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Original Research Paper

Ethanol based foamed asphalt as potential alternative for low emission asphalt technology

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ABSTRACT

Foamed asphalt typically relies on water as a foaming agent because water becomes gaseous at elevated temperatures, generating numerous tiny bubbles in the asphalt and causing spontaneous foaming. In this study, ethanol was used as a potential alternative to water as a foaming agent. Ethanol is expected to be a physical blowing agent in the same manner as water, except it requires less energy to foam due to its 78 °C boiling point. This study compares the performance of water and ethanol as foaming agents through the measurements of rotational viscosity, the reduction in temperature during foaming, and volatile loss. The ethanol-foamed asphalt binders were prepared at 80 °C and 100 °C, while the water-foamed asphalt binders were prepared at 100 °C and 120 °C. Additionally, the rolling thin film oven (RTFO) was used to generate short-term aging of the foamed asphalt binders. A rotational viscometer was used to determine the viscosity of the asphalt binders at 80 °C, 100 °C, 120 °C, 140 °C, and 160 °C. Overall, ethanol can function in the same manner as water but requires less energy to foam. It is proven based on the smaller drop in temperature of the asphalt binder foamed using ethanol compared with that prepared with water. This is due to the lower latent heat capacity of ethanol, which requires less energy to vaporize compared with water. Through the rotational viscometer test, ethanol performs better in lowering the viscosity of asphalt binders, which is essential in allowing production processes at low temperatures, as well as a better workability and aggregate coating. Ethanol can be expelled from the foamed asphalt binders at a higher rate due to its lower boiling point and latent heat.

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1. Introduction

Over the past years, extensive measures, like those to reduce air pollution and sustainable development protocols, have been taken by numerous organizations to reduce the severity of pollution. In order to support sustainable development, warm mix asphalt (WMA) was invented in Europe and further developed in the continent and other countries to permit hot mix asphalt (HMA) to be produced at a lower temperature to help lower the energy demand and greenhouse gas emissions, as well as create better working conditions for construction workers and plant operators (Gandhi and Amirkhanian, 2007; Goh and You, 2012; Hurley and Prowell, 2005a, 2005b, 2006; Prowell et al., 2007; Wasiuddin et al., 2007). A few WMA technologies were introduced including foaming methods, organic additives, and chemical additives (Chowdhury and Button, 2008). The energy savings, emission reductions, and lower construction costs can be enhanced if the production process is conducted at even lower temperature settings, especially when WMA foaming methods are used (Colbert et al., 2016). Asphalt foaming techniques have been used over the last couple of decades as an alternative to traditional methods in preparing asphalt mixtures. The water-based

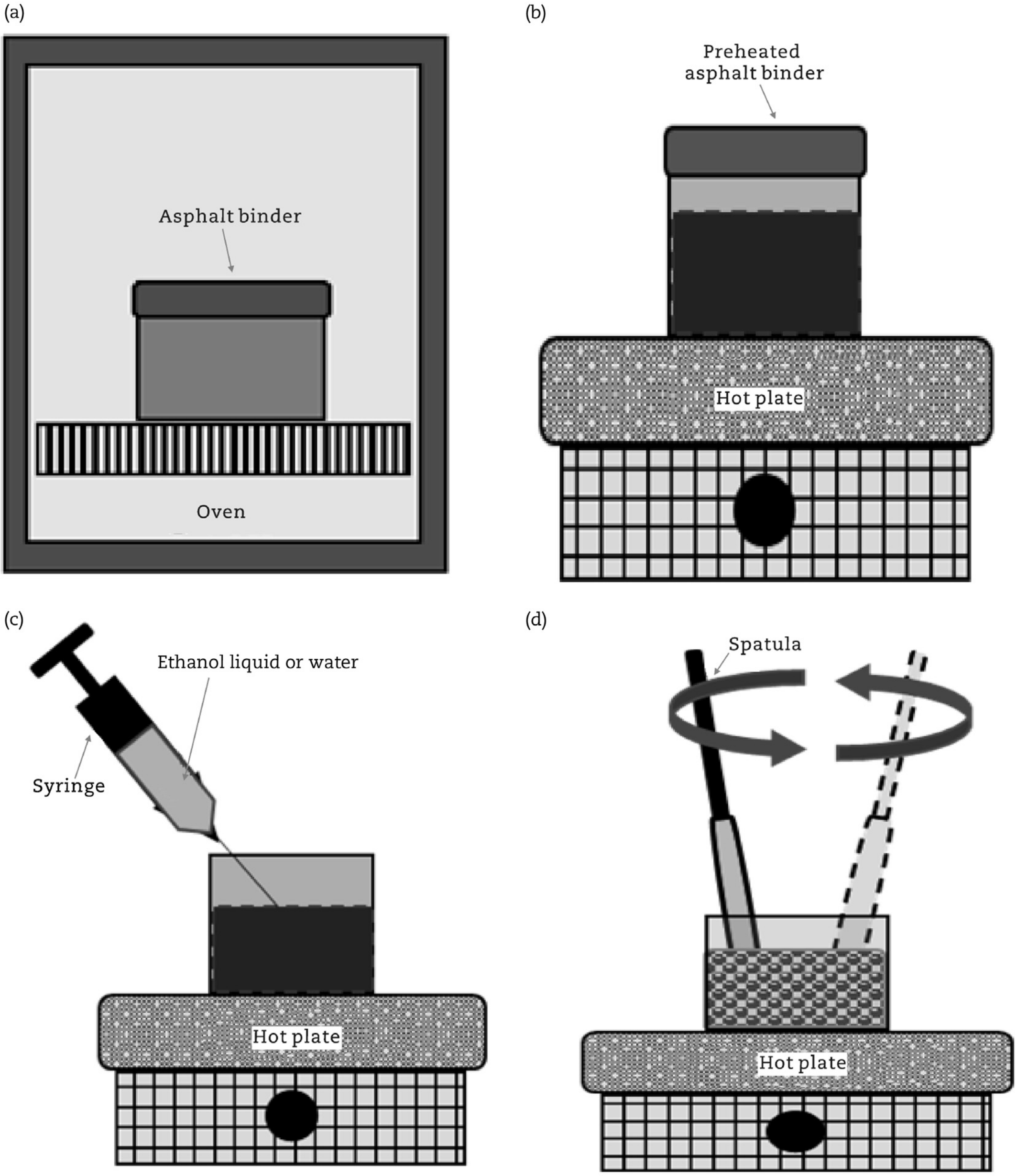

Fig. 1 – Preparation of the foamed asphalt. (a) Preheat the asphalt binder that was initially poured into a small container in an oven at the test temperature. (b) Place the container with asphalt binder on a preheated hot plate. (c) Add in specified amount of foaming agent (ethanol or water). (d) Stir the binder and the foaming agent(s) for about 30 s before recording the temperature.

Table 1 – Properties of asphalt binder PG58-28.

Property	Standard procedure	Requirement	Result
Specific gravity	ASTM D70	–	1.024
Flash point	ASTM D92	>230 °C	275 °C
Rotational viscosity	AASHTO T316	3 Pa·s at 135 °C	0.30 Pa·s
Mass loss	AASHTO T240	<1%	0.045%
Dynamic shear rheometer	AASHTO T315	Un-aged: >1.0 kPa	6.56 kPa
		*RTFO-aged: >2.2 kPa	16.7 kPa
		**PAV-aged: <5000 kPa	85.85 kPa
Bending beam rheometer	AASHTO T313	Max creep stiffness: 300 MPa	176 MPa
		Min *m*-value: 0.3	0.347

Note: *RTFO-aged means the condition of asphalt binders after going through the aging process using the rolling thin film oven (RTFO) to simulate the effects of oxidation during the mixing and construction period. The aging process was conducted in accordance with the standard test procedure, AASHTO T240. **PAV-aged means the condition of asphalt binders after going through continuous aging processes using the rolling thin film oven and pressurized aging vessel (PAV) to simulate the behavior of asphalt binders after the asphalt pavement being placed in the field for seven to ten years. The aging process was conducted in accordance with the standard test method, AASHTO R28.

process is a simple concept that relies on the foaming of water when it is introduced to a preheated asphalt binder. When a small amount of water is added to the hot asphalt binder, the water vaporizes and increases the volume of the asphalt binder, resulting in a better coating and workability of the asphalt mixture (Mohd Hasan et al., 2013). Because the foamed binder is constantly exposed to high temperatures during mixing, the bubbles collapse and the asphalt binder behaves like a normal binder. However, an excessive amount of water should be avoided to lower the tendency of moisture damage problems (e.g., stripping) to occur. This water-based process permits a temperature reduction in the asphalt mix ranging from 20 °C to 30 °C (Larsen et al., 1985; Masson et al., 2001; Miura et al., 2001). Various types of water-based systems are available on the market to support the application of foaming WMA (Astec, 2014; MAXAM, 2014; Stansteel, 2014).

The foaming process of asphalt binders typically relies on the use of air and water as foaming agents (Mohd Hasan et al., 2013; Ozturk, 2013; Xu et al., 2012). These physical foaming agents become gaseous at elevated temperatures. The foaming process can greatly increase the surface area of asphalt binders in the unit volume (Ozturk, 2013). This allows the aggregate particles to be easily coated by the asphalt binders even at lower mixing temperatures (Croteau and Tessier, 2008). Even though WMA technologies have shown a better performance in terms of energy savings and emission reductions, further studies are essential to fully understand and improve their performance and efficiency, especially for the foaming techniques since they are commonly used in the United States due to their cost-effectiveness (Mohd Hasan et al., 2013).

The objective of this study is to evaluate a newly proposed physical foaming agent toward enhancing foaming WMA technology. Ethanol has been selected in this study due to its low latent heat and boiling point compared with water. Numerous benefits of ethanol are expected to be explored throughout this research.

(1) The foamed binder and WMA mixture may be produced at lower temperatures with ethanol, perhaps as low as 80 °C since the boiling point of ethanol is approximately 78 °C.
(2) The asphalt binder's temperature should not greatly change during the injection mixing process when the foamed asphalt binder is produced due to the lower latent heat capacity of ethanol, which requires less energy to vaporize compared with than to water. The high latent heat of water in a phase transition requires extra energy to generate bubbles during the foaming of the asphalt.
(3) The ethanol will be burnt with gas during the mixing process, and the moisture susceptibility can potentially be lowered.
(4) Even though the additional cost of ethanol and the foaming setup is required to produce the foamed asphalt binder, the lower production temperature should offset this cost with lower energy consumptions and emissions.

2. Materials for experimental work

Asphalt binder PG58-28 was used as the main material in this study. To prepare the foamed asphalt binders, tap water and ethanol liquid were used as foaming agents. Fig. 1 shows the steps involved in the preparation of the foamed binder. The

Table 2 – Physical and mechanical properties of ethanol.

Property	Description
Appearance	Clear, colorless liquid
Vapor pressure at 20 °C	48 mmHg
Vapor density	1.6 (air = 1)
Boiling point	77.1 °C
Freezing point	−144 °C
Solubility in water at 20 °C	100%
Specific gravity at 20/20 °C	0.7909
Density at 15.56 °C	6.61 lbs/gal
Evaporation rate	3.3 (butyl acetate = 1)
Percentage volatiles	100%
Formula	CH_3CH_2OH

properties of asphalt binder and ethanol (200 proof ethyl alcohols) are presented in Tables 1 and 2, respectively.

3. Testing protocols

In this study, a rotational viscometer (RV) and a RTFO were used to evaluate the performance of ethanol-foamed asphalt binders and compare them with the properties of water-foamed asphalt binders. The foamed asphalt binders were prepared using water and ethanol at two different temperatures for each foaming agent. The ethanol-foamed asphalt binders were prepared at 80 °C and 100 °C, while the water-foamed asphalt binders were prepared at 100 °C and 120 °C. The RV was conducted at various temperatures: 80 °C, 100 °C, 120 °C, 140 °C, and 160 °C. Additionally, the RTFO was used to generate short-term aging of the foamed asphalt binders to estimate the effects of mixing temperatures on the aging level of asphalt binders.

3.1. *Foamed asphalt binder preparation*

A simple production of water-based, and foamed asphalt binders that had been used by Goh and You (2011) was adopted in this study. This method includes injecting water or ethanol (1%, 3% and 5% by weight of the binder) into the hot asphalt binders using a syringe at the bottom of the container followed by stirring with a spatula. Table 3 shows the details and designations of the foamed asphalt binders that were prepared in this study. The designation of the foamed asphalt binder is based on the type of foaming agent, percentage used, and the foaming temperature. For instance, the W1%-100 is used to represent the foamed asphalt binder prepared using 1% water based on the total mass of the asphalt binder at 100 °C.

3.2. *Temperature reduction test during the foaming process*

This test was conducted to measure the reduction in temperature during the foaming of an asphalt binder. The temperatures of the asphalt binder sample were recorded using a thermometer before (t_0) and after (t_f) the foaming process. The designated duration for a test is approximately three minutes, which was consistently standardized throughout the assessment. The foaming agent that results in a smaller reduction in the asphalt binder's temperature during the foaming process is highly favorable. Theoretically, it is expected that the asphalt binder's temperature should not greatly change during the preparation of the foamed asphalt binder with ethanol due to its lower latent heat capacity, which requires less energy to vaporize compared with water. The high latent heat of water in a phase transition may require extra energy to generate bubbles during the foaming of the asphalt. The asphalt binder was foamed using each foaming agent at 1% and 3% based on the weight of the asphalt binder and evaluated at three different temperatures (80 °C, 100 °C, and 120 °C). Fig. 2 shows the procedures that were used in this test. First, the asphalt binder was preheated in an oven at the designated temperature for 90 min, as presented in Fig. 2(a). It was followed by placing the asphalt samples, which are in an aluminum can, on a calibrated hot plate that was initially set at a temperature of 5 °C higher than the foaming temperature (Fig. 2(b)). For instance, 105 °C for a foaming process that was performed at 100 °C. This is to ensure that all samples can be maintained at similar temperatures and avoid sudden drops in the binder's temperature due to the surrounding temperature. It is also to eliminate temperature fluctuation due to the room's ambient temperatures while the assessment is conducted. Prior to testing, a specified amount of foaming agent was prepared and injected into the asphalt binder. A spatula was used to stir the asphalt binder and foaming agent for about 30 s, and a mercury thermometer was used to record the temperature, as shown in Fig. 2(c). The temperature was recorded when the mercury in the thermometer stopped moving, which took approximately three minutes. Fig. 3 shows the overall test setup that was used in this evaluation. An analog timer with an alarm and a stand to hold the thermometer were used to maintain the consistency of the test. The temperatures of both foaming agents were also measured before conducting the test, where both were found to be approximately (23.5 ± 0.5) °C depending on the ambient room temperatures.

Table 3 – Foaming asphalt binder parameter.

Foaming agent	Dosage (%)	Production temperature (°C)	Designation
Water	1	100	W1%-100
	3		W3%-100
	5		W5%-100
	1	120	W1%-120
	3		W3%-120
	5		W5%-120
Ethanol	1	80	E1%-80
	3		E3%-80
	5		E5%-80
	1	100	E1%-100
	3		E3%-100
	5		E5%-100

3.3. *Rolling thin film oven and mass loss test*

The RTFO was used to generate short-term aging of the foamed asphalt binder. The aging process was performed in accordance with the standard procedure, AASHTO T240. Each foamed asphalt binder was exposed to temperatures similar to what were used for the preparation of a foamed asphalt binder as presented in Table 3. The foamed asphalt binder was poured into a glass cylinder and exposed to designated temperatures for approximately 85 min to simulate the aging mechanism during the construction process. The RTFO protocol also provides a quantitative measurement of the volatiles lost (mass loss test) during the aging process, as shown in Eq. (1).

$$\text{Mass Loss}(\%) = \frac{\text{Original Mass} - \text{Final Mass}}{\text{Original Mass}} \times 100 \tag{1}$$

Fig. 2 – Test procedure. (a) Asphalt binder preheated in an oven for at least 90 min at foaming temperature. (b) The container placed on a hot plate to avoid temperature reduction due to room temperature. (c) Measurement of temperature after binder foaming process.

At elevated temperatures when the asphalt mixture is produced, the smaller molecules in asphalt binders and foaming agents are driven off, resulting in an increase in the asphalt's viscosity. The effects of heat and flowing air on a moving film of semi-solid asphaltic material are considered in this procedure. The effects of foaming temperatures, types, and percentages of foaming agents were also analyzed from the outcomes of this test.

3.4. *Rotational viscosity test*

The RV test was conducted using the Brookfield DV-II+ on unaged and RTFO-aged ethanol-foamed asphalt binders and compared with water-foamed asphalt binders. All of the samples were tested using spindle #27. When preparing the samples, the foamed asphalt binder was preheated at the foaming temperature to avoid excessive aging of the binder

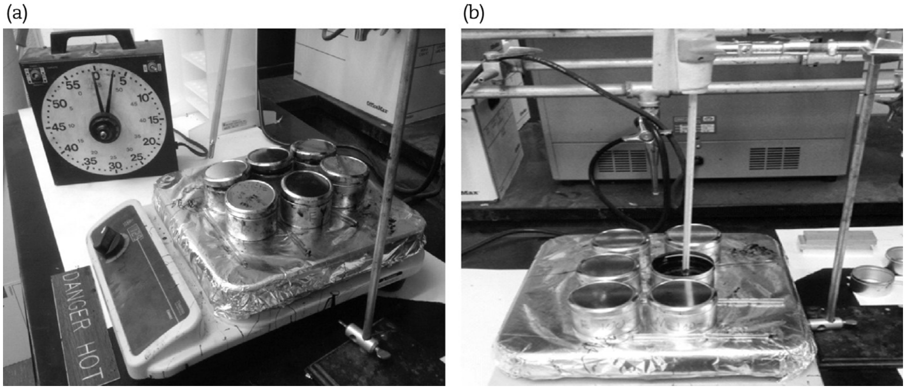

Fig. 3 – Test setup for assessment of temperature difference. (a) Analog timer used in this evaluation. (b) Thermometer used to measure the temperature of the foamed binder.

and the loss of foaming agent from the asphalt binder. Then, each sample chamber was filled with (10.5 ± 0.5) g foamed binder. This test was conducted from the lowest temperature, which is 80 °C, and was followed by 20 °C increments up to 160 °C. During the test, the sample was preheated in the thermo-cell to the desired temperature within 30 min and allowed to equilibrate for 10 min at the desired temperature before recording the value. Three readings were taken one minute apart to determine the average value. The test began at a 20 rpm viscometer speed and turned to higher speeds in order to ensure the viscometer torque is in a recommended range.

Based on the viscosity of un-aged and RTFO-aged foamed asphalt binders, the aging factor of each foamed asphalt binder was computed using Eq. (2). A higher aging factor is essential to ensure that the foaming agent is expelled from the foamed asphalt binder at a higher rate during the construction stage and allows the asphalt binder to exhibit its characteristics based on the actual performance grade.

$$\text{Aging Factor} = \frac{\text{Viscosity}_{\text{RTFO-aged}}}{\text{Viscosity}_{\text{Virgin}}} \tag{2}$$

4. Results and discussions

4.1. *Evaluations of temperature reduction during the foaming process*

Fig. 4 presents the temperature reductions that were measured during the foaming process. Based on the results, the temperature reduction of foamed asphalt binders prepared using ethanol is lower compared with the asphalt binders foamed using water, especially for the foamed asphalt binders prepared using 1% ethanol, which can be clearly seen at each foaming temperature. This is due to the lower latent heat capacity of ethanol, which requires less energy to vaporize compared with water. Additionally, a higher content of ethanol or water that was injected into the asphalt binder during the foaming process resulted in a higher temperature reduction, except for the foaming process conducted at 120 °C using 3% ethanol, 1% water, and 3% water. Fig. 5 shows the foaming that was observed while the temperature was recorded during the test.

4.2. *Evaluations of the virgin asphalt binder*

The RV test was started by assessing the un-aged foamed asphalt binders. Fig. 6(a) and (b) shows the rotational viscometer test results of the water-foamed asphalt binder and ethanol-foamed asphalt binder, respectively. Each point on the curves represents the average of three replicates ($n = 3$). Based on Fig. 6(a), there is no considerable difference between the viscosity of the PG58-28 and water-foamed asphalt binder, especially for the specimen prepared at 100 °C. This indicates that the viscosity of the asphalt binder is not affected by the application of water as a foaming agent. It was found that a higher composition of ethanol resulted in a lower asphalt viscosity. Based on Fig. 6(b), applications of ethanol lowered the viscosity of the asphalt binder, which is essential to increase the workability and compactability of asphalt mixtures during the construction process. This will also promote a better dispersion of the binder to ensure a better aggregate coating compared with the asphalt binder in its typical liquid state at a low temperature. Ethanol has played an important role in altering the viscosity of foamed asphalt binders. When ethanol is added to the preheated asphalt binder, bubbles are generated, which results in the volume expansion of the asphalt binder. This allows the asphalt mixture to be prepared at a low temperature. However, there are no clear differences in the viscosity when the foamed asphalt binder is prepared at different temperatures, as can be seen in Fig. 6(b).

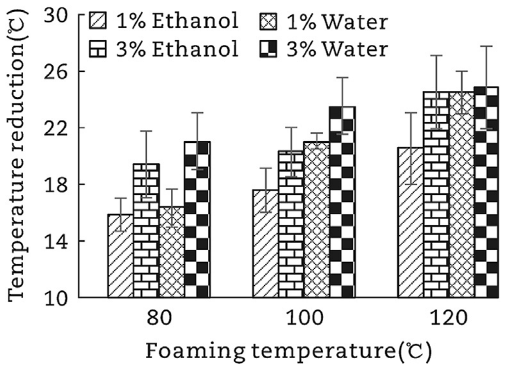

Fig. 4 – Temperature reduction detected during the foaming process.

4.3. *RTFO-aged asphalt binder performance*

The RV test was conducted to examine the changes that take place in the viscosity of foamed asphalt binders after the RTFO aging process. Hypothetically, a higher viscosity was expected to be associated with the volatile loss of light components from the asphalt binder and foaming agent. Fig. 7 shows the mass loss of the foamed asphalt binder and control sample, PG58-28. The result indicates that the foamed asphalt binder prepared and aged at a higher temperature (e.g., 100 °C for ethanol-foamed binder) exhibited a greater volatile loss compared with that prepared at a lower temperature.

Fig. 5 – Foaming observed during the test.

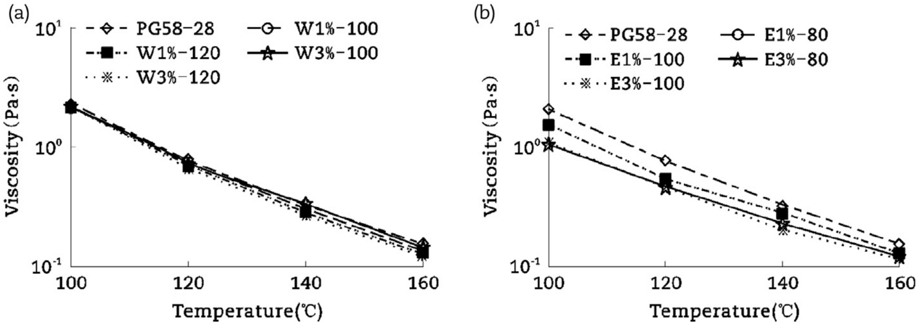

Fig. 6 – Comparison of rotational viscosity of un-aged foamed asphalt binders. (a) Water. (b) Ethanol.

Additionally, all foamed asphalt binders had higher mass losses compared with the control sample (PG58-28), even though the control sample had been through an aging process at an elevated temperature, 163 °C. This is due to the volatile loss which took place due to the evaporation of trapped foaming agents in the foamed asphalt binder while experiencing a temperature higher than its boiling point.

Fig. 8(a) and (b) shows the RV curves of RTFO-aged foamed asphalt binders. Generally, the viscosity of all RTFO-aged samples is higher than un-aged samples, as indicated by aging factor values of more than 1.0 (Table 4). Both the water-foamed asphalt binder and the ethanol-foamed asphalt binder have a lower viscosity compared with the control binder, which allows the production and compaction of foaming WMA mixtures to be conducted at temperatures lower than those conventionally used for HMA. The figure also shows that there is no clear difference in water-foamed binders when different compositions of foaming agent are used (Fig. 8(a)), which is consistent with the trend in the un-aged samples. The mean viscosity of the ethanol-foamed asphalt binder is 3.7% higher than that of the water-foamed asphalt binder when both binders were RTFO-aged at 100 °C. This result indicates that the amount of ethanol expelled from the ethanol-foamed asphalt binder is higher than that of water vaporized from the water-foamed asphalt binder. Another indicator that supports this finding is the aging factor tabulated in Table 4. The aging factor is calculated based on the viscosity of an RTFO-aged sample over the viscosity of an un-aged specimen. Based on the results, all aging factors are higher than 1.0, which indicates that the RTFO-aged sample has a higher viscosity than the un-aged sample. Moreover, ethanol can be considered a good option to replace water as a foaming agent in order to solve the problem related to the resistance to moisture damage of foaming WMA.

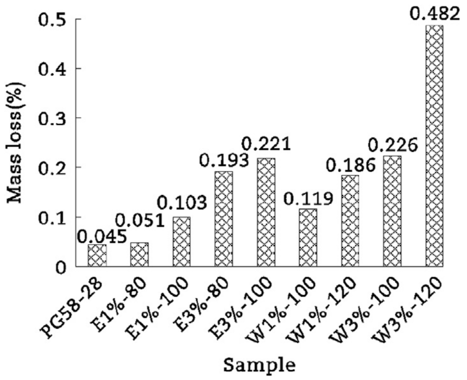

Fig. 7 – Volatile loss of foamed binder using the rolling thin film oven test.

4.4. *Effects of foaming agent on rotational viscosity*

The assessment continued with RV tests on both foamed asphalt binders prepared with 5% of the foaming agent based on the mass of binder. The results are presented in Fig. 9(a) and (b) for the water-foamed asphalt binder and ethanol-foamed asphalt binder. It is found that the viscosity of the foamed asphalt binder prepared with 5% water only slightly decreases compared with the PG58-28. The differences are slightly noticeable when the samples are tested at higher temperatures. However, there is no difference in the specimens tested at 100 °C, as shown in Fig. 9(a). Overall, the trend shows that ethanol demonstrates a greater efficiency in lowering the viscosity of the asphalt binder compared with water, even at low production temperatures, as shown in Fig. 9(b). This can be attributed to ethanol, which has lower latent heat compared with water and requires less energy to start foaming and initiate the flow of binder in the sample chamber during the test. Additionally, besides increasing the production of bubbles in asphalt binders at lower temperatures, the size of the bubbles presenting in the ethanol-foamed asphalt binder is smaller and last for a longer period of time during the foaming process. This indicates a better bubble cell nucleation stability compared with that of the water-foamed asphalt binder. However, an excessive amount of ethanol should be avoided to ensure that it does not affect the performance of WMA mixtures, as well as other aspects in terms of costs, energy consumption, and the amount of GHG emitted into the environment, which is associated with producing ethanol. Fig. 10 shows the viscosities of foamed binders prepared with water and ethanol at 100 °C. Two foaming agent contents were used in the sample preparation, which are 1% and 3% based on the weight of the asphalt binder. The results show that the ethanol-foamed binders exhibited lower viscosities compared with foamed binders prepared with water. Additionally, greater amounts of water content used while preparing the foamed binder also did not significantly alter

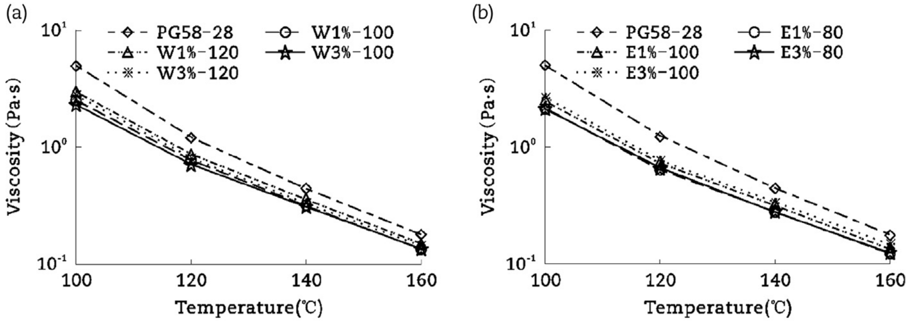

Fig. 8 – Comparison of rotational viscosity of RTFO-aged foamed asphalt binder. (a) Water. (b) Ethanol.

the sample viscosity, as shown by W1%-100 and W3%-100 samples.

Based on a recently published paper (Mohd Hasan and You, 2015), the ethanol-foamed WMA has high potential to reduce the detrimental impacts of the asphalt industry. Based on the Eco-indicator 95 analysis using a life cycle assessment (LCA) software, SimaPro 7.3, it can lower the greenhouse gas emissions, ozone layer depletions, acidification, eutrophication, summer smog, winter smog, and energy resources. Additionally, the ethanol-foamed WMA has performed better compared with water-foamed WMA and HMA mixtures in terms of lowering the cumulative energy consumptions and greenhouse gas emissions.

5. Statistical analysis

The data obtained was further analyzed using one-way analysis of variance (ANOVA) to determine the effects of foaming agents on the properties of foamed binders. Other variables such as dosages and foaming temperatures were also analyzed to statistically evaluate their influence on the tested samples. The ANOVA was used with a confidence interval of 95% ($\alpha = 0.05$) throughout the analyses. The one-way ANOVA is used to compare means of two or more samples based on the F distribution. The ANOVA tests the null hypothesis that samples in two or more groups 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 which sets differs. So, a pairwise comparison test was used to establish the differences in the results as a follow-up analysis. 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 comparisons that is based on a sequential test design. In general, the Tukey test is most commonly used compared with the Newman–Keuls test since it is the most conservative method and 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).

Table 4 – Aging factor of foamed asphalt binders.

Sample	Temperature (°C)			
	100	120	140	160
E1%-80	1.406	1.247	1.108	1.063
E1%-100	1.643	1.354	1.124	1.060
E3%-80	1.955	1.402	1.268	1.070
E3%-100	2.312	1.710	1.699	1.293
W1%-100	1.212	1.109	1.064	1.050
W1%-120	1.418	1.305	1.295	1.211
W3%-100	1.049	1.018	1.067	1.045
W3%-120	1.289	1.236	1.255	1.196

The one-way ANOVA results of the effects of foaming agent and the temperature reduction of the asphalt binder during foaming process are shown in Table 5. The analysis shows that there is no significant effect of the types of foaming agent on the temperature reduction of the asphalt binder, as indicated by the p-value, which is slightly higher than 0.05. Based on the Tukey test, the temperature reductions of the asphalt binder that was foamed using water and ethanol are significantly comparable.

Table 6 summarizes the ANOVA test of the influence of foaming agents on the rotational viscosity of foamed binders as compared with the control binder at different temperatures. The addition of ethanol significantly lowered the viscosity of asphalt binders to as low as 80 °C, as shown by the p-value in Table 6. The application of water as a foaming agent exhibited a significant reduction in the binder's viscosity at the test temperature of approximately 120 °C. The viscosity of water-foamed binders is not significantly different compared with that of the viscosity of the control binder at 80 °C and 100 °C, as presented by p-values exceeding 0.05 and the Tukey test results.

The ANOVA and the Tukey test were also performed to identify the effects of foaming agents (water and ethanol) on the aging index of foamed binders at different dosages. Both test results are presented in Table 7. The results indicate that there are significant differences between the aging indexes of foamed binders prepared with water and ethanol at a 99% confidence interval (p-values are less than 0.01). Additionally, the Tukey pairwise comparison analysis shows that the ethanol-foamed binders have a higher aging index than the water-foamed binders. This finding shows that ethanol can be expelled from the asphalt binder at a higher rate compared with water after going through the mixing process.

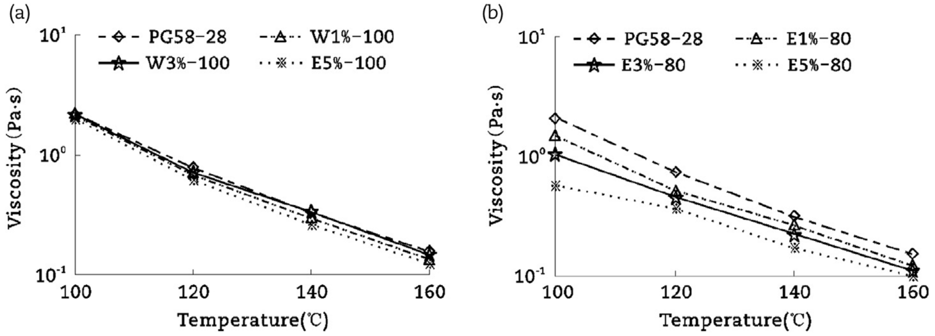

Fig. 9 – Viscosity of the foamed asphalt binder prepared with three different concentrations of foaming agents. (a) Water. (b) Ethanol.

6. Conclusions and recommendations

Experiments were conducted to compare the performance of water and ethanol as foaming agents through the measurement of rotational viscosity, the reduction in temperature during foaming, and volatile loss. Prior to testing, the foamed asphalt binders were prepared with water and ethanol at two different temperatures for each foaming agent. The ethanol-foamed asphalt binders were prepared at 80 °C and 100 °C, while the water-foamed asphalt binders were prepared at 100 °C and 120 °C. Additionally, the RTFO was used to generate short-term aging of the foamed asphalt binders. The aging process was performed in accordance with the standard procedure, AASHTO T240. Each foamed asphalt binder was exposed to temperatures similar to what were used in the preparation of the foamed asphalt binder. The rotational viscometer was used to determine the viscosity of asphalt binders at 80 °C, 100 °C, 120 °C, 140 °C, and 160 °C. The test was conducted on un-aged and RTFO-aged ethanol-foamed asphalt binders and compared to the results of the water-foamed asphalt binders under similar aging conditions. During the sample preparation, the foamed asphalt binder was preheated at the foaming temperature to avoid excessive aging of the binder and the loss of foaming agent from the asphalt binder. Overall, ethanol can function in the same manner as water but requires less energy to foam. Based on the findings, several conclusions can be drawn from this study.

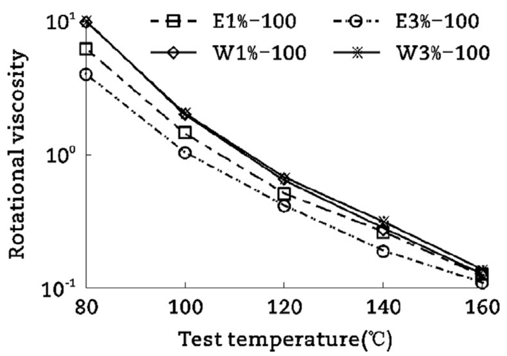

Fig. 10 – Comparison of foamed binders prepared with ethanol and water as foaming agent at 100 °C.

(1) The temperature reduction of an asphalt binder foamed using ethanol is smaller compared to the foamed asphalt binder prepared with water, which can be due to the lower latent heat of ethanol.
(2) The application of water as a foaming agent does not help to reduce the viscosity of asphalt binders.
(3) Ethanol performs better in lowering the viscosity of asphalt binders, which is essential in allowing production processes at low temperatures, as well as producing a better workability and aggregate coating.
(4) Ethanol can be expelled from the foamed asphalt binder at a higher rate due to the lower boiling point and latent heat of ethanol, based on the computed aging factor.
(5) Based on the statistical analysis, the viscosity of ethanol-foamed binders is significantly lower than the viscosities of the control and the water-foamed binders at temperatures as low as 80 °C. The viscosity of water-foamed binders has become significantly lower than that of the control binder at temperatures of approximately 120 °C. However, the types of foaming agent do not have significant effects on the binders based on the ANOVA test. Additionally, it is statistically proven that ethanol can be expelled from the asphalt binder at a higher rate than water after being used to foam the asphalt.

Several recommendations have been made to further understand the material and ensure its applicability.

(1) Analyses will be conducted to evaluate the chemical reactions that occur during the foaming process of the asphalt binder.
(2) Rheological and advanced binder testing will be performed using Superpave binder tests and other advanced binder tests.
(3) Experimental work will continue in order to characterize the ethanol-foamed WMA mixture. The volumetric properties, compaction energy index, workability, coating index, and the long-term performance will be investigated.
(4) Evaluation of the environmental impacts will be monitored through using the gas chromatography analysis of emissions, as well as the LCA to estimate the cumulative energy demand and the impacts it has on the environment and human health throughout the cradle to grave lifespan of the material.

Table 5 – One-way ANOVA effects of foaming agent on the temperature reduction during foaming process.

Variable	*p*-value	Tukey pairwise comparison
Foaming agent	0.054	There is no significant difference in the temperature reduction of the asphalt binder during the foaming process using ethanol and water.

Table 6 – One-way ANOVA effect of foaming agent on the rotational viscosity at different temperatures.

Foaming agent	Temperature (°C)	*p*-value	Tukey pairwise comparison
Ethanol	80	<0.001	The viscosity of ethanol-foamed binders is significantly lower than that of the control binder (PG58-28).
	100	0.001	
	120	0.016	
Water	80	0.095	The viscosity of water-foamed binders is not significantly different than that of the control binder (PG58-28).
	100	0.225	
	120	0.002	The viscosity of water-foamed binders is significantly lower than that of the control binder (PG58-28) at 120 °C.

Table 7 – One-way ANOVA for aging index results.

Dosage (%)	*p*-value	Tukey pairwise comparison
1	0.008	The aging indexes of ethanol-foamed and water-foamed binders are significantly different. The ethanol-foamed binders have a higher aging index than the water-foamed binders.
3	<0.001	

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