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Evaluation of Coal Combustion Products in Hot-Mix Asphalt Mixture

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16 Abstract

Very fine coal combustion products (CCPs) are a by-product of burning coal when generating electricity. Fly ash has generally been used in portland cement concrete. However, some CCPs have been used in hot-mix asphalt (HMA) as mineral fillers. Due to current changes of Environmental Protection Agency (EPA) emission requirements, large volumes of fly ash containing sulfur are produced. This ash cannot be used in traditional concrete. Therefore, this research was undertaken to investigate if some of these finer CCPs containing sulfur can be used beneficially in HMA. In this project, fly ash was blended with PG 58-28 asphalt binder at various percentages (5%, 10%, and 15%). A rotational viscosity test was performed on the blend to see what percentages of fly ash (by mass of asphalt binder) would be workable. All percentages were found to be viable. Hamburg wheel tracking tests were then conducted on these Superpave HMA mixtures. Based on the Hamburg test results, the best performing mixture with 15% of fly ash was selected to conduct further tests, such as Modified Lottman, Dynamic modulus, and S-VECD test, and compare with the control group (without fly ash). This report presents these results.

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Final Report

Prepared by

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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Abstract

Very fine coal combustion products (CCPs) are a by-product of burning coal when generating electricity. Fly ash has generally been used in portland cement concrete. However, some CCPs have been used in hot-mix asphalt (HMA) as mineral fillers. Due to current changes of Environmental Protection Agency (EPA) emission requirements, large volumes of fly ash containing sulfur are produced. This ash cannot be used in traditional concrete. Therefore, this research was undertaken to investigate if some of these finer CCPs containing sulfur can be used beneficially in HMA. In this project, fly ash was blended with PG 58-28 asphalt binder at various percentages (5%, 10%, and 15%). A rotational viscosity test was performed on the blend to see what percentages of fly ash (by mass of asphalt binder) would be workable. All percentages were found to be viable. Hamburg wheel tracking tests were then conducted on these Superpave HMA mixtures. Based on the Hamburg test results, the best performing mixture with 15% of fly ash was selected to conduct further tests, such as Modified Lottman, Dynamic modulus, and S-VECD test, and compare with the control group (without fly ash). This report presents these results.

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Table of Contents

List of Tables

List of Figures

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Chapter 1: Introduction

1.1 Background

Coal combustion products (CCPs), also known as fly ash, are a by-product of coal ignition during generation of electricity. Fly ash has been effectively used in portland cement concrete, embankments, and soil stabilization. However, the applications of fly ash in hot-mix asphalt (HMA) pavements are very limited (Asi & Assa'ad, 2005; Tapkin, 2008; Bautista, 2015; Mistry & Roy, 2016). According to the American Coal Ash Association (ACAA), only 48% out of 129 million tons of CCPs are used in different applications, and the rest (52%) is placed in landfills. Moreover, only 0.13% CCPs are being used as mineral fillers in Hot-Mix Asphalt (HMA) (Faheem et al., 2017). In the recent past, the Environmental Protection Agency (EPA) changed the emission requirements of electric power generation resulting in a large volume of fly ash in many coal-fired power stations that cannot be used as replacements of portland cement in concrete because of the presence of sulfur in fly ash. Therefore, agencies are investigating different methods of using these by-products beneficially, such as use in asphalt binders. Bautista (2015) found that using fly ash improved the properties of asphalt mastic more than those with limestone fines as mineral filler. Faheem et al. (2017) concluded that some CCPs can act as enhancers and extenders to the binder and replacing 10% of asphalt binder by volume with CCPs can potentially improve aging resistance, moisture damage resistance, fatigue life, and thermal cracking resistance. However, investigations of the performance of HMA mixture with the asphalt mastic containing CCPs are very limited.

1.2 Objective

This study focused on evaluating the performance of HMA mixtures with various fly ash content and then comparing with a control mixture without fly ash. Hamburg wheel tracking device (HWTD), modified Lottman, dynamic modulus, and simplified viscoelastic continuum damage (S-VECD) tests were conducted on Superpave mixtures with fly ash for evaluation.

1.3 Report Outline

This report is divided into four chapters. Chapter 1 states the background, problem statement, and objective of the research. Chapter 2 describes the materials and experimental work performed. Chapter 3 presents the results and analysis. Finally, Chapter 4 summarizes conclusions based on this study.

Chapter 2: Materials and Laboratory Experiments

2.1 Materials

In this study, local CCPs, as shown in Figure 2.1, were supplied by Kansas City Fly Ash LLC/Eagle Materials (KCFA) from the Kansas City Power & Light (KCP&L) sources. The ash was an ASTM Class C fly ash. It was blended with an asphalt binder at various percentages, 5%, 10%, and 15%, by mass of the asphalt binder, as proposed by the Kansas Department of Transportation (KDOT).

Figure 2.1: Fly Ash

The scanning electron microscopy (SEM) test was conducted to explore the microstructure characteristics. Figure 2.2 shows the SEM image of fly ash with 2,000 times magnification. The main elements detected by SEM are showed in Table 2.1. The detected elements include O, Ca, S, and Si.

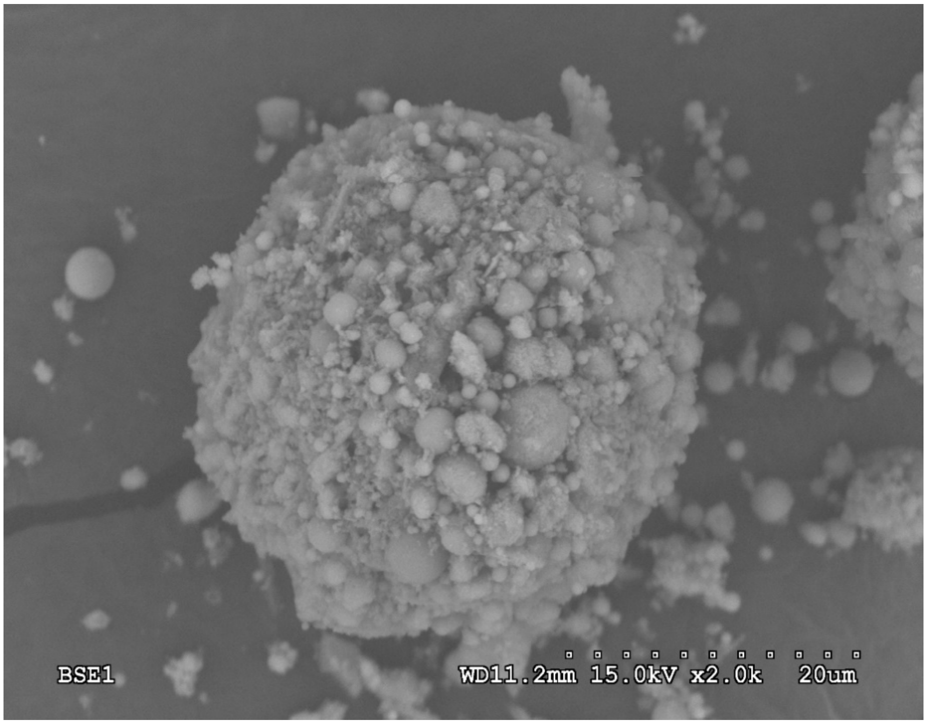

Figure 2.2: SEM Results of Fly Ash

Table 2.1: Main Elements of Fly Ash

Element	Atomic%
O	59.09
Ca	15.04
S	9.24
Si	6.90
Al	4.82
Te	3.19
Mg	1.72
Total	100

In this study, HMA mixtures used five virgin aggregates (CS-1, CS-2A, CS-2, SSG, and SSG-1) and RAP. Virgin aggregates and RAP were collected from Shilling Construction Co. Inc. in Riley County, Kansas. The gradation of each aggregate is shown in Table 2.2. A PG 58-28 asphalt binder was used in this research for the HMA mixtures. The viscosity of the asphalt binder was 312 cP.

Table 2.2: Aggregate Gradation

Aggregate Type	% Retained									
	¾"	½"	3/8"	#4	#8	#16	#30	#50	#100	#200
CS-1		36	73	95	99	99	99	99	99	99.0
CS-2A				5	48	78	88	92	94	95.8
CS-2				24	50	62	69	75	78	80.2
SSG					25	60	80	91	98	99.0
SSG-1			7	73	99	99	99	99	99	99.0
RAP		4	10	26	44	60	71	83	88	90.6

2.2 Experimental Work

2.2.1 Binder Preparation

Fly ash was blended with heated asphalt cement with mass percentages of 5%, 10%, and 15%. A spiral mixer installed on a drill was used to mix the fly ash and binder together to obtain a "somewhat" homogeneous binder. After mixing, a rotational viscometer (RV) test was conducted to check the workability of the blended binders. Usually, the RV test for the Superpave PG asphalt binder is conducted at 135 °C, and typical viscosity values for the asphalt binder at this temperature are 200 cP to 2000 cP (Pavement Interactive, n.d.). Based on the test results, tabulated in Table 2.3, viscosity values of all blends fall in this viscosity range, indicating good workability. However, as time went by, separation occurred in the binders with 10% and 15% fly ash. Therefore, fly ash was blended with the binder just before being put into the asphalt mixtures.

Table 2.3: Viscosity Test Results

Fly Ash Content (%)	Viscosity (cP)
0	312
5	330
10	352
15	375

2.2.2 Mix Design

HMA mixtures were developed in the laboratory following KDOT requirements. KDOT defines mixtures by their nominal maximum aggregate size (NMAS). A 12.5-mm NMAS mix design was developed in this project. The mixture gradation is shown in Figure 2.3. Table 2.4 shows the gradation of the combined blend and KDOT requirements. Since the percentage of recycled asphalt pavement (RAP) materials used in this study was 20%, a PG 58-28 was needed. All aggregates were heated within the mixing temperature range as the binder was blended. RAP was heated to 60 °C. All mixtures were prepared using a mechanical mixer. After mixing, loose mixtures were aged for two hours at the compaction temperature. Then a Superpave gyratory compactor was used to compact the asphalt mixture with the maximum number of gyrations selected based on the design cumulative equivalent single axle loads (ESALs). A target air voids of 4% was expected to be achieved for the compacted cylindrical samples. Two compacted specimens were made for the bulk specific gravity (G_{mb}) test and 1,500 g of loose mixture was used for the theoretical maximum specific gravity (G_{mm}) test to compute air voids of compacted specimens. Based on the required air voids, the asphalt binder content of mixtures with 0%, 5%, 10%, and 15% fly ash, respectively, were 6%, 6.2%, 6.5%, and 6.8%.

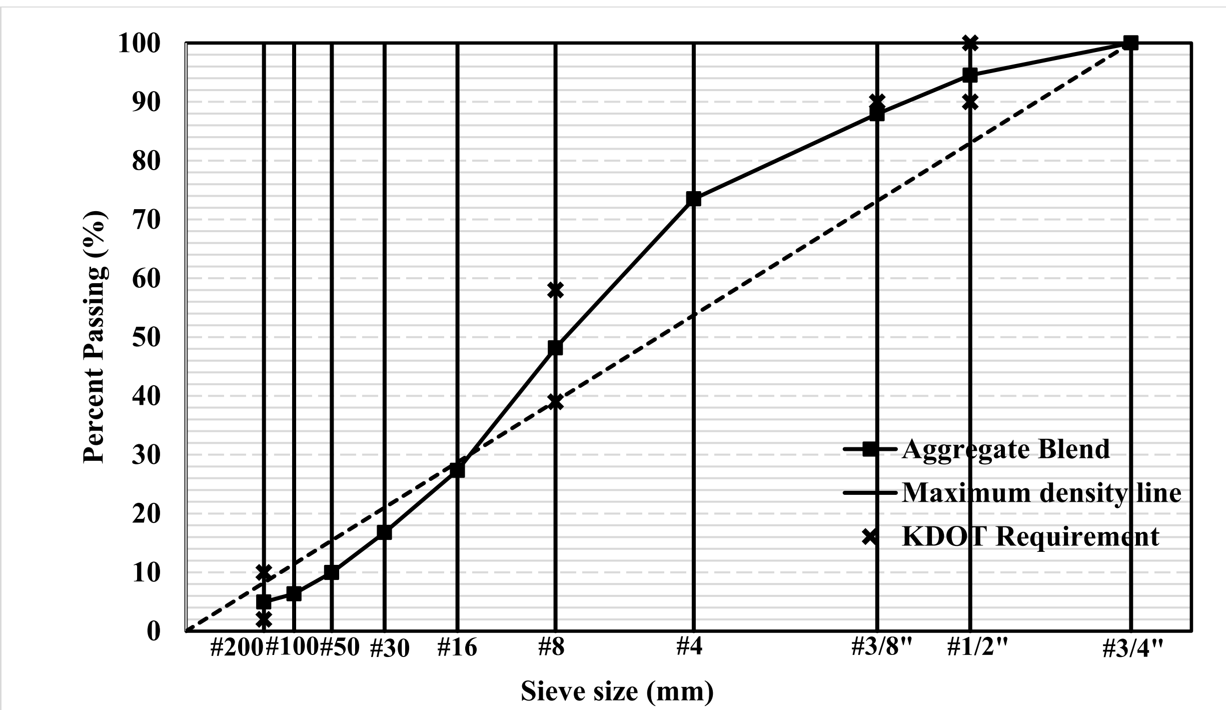

Figure 2.3: 0.45 Power Chart for Blended Aggregates

Table 2.4: Percentages of Aggregates, Gradation of Blend, and KDOT Requirements

Aggregate Type	% in Mix	% Retained										
		1”	¾”	½”	3/8”	#4	#8	#16	#30	#50	#100	#200
CS-1	13			4.7	9.5	12.4	12.9	12.9	12.9	12.9	12.9	12.9
CS-2A	24					1.2	11.5	18.7	21.1	22.1	22.6	23.0
CS-2	8					1.9	4.0	5.0	5.5	6.0	6.2	6.4
SSG	27					0.0	6.8	16.2	21.6	24.6	26.5	26.7
SSG-1	8				0.6	5.8	7.9	7.9	7.9	7.9	7.9	7.9
RAP	20			0.8	2.0	5.2	8.8	12.0	14.2	16.6	17.6	18.1
Design Single Point				5	12	27	52	73	83	90	94	95.0
SR-12.5A Master Limits		0	0-2	0-10	10 Min.		42-61					90-98

2.2.3 Hamburg Wheel Tracking Device (HWTD) Test

The HWTD is now an accepted test for evaluating the effects of rutting and moisture damage. The HWTD test simulates field traffic by rolling a pair of steel wheels repeatedly across the surface of HMA specimens in a heated water bath with a temperature of 50 °C. The test procedure followed is the Tex-242-F test method of the Texas Department of Transportation (TxDOT). Test specimens were compacted to 7±1% air voids with 150 mm diameter and 62±1 mm height. A total of 12 specimens were prepared for each mixture, since a set of tests required four specimens with three replicates. The edges of test specimens were trimmed to fit in the molds to form the test specimen configuration. The maximum number of wheel passes and the maximum rut depth were the inputs into the HWTD operating software before testing. The test criteria of the Tex-242-F test method are summarized in Table 2.5.

Table 2.5: Hamburg Wheel Tracking Test Criteria

Binder Grade	Number of Wheel Passes	Maximum Rut Depth (mm)
PG 64-22	10,000	12.5
PG 70-22	15,000	12.5
PG 76-22	20,000	12.5

For this study, 40,000 wheel passes and a 20-mm maximum rut depth were set as the failure criteria. The test started once the water temperature reached 50 °C. The rut depth was measured every 100 wheel passes. The test automatically stopped when either the maximum number of wheel passes or the maximum rut depth was reached. The number of passes to failure and rut depth were recorded at the end of test.

2.2.4 Modified Lottman Test

The modified Lottman test evaluates the moisture susceptibility or stripping potential of HMA mixtures. In this study, the test procedure followed was KDOT test method KT-56 (2014), Resistance of Compacted Asphalt Mixture to Moisture-Induced Damage. Six samples with 150 mm diameter, 95±5 mm height, and 7±0.5% air voids were prepared in this moisture susceptibility test. The samples were sorted into two subsets of three specimens each by getting approximately equal average air voids. One of the subsets was taken as an unconditioned group which was tested dry. The other subset was conditioned through a freeze-thaw cycle after partial saturation. First, the samples were vacuum saturated until the volume of water was in between 70% and 80% of the volume of air. After saturation, the specimens were frozen at -18±3 °C for a minimum of 16 hours. Then the specimens were placed in a hot water bath with a temperature of 60±1 °C for 24±1 hours. Afterwards, the samples were placed in a 25±0.5 °C water tank for 2 hours ± 10 minutes to cool down to the test temperature. Finally, the indirect tensile strength (ITS) test was conducted on the conditioned and unconditioned samples with a loading speed of 50 mm per minute until failure. The peak loads were recorded to calculate ITS by using Equation 2.1.

$$\mathbf{ITS} = \frac{\mathbf{2000 \times P}}{\mathbf{\pi \times t \times D}}$$ **Equation 2.1**

Where:

ITS = indirect tensile strength (kPa),

P = maximum load (N),

t = specimen thickness (mm), and

D = specimen diameter.

Then the tensile strength ratio was calculated using Equation 2.2.

$$\mathbf{TSR} = \frac{\mathbf{ITS}_{c}}{\mathbf{ITS}_{UC}}$$ **Equation 2.2**

Where:

TSR = tensile strength ratio,

ITS_c = average indirect tensile strength of conditioned subset, and

ITS_{uc} = average indirect tensile strength of unconditioned subset.

2.2.5 Dynamic Modulus Test

Dynamic modulus is a fundamental property of HMA mixtures. It defines the viscoelastic nature of HMA mixtures and describes the stiffness over a wide range of temperatures and loading frequencies (Witczak & Bari, 2004). In this study, the dynamic modulus test was performed according to the AASHTO TP 62-07 Standard Method of Test for Determining Dynamic Modulus of Hot Mix Asphalt (HMA). Compacted samples with 150 mm diameter and 170 mm height were prepared before coring. For each mixture, three samples were fabricated with a 7±0.5% target air voids after coring and trimming to 100 mm diameter and 150 mm height. Six metal studs were glued to the sides of the samples to attach the LVDTs. The tests were conducted at temperatures of 4 °C, 21 °C, and 37 °C, and frequencies of 24, 10, 5, 1, 0.5, and 0.1 Hz in this study. The samples were preconditioned in an environmental chamber prior to set up in the Asphalt Mixture Performance Tester (AMPT) machine. After setup, the test started once the test temperature was reached, and test results were automatically collected by the AMPT software.

2.2.6 Simplified Viscoelastic Continuum Damage (S-VECD) Test

The S-VECD test is usually conducted to evaluate the fatigue behavior of HMA mixtures. In this study, the S-VECD tests were performed according to the AASHTO TP 107-14 Standard Method of Test for Determining the Damage Characteristic Curve of Asphalt Mixtures from Direct Tension Cyclic Fatigue Tests. Compacted samples with 150 mm diameter and 180 mm height were fabricated. After coring and trimming the compacted samples to 100 mm diameter and 130±2.5 mm height, samples with air voids of 7±0.5% were adopted for the S-VECD tests. A top and a bottom platen as well as the metal studs for the LVDTs were glued to the samples and cured at least 10 hours before test. The test specimens were put into an environmental chamber for at least 2 hours to reach the test temperature of 18 °C. After preconditioning, the test specimen was set up into the test machine and quickly tightened to the bottom and top support platen. Once the test temperature was reached, a fingerprint dynamic modulus test at a frequency of 10 Hz was first performed with a target strain range of 50 to 75 micro-strain. After the fingerprint test, the specimen was left to rest for a minimum of 15 minutes before starting the fatigue test. A peak-to-peak strain of 300 με (s_1) was required to be applied on the first sample. The number of cycles to failure (Nf_1) would determine the strain for the second and third test samples, as shown in Table 2.6 (AASHTO TP 107-14). The test stopped when the samples failed and a sudden drop would show up in the dynamic modulus-phase angle graph. All test outputs are automatically collected and can be exported from the software for analysis.

Table 2.6: On-Specimen Strain Levels for the Second and Third Specimens

Case	Sample 2	Sample 3
500< Nf_1<1,000	s_1 - 100	s_1 - 150
1,000< Nf_1<5,000	s_1 - 50	s_1 - 100
5,000< Nf_1<20,000	s_1 + 50	s_1 - 50
20,000< Nf_1<100,000	s_1 + 100	s_1 + 50
100,000< Nf_1	s_1 + 150	s_1 + 100

Chapter 3: Results and Discussion

3.1 HWTD Test Results

The HWTD test results are shown in Table 3.1. Figure 3.1 shows the typical test output of a sample of mixture with 15% fly ash. All mixtures failed since the maximum rut depth was reached. The control mix (0% fly ash) failed with 12,263 passes at 20-mm rut depth. The mixtures with 5% and 10% fly ash failed at 7,520 and 6,941 passes, respectively. And the number of passes to failure increased to 11,283 with 15% fly ash, which was close to that for the control mix. Therefore, the addition of 15% fly ash in an HMA mixture would increase the rutting resistance compared to 5% or 10% fly ash.

Table 3.1: HWTD Test Results

Fly Ash Content	Asphalt Content	Left Wheel		Right Wheel		Average		Average No. of Passes
		Pass No.	Rut Depth (mm)	Pass No.	Rut Depth (mm)	Pass No.	Rut Depth (mm)	
0%	6.0%	9,682	20.3	7,284	20.01	8,483	20.16	12,263
		10,576	20.05	27,854	20.02	19,215	20.04	
		10,550	20.1	7,634	20.26	9,092	20.18	
5%	6.2%	-	-	-	-	-	-	7,520
		6,562	20.05	6,406	20.11	6,484	20.08	
		10,624	20.10	6,488	20.01	8,556	20.06	
10%	6.5%	4,900	20.05	9,288	20.08	7,094	20.07	6,941
		7,146	20.05	6,428	20.01	6,787	20.03	
		6,922	20.05	6,500	20.1	6,711	20.08	
15%	6.8%	8,930	20.12	10,402	20.04	9,666	20.08	11,283
		13,906	20.23	11,894	20.01	12,900	20.12	
		11,088	20.02	13,192	20.35	12,140	20.19	

* Data missing due to the unexpected machine problem during the test

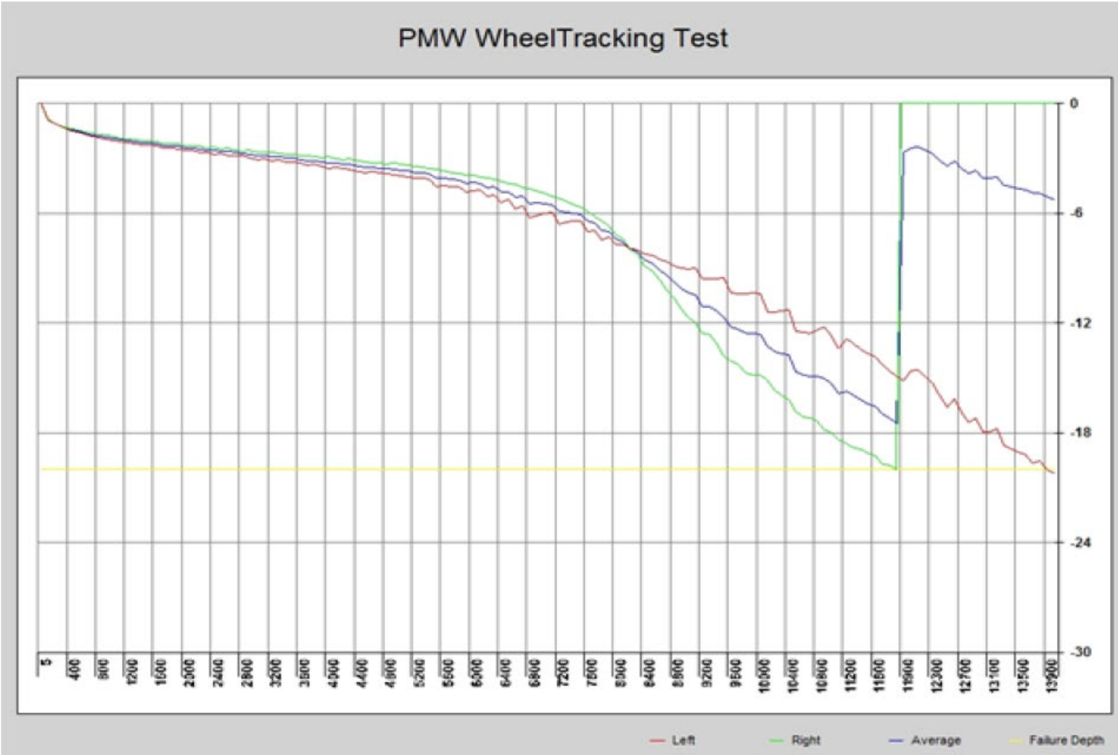

Figure 3.1: HWTD Output of Mixture with 15% Fly Ash

Further evaluation of mixture performance, post-compaction consolidation, creep slope, stripping slope, and stripping inflection point can be obtained by plotting a curve between rut depth and number of wheel passes, as shown in Figure 3.2. The deformation at 1,000 wheel passes is called post-compaction consolidation since the wheel is densifying the mixture within the first 1,000 wheel passes (Yildirim et al., 2007). The creep slope relates to rutting susceptibility. It is the number of wheel passes required to create 1 mm of rut depth. The stripping slope relates to moisture damage. It is the number of wheel passes creating 1 mm of rut depth after the stripping inflection point. The stripping inflection point is the number of wheel passes at the interaction point of creep slope and stripping slope. In general, high creep slope, stripping inflection point, and stripping slope indicate less moisture susceptibility of a mixture (Yildirim et al., 2007).

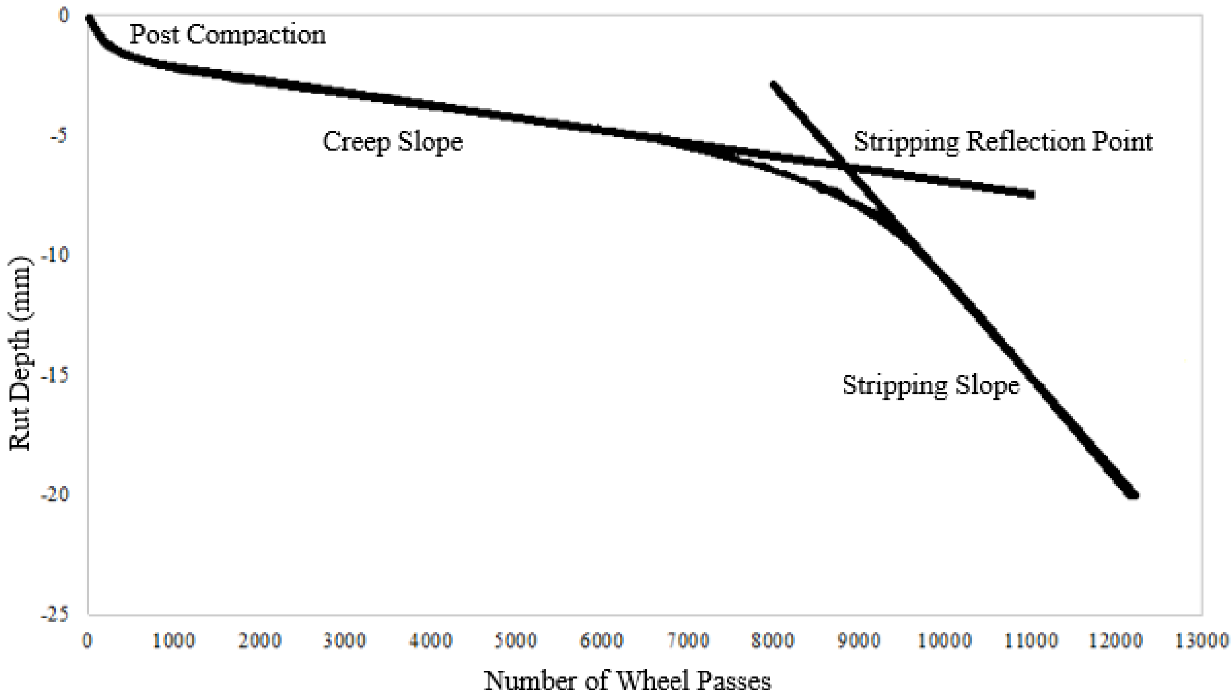

Figure 3.2: HWTD Outputs

Table 3.2 showed the test results of creep slope, stripping inflection point, and stripping slope of mixtures with various fly ash contents. For the control mix, the highest creep slope, stripping slope, and stripping inflection point were observed, as well as the wheel passing number at failure. Therefore, the control mixture with no fly ash was more resistant to rutting and moisture damage. The creep slope, stripping slope, and stripping inflection point of the mixture decreased when 5% and 10% fly ash were added. However, those values increased when the fly ash content reached 15%. The creep slope and stripping slope were almost the same as the control group.

Table 3.2: HWTD Test Output Parameters

Fly Ash Content	Creep Slope	Stripping Reflection Point	Stripping Slope
0%	2,108	7,422	361
5%	1,161	4,193	277
10%	1,125	3,648	221
15%	2,104	6,645	360

Since all mixtures failed in the HWTD test, the best performing mixture (with 15% fly ash) was selected to conduct more performance tests and compare with the control group (without fly ash).

3.2 Modified Lottman (KT-56) Test Results

The KT-56 test results for all mixtures are listed in Table 3.3. As shown in Table 3.3, all mixtures met the KDOT criterion of a minimum 80% TSR. Mixtures containing 15% fly ash had the minimum required TSR, which indicated that adding 15% fly ash could maintain the moisture resistance. Based on the average tensile strength of conditioned and unconditioned samples as a function of fly ash content, the highest tensile strength was observed for the mixture with 15% fly ash.

Table 3.3: Modified Lottman Test Results

Fly Ash Content		Air Voids (%)	Tensile Strength (kPa)	Avg. (kPa)	TSR (%)
0%	Conditioned	7.1	239	246	80
		6.6	274		
		7.0	226		
	Unconditioned	6.9	305	307	
		6.8	290		
		7.0	328		
15%	Conditioned	6.9	331	261	80
		6.9	233		
		6.9	219		
	Unconditioned	7.0	356	327	
		6.9	317		
		6.9	309		

3.3 Dynamic Modulus Test Results

In order to compare the test results for different mixtures, a master curve, as shown in Figure 3.3, was prepared by shifting different test temperatures to a reference temperature, 18 °C, also the test temperature of S-VECD. Based on the master curve, the dynamic modulus of mixture with 15% of fly ash was a little bit higher. The mixture with 15% of fly ash is slightly stiffer and more susceptible to fracture cracking than the control mix.

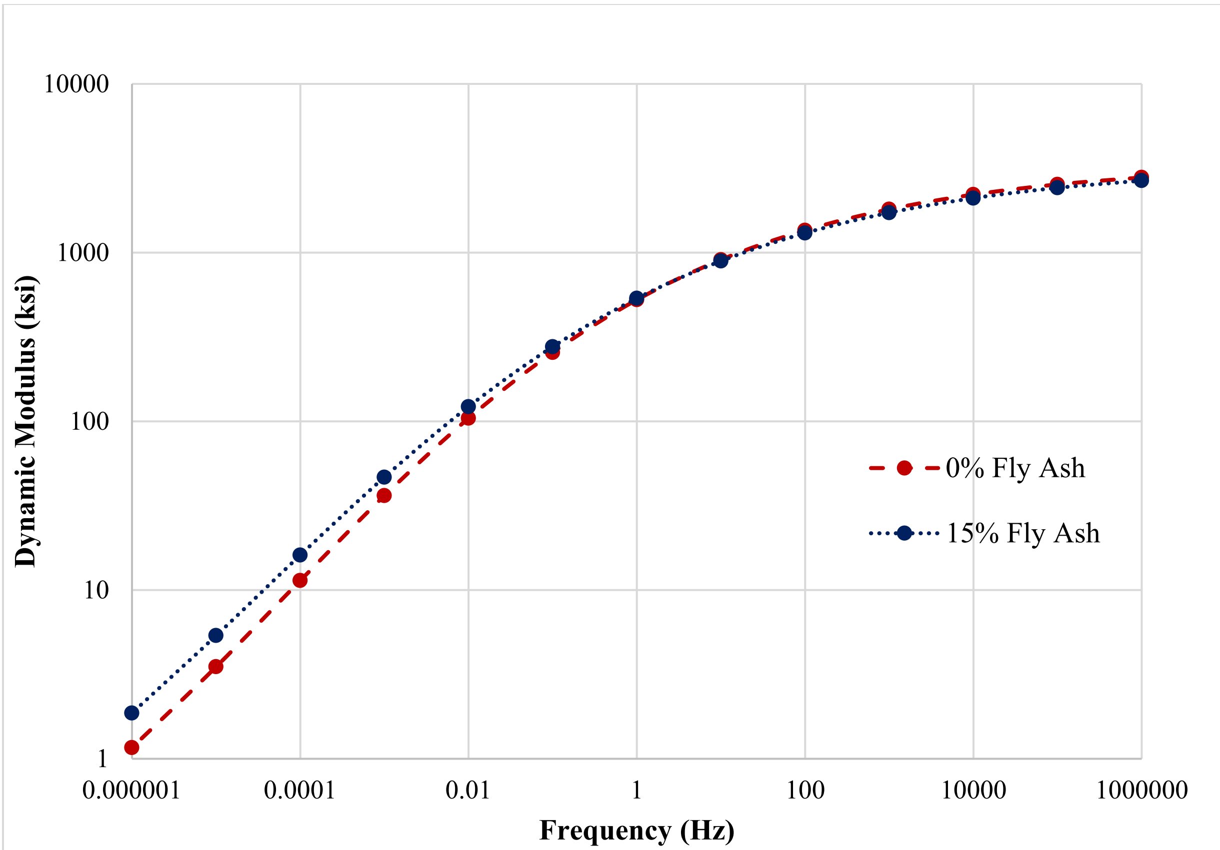

Figure 3.3: Dynamic Modulus Master Curve at 18 °C

3.4 S-VECD Test Results

To study the mixture resistance of fatigue cracking, a damage characteristic curve (C-S) was developed using the test results. The following power model, Equation 3.1, was used to investigate the damage parameter for various mixtures:

$$\mathbf{C = 1 - y}\boldsymbol{S^{z}} \qquad \textbf{Equation 3.1}$$

Where:

C = pseudo stiffness at failure,

S = damage internal state variable at failure, and

y, z = fitting coefficients for the power model.

Alpha-Fatigue software was used to obtain the fatigue damage characteristics using results from the S-VECD tests and previously described dynamic modulus tests. Fitting coefficients y and z and pseudo strains at failure were automatically calculated by the software. Damage Characteristic Curve was developed using the power model showed above by changing pseudo stiffness (C) from 1 to the value at failure (Tavakol & Hossain, 2016). Figure 3.4 illustrates the damage characteristic curves of control mix and mixture with 15% of fly ash. For a given normalized pseudo stiffness (C), higher damage (S) indicated a better resistance to damage (Xie et al., 2015). In the figure, the C-S curves of the control mix and 15% fly ash mixture were very close, indicating that these two mixtures had very similar resistance to damage.

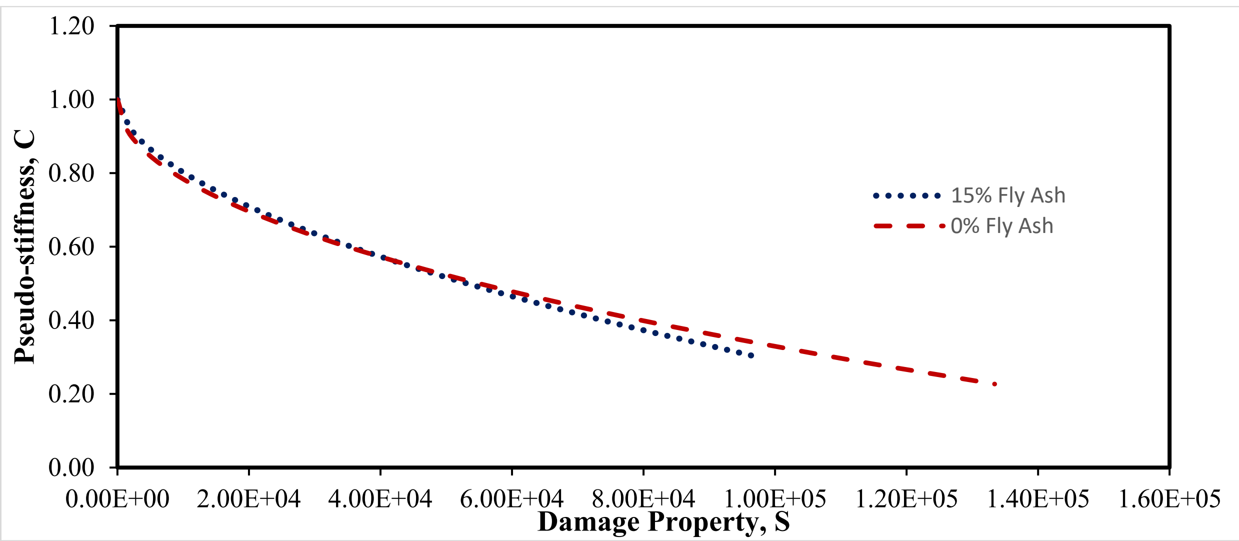

Figure 3.4: Damage Characteristic Curve at 18 °C

3.5 Statistical Analysis

This study utilized Statistical Analysis System (SAS)® software to perform statistical analysis of HWTD and KT-56 test results.

A generalized linear mixed model (GLMM) approach was used to analyze the HWTD data. This approach enables statisticians to incorporate both fixed and random effects in a model (Milliken & Johnson, 2009). In this test, there was only one treatment factor: fly ash content with four levels, 0%, 5%, 10%, and 15%. The following model was used to investigate the differences in rutting resistance (in terms of number of passes to failure in HWTD) among various mixtures with varying fly ash contents:

$$y_{ij} = \mu + \alpha_i + \varepsilon_{ij} \qquad \textbf{Equation 3.2}$$

Where:

y = the response variable (no. of passes to failure in HWTD),

μ = the intercept,

α_i = the effect of i^{th} level of fly ash content, i = 1, 2, 3, 4, and

ε_{ij} = the response error for the j^{th} sample from the i^{th} fly ash content.

Statistical Analysis System (SAS) software was used to perform the statistical analysis. The results were shown in Table 3.4 and Figure 3.5. Figure 3.5 clearly showed that there was a significant difference between the least square means of the number of passes at failure of the mixture with 0% and 15% fly ash and the mixtures with 5% and 10% fly ash. The analysis results in Table 3.4 illustrated the same conclusion. The p-value of comparing 0% and 15% fly ash to 5% and 10% fly ash was equal or slightly larger than 0.05, but much smaller than the p-value of comparing 0% to 15% fly ash, and 5% to 10% fly ash.

Table 3.4: Differences of Least Squares Means (of Fly Ash Content) for Multiple Comparisons

Fly Ash Content	Fly Ash Content	Estimate	Standard Error	DF	t Value	Pr > │t│
0	5	4743.3	2811.6	18	1.69	0.11
0	10	5396.3	2514.8	18	2.15	0.05
0	15	694.7	2514.8	18	0.28	0.79
5	10	653.0	2811.6	18	0.23	0.82
5	15	-4048.7	2811.6	18	-1.44	0.17
10	15	-4701.7	2514.8	18	-1.87	0.08

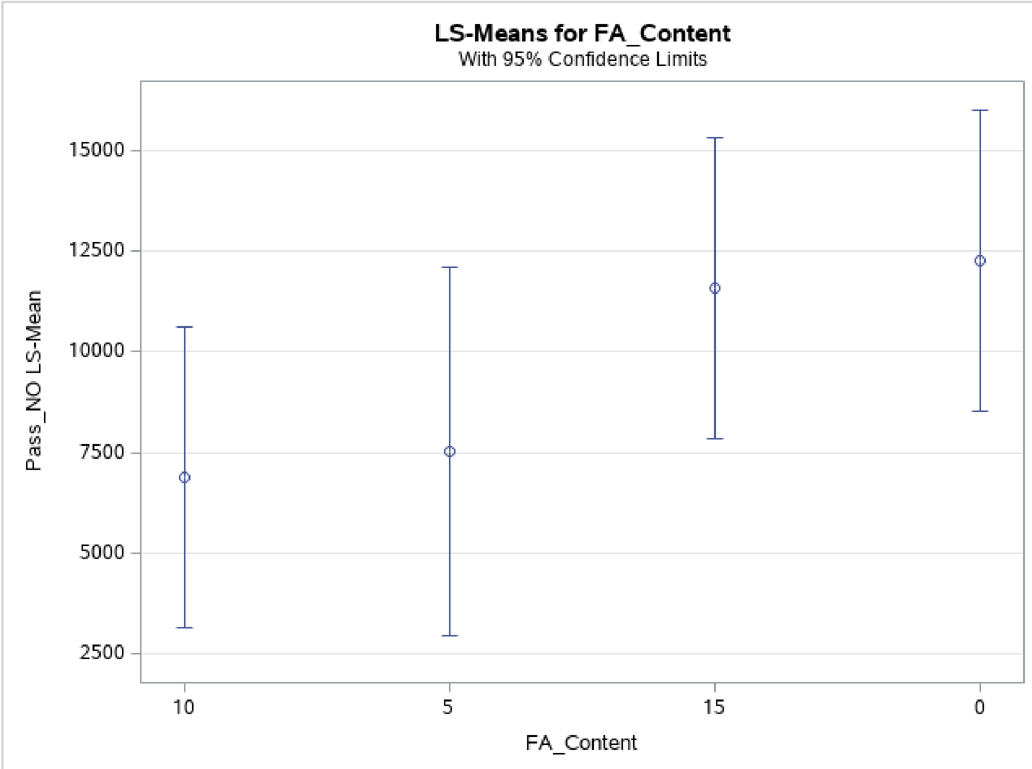

Figure 3.5: Differences in Number of Passes for Various Fly ash Contents

Therefore, adding fly ash significantly affected the rutting potential irrespective of the quantity of fly ash. However, when added fly ash content was increased to 15%, the effect of fly ash became insignificant

The GLMM approach was also used to analyze the KT-56 tests data. In this test, there were two treatment factors: (i) fly ash content at two levels- 0%, and 15%; (ii) condition state with two levels- conditioned and unconditioned.

The results obtained from SAS software were shown in Table 3.5 and Figure 3.6.

Table 3.5: Differences in Least Squares Means for Multiple Comparisons

Fly Ash Content	Fly Ash Content	Estimate	Standard Error	DF	t Value	Pr > |t|
0	15	-0.5	25.09	10	-0.02	0.98

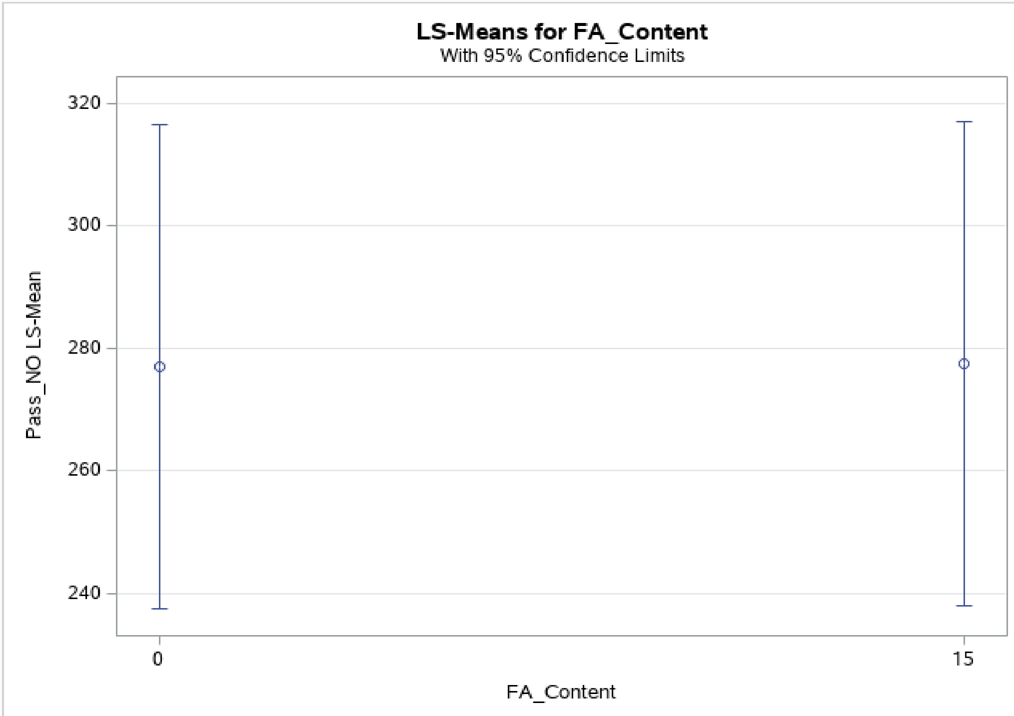

Figure 3.6: Difference in Tensile Strengths of Different Fly Ash Contents.

Based on Figure 3.6, there was no significant difference between the least square means of tensile strengths derived from 15% fly ash and the control group. The p-values showed in Table 3.5 support the same conclusion. The p-values were larger than 0.05, which means there was no significant difference of tensile strength for two different fly ash contents. Adding 15% of fly ash would not significantly affect the mixture tensile strength.

3.6 Economic Analysis

All test results obtained in this study showed that the asphalt mixture with 15% fly ash has similar performance in terms of rutting, fatigue cracking and stripping resistance when compared with that of mixture with no fly ash. However, added fly ash results in an increase in virgin binder content when doing the mix design. Therefore, an economic analysis was conducted to check whether using 15% fly ash would promote in economy or not.

Table 3.6 shows the binder content of mixtures with 0% and 15% of fly ash. The price of PG 58-28 binder is currently running about $470 per ton, and the average cost of fly ash is about $60 per ton. Based on these prices, the cost of added virgin binder and fly ash can be calculated.

For example, assume the mass of the HMA mixture is 1,000 tons. For control mix (no fly ash), the cost only includes added virgin binder (as shown in Table 3.6), which is 1,000 * 5% * $470 = $23,500. For mixture with 15% of fly ash, the cost is 1,000 * 5.8% * (1-15%) * $470 + 1,000 * 5.8% * 15% * $60 = $23,693, which is slightly higher than the mixture without fly ash. Therefore, the addition of 15% of fly ash in the HMA mixture is unlikely to result in economy.

Table 3.6: Binder Content

Fly Ash Content	Total Binder Content	Virgin Binder Content
0	6.0	5.0
15	6.8	5.8

Chapter 4: Conclusions

4.1 Conclusions

The objective of this research was to investigate asphalt mixture performance with various fly ash contents. Mixtures with 0%, 5%, 10%, and 15% fly ash were tested in HWTD, modified Lottman, dynamic modulus, and S-VECD tests to evaluate mixture performance. The following conclusions can be made based on the analysis of the test results:

- The HWTD test results showed that all mixtures failed at 20 mm rut depth. Based on the number of wheel passes to failure, the research team can conclude that the control mixture without fly ash had the highest rutting resistance. Meanwhile, mixture with 15% fly ash also had a relatively high resistance of rutting compared to the mixtures with 5% and 10% fly ash. HWTD output parameters of creep slope, stripping slope, and stripping inflection point also indicated the same conclusion—that the control mix and mixture containing 15% of fly ash have relatively high moisture resistance.
- Modified Lottman test results illustrated that both control and 15% fly ash mixtures met the minimum 80% KDOT requirement for TSR.
- Dynamic modulus test results indicate that the stiffness of the mixture with 15% fly ash was slightly higher than the control mix at lower frequencies, but the difference was not significant. Also, these two mixtures showed approximately the same fatigue performance according to their S-VECD test results.

All test results indicated that asphalt mastic with fly ash is unlikely to enhance pavement performance in terms of rutting, fatigue cracking, and moisture susceptibility resistance.

References

Asi, I., & Assa'ad, A. (2005). Effect of Jordanian oil shale fly ash on asphalt mixes. *Journal of Materials in Civil Engineering*, *17*(5), 553–559.

Bautista, E. (2015). *Experimental evaluation of the effect of coal combustion products on constructability, damage and aging resistance of asphalt mastics* (Doctoral dissertation). Retrieved from http://dc.uwm.edu/etd/858

Faheem, A. F., Cloutier, C., Bautista, E., & Sobolev, K. (2017). *Impact of coal combustion product incorporation in asphalt mixture performance*. Presented at 96th Annual Meeting of the Transportation Research Board, Washington, DC.

KT-56 Kansas Test Method. (2014). Resistance of compacted asphalt mixture to moisture induced damage. *Kansas Department of Transportation construction manual*, *Part V*. Topeka, KS: Kansas Department of Transportation.

Milliken, G. A., & Johnson, D. E. (2009). *Analysis of messy data, Volume 1: Designed experiments* (2nd ed.). Boca Raton, FL: CRC Press.

Mistry, R., & Roy, T. K. (2016). Effect of using fly ash as alternative filler in hot mix asphalt. *Perspectives in Science, 8*, 307–309.

Pavement Interactive. (n.d.). *Rotational viscometer*. Retrieved July 12, 2020, from https://pavementinteractive.org/reference-desk/testing/binder-tests/rotational-viscometer/

Tapkin, S. (2008). Mechanical evaluation of asphalt–aggregate mixtures prepared with fly ash as a filler replacement. *Canadian Journal of Civil Engineering, 35*(1), 27–40.

Tavakol, M., & Hossain, M. (2016). *Minimum virgin binder limits in recycled Superpave mixes in Kansas* (Report No. K-TRAN: KSU-13-5). Topeka, KS: Kansas Department of Transportation.

Witczak, M., & Bari, J. (2004). *Development of a master curve (E*) database for lime modified asphaltic mixtures*. Arlington, VA: National Lime Association.

Xie, Z., Shen, J., Earnest, M., Li, B., & Jackson, M. (2015). Fatigue performance evaluation of rubberized porous European mixture by simplified viscoelastic continuum damage model. *Transportation Research Record, 2506*, 90–99. https://doi.org/10.3141/2506-10

Yildirim, Y., Jayawickrama, P. W., Hossain, M. S., Alhabshi, A., Yildirim, C., Smit, A. D. F., & Little, D. (2007). *Hamburg wheel-tracking database analysis* (Report No. FHWA/TX-05/0-1707-7). College Station, TX: Texas Transportation Institute.

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