisture susceptibility	Production method	0.003	The AccuFoamer produced sample with a significantly higher TSR
SCB	Production method	0.567	No significant difference

resulted in a better resistance to rutting, as shown by the distinct differences in slopes. A steeper slope indicated that the mixture was more susceptible to permanent deformation, which is attributed to the stiffness and compactability of the mixture. These are highly influenced by the mixing and compaction temperatures that were used during the sample's fabrication. The foamed WMA mixture prepared at 100 °C was less susceptible to rutting then the foamed WMA mixture produced at 80 °C. The control HMA mixture had the highest resistance to rutting as compared to the foamed WMA mixtures due to the highest production temperature, hence resulting in the greatest mixture stiffness, interlocking of aggregate, and stability to dissipate the load during the loading process.

7. Statistical analysis

The one-way analysis of variance (ANOVA) test was performed to compare the performance of foamed binders and foamed WMA mixtures prepared using manual injection and the AccuFoamer foaming device. The ANOVA was conducted at a confidence interval of 95% ($\alpha = 0.05$) throughout the analyses. The one-way ANOVA is used to compare the means of two or more samples that are drawn from the same population. In an ANOVA test, a significant result indicates that at least two groups differ from each other. However, the result does not specify the sets that differ so a pairwise comparison test can be used as a follow up analysis to establish the differences in the results. One of the most common methods of pairwise comparisons is the Tukey test. The test is based on the "studentized range" or "student's q" that is similar to a t-distribution. The Newman–Keuls test is another method of pairwise comparison which is based on a sequential test design. In general, the Tukey test is most commonly used compared to the Newman–Keuls test since it can keep the level of the Type I error equal to the chosen alpha level ($\alpha = 0.05$). The Newman–Keuls test is most often used in the data analysis related to the psychology area of study (Abdi and Williams, 2010).

Based on the results presented in Table 6, the experimental data of the performance of the ethanol-foamed binders prepared using both techniques are significantly comparable based on the ANOVA and Tukey test results.

Table 7 shows the results of the statistical analysis of the performance of ethanol-foamed WMA mixtures produced using the manual injection technique and the AccuFoamer foaming device. Most of the performance exhibited a comparable performance, except the moisture susceptibility of foamed mixtures (p-value = 0.003). Based on the Tukey test, the specimens prepared using foamed binders produced using the AccuFoamer had significantly higher TSR than the samples produced using manual injection. However, the TSR of samples produced using both methods have fulfilled the test requirement, where the TSR values are more than 0.8.

8. Conclusions

Based on the findings, several conclusions can be made as follows.

1. The behaviors of the foamed-asphalt binders prepared via both methods in terms of viscosity, low temperature cracking, and expansion ratio are significantly comparable.
2. However, the mixtures produced using asphalt binder that was foamed using the laboratory-foaming device are found to exhibit significantly higher TSR values. Additionally, a higher temperature used in the fabrication of a sample resulted in higher tensile strength values.
3. The foamed WMA mixtures are found to have a better resistance to cracking, as indicated by a higher tensile strength as compared to the control HMA. There is no considerable difference in the tensile strength of foamed WMA mixtures prepared using both techniques at 80 °C and 100 °C.
4. The results show that both approaches in the production of foamed WMA samples have exhibited comparable rut depths. Higher production temperatures resulted in a better resistance to rutting. The control HMA mixture has the highest resistance to rutting as compared to foamed WMA mixtures due to the highest production temperature, resulting in a greater mixture stiffness, interlocking of aggregate, and load dissipation during the loading process.
5. Overall, referring to the statistical analysis results of the performance of the ethanol-foamed binders and mixtures prepared using both techniques are significantly comparable based on the ANOVA and Tukey test results at a 95% confidence interval, except the moisture susceptibility test result.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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