Application of Fly Ash in ASHphalt Concrete:
from *Challenges* to *Opportunities*

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ABSTRACT

Fly ash has been effectively used for many years in producing high performance concrete, with limited use in asphalt pavements. This is possibly because the performance benefits that fly ash provides to asphalt mixtures are under-investigated. The reported research investigated the interaction of fly ash with different types of asphalt binders and documented important improvements found in the critical properties of asphalt. Microstructural investigation demonstrated in previous work, that crack-arresting behavior was successfully induced by evenly distributed fly ash particles within the bitumen matrix. Investigation of the rheological performance of blends of asphalt binders with different types of ash using dynamic shear rheometer confirmed the feasibility of using fly ash to improve the performance of asphalt

binders. Research data demonstrated increased resistance to oxidative aging. A longer service life could now be feasible due to increased resistance to mechanical and environmental loading. Testing of hot mix asphalt (HMA) demonstrated that the substitution of 10% of asphalt binder with fly ash (i.e. bitumen extension) did not impair workability and compactability of HMA. These experimental results indicated that the use of fly ash in bitumen materials is an attractive option.

This research presents a unique case study of road paving with an ASHphalt mix (asphalt with ash) using standard production and construction techniques. The novel beneficial effects of ASHphalt are demonstrated. A major step is achieved in introducing ASHphalt as a sustainable approach for building future infrastructure with a clear opportunity for new and existing roads and highways.

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1. Introduction

Today there are rapidly increasing demands on pavements infrastructure in terms of traffic loadings and service life. While the number of road miles only increased by 5.8% from 1980 to 2010, the number of vehicles on the road increased by 95.4% over the same period. The total vehicle miles travelled in the United States is expected to increase by 50% in the next 20 years and freight movement is expected to double by 2025.

The United States has more than 2 million miles of paved roads and highways, and 94% of those are surfaced with asphalt concrete. Each year, 4,000 asphalt plants in the U.S. produce 500 to 550 million tons of asphalt pavement material worth in excess of $30 billion. Increased traffic demands and factors such as the escalating price in crude oil plus rising energy costs, all contribute to increased production costs of asphaltic concrete. With the continual repair of an aging U.S. transportation infrastructure and increasing transportation volumes on U.S. highways, there is an urgent need for high-performance paving materials incorporating substantial quantities of industrial by-products (e.g., waste glass, fly ash) with improved performance and service life that meet sustainability objectives.

Improving asphalt performance can be achieved through various modifications such as polymer modified asphalt. However, modified asphalts are typically produced at more expensive prices. The introduction of fly ash into asphalt mixtures (ASHphalt) was reported to improve the performance of the asphalt binders at levels compared to those achieved through polymer modification (Sobolev *et al.* 2012).

Researchers have extensively investigated the use of by-products such as fly ash in the construction industry to improve material properties (Sobolev and Naik 2005). Fly ash has been used extensively in concrete production; however, there are limited applications in which fly ash has been used in asphalt pavements (Ali *et al*. 1996; Churchill *et al*. 1999; Asi *et al*. 2005; Faheem and Bahia, 2010). The use of fly ash in bitumen materials is attractive as it improves performance and reduces costs and environmental impacts (Tapkin 2008).

Indeed, researchers have been investigating the effects in asphalt of different fillers as early as the 1900s; the inclusion of fillers in asphalt was found to increase the stiffness of the mastic (Richardson 1905). Einstein in 1911 observed the loading of fillers to a matrix increases the stiffness of the composite in a linear manner, with a rate of increase called the Einstein coefficient (Einstein 1911). This linear increase can only be observed within diluted filler volume concentration, which varies between 10% to 40% depending on the filler and the matrix (Shenoy 1999, Lakes 2002). The increase in stiffness is theorized such that, when the inter-particle distance is large compared with the mean particle size, the particle movement is so slow that its kinetic energy can be neglected and there is no slip relative to the particle surface. Thus, the filler particles such as fly ash are practically hindering the matrix flow, thereby increasing its stiffness.

Carpenter (1952) and Zimmer (1970) determined that fly ash had an excellent effect on the retained compressive strength for asphalt concrete specimens immersed in water. Warden *et al.* (1952) determined that fly ash was a suitable filler material in terms of mixing, placing and compaction, stability, resistance to water damage, and flexibility. Sankaran and Rao (1973), Henning (1974), and Tapkin (2008) found that additions of fly ash provided higher stability for asphalt mixtures. Tons *et al.* (1983) observed that fly ash improved asphalt hardening, moisture and freeze-thaw resistance, rutting resistance, fatigue life, density, and tensile strength. Suheibani (1986) evaluated fly ash as an asphalt extender and found that addition of this filler provided superior fatigue life, rut depth resistance and tensile strength. Based on a workability index at various temperatures, Cabrera and Zoorob (1994) found that fly ash could be mixed and compacted at temperatures as low as 110°C and 85°C, respectively, without any detrimental effects on engineering and performance properties. Faheem and Bahia (2010) reported on the interaction between the mineral filler and asphalt binder, where the stiffening effect of the filler on the binder follows a linear filling trend, in which the interaction between filler and binder is minimal.

Despite these reported benefits, the application of fly ash in asphalt technology has not been well utilized. This in part is due to an incomplete understanding of the mechanisms by which fly ash fillers influence performance of asphalt pavements. In addition, most of the reported research only investigated the influence of ash on asphalt binders without looking at the influence on mixture performance and long term performance during service life. Over all, most of the studies conducted did not provide protocol guidance to practitioners on how to incorporate fly ash in standard pavement material production. Fly ash in asphalt bitumen can be considered as filler in a viscoelastic matrix. The blend of bitumen and particulate filler to create a dense mix is referred to as "mastic." Fillers for asphalt pavement applications are defined by the AASHTO M 17 (ASTM D 242) as finely divided minerals, such as rock dust (such as granite and limestone), slag dust, hydrated lime, hydraulic cement, fly ash, loess, or other suitable mineral matter. The typical maximum particle size of fillers in asphalt is less than 75 microns. Although fillers in general usually represents less than 8% of Hot Mix Asphalt (HMA) by mass, the interactions of fillers with asphalt binder, and/or coarse and fine aggregates, clearly affect HMA field performance.

A standard test to characterize asphalt binders is by measuring their stiffness modulus using a dynamic shear rheometer (DSR). This modulus is designated as G* and it varies with testing temperature and loading frequency. Testing specimens at various frequencies (representing the traffic loading speeds) at a given temperature (representing a climatic zone) provides needed information to gauge the suitability of a given binder to be employed in asphalt pavements using fundamental rheological evaluations.

The study by Faheem *et al.* (2009) measured G* ratio at different filler contents for fly ash and granite blends among other fillers. The G* ratio is calculated by dividing the complex modulus of the mastic (G*) divided by the phase angle δ of the binder. Figure 1 shows the increase in the G* ratio with the addition of fillers. The initial rate of increasing stiffness is comparable between the fillers. For the granite filler, around 35% by volume, the rate of stiffening starts to increase rapidly until 50% by volume where no more filler could be added without introducing air voids. On the other hand, the fly ash transition is more gradual. As shown in the figure, at 50% concentration by volume of mastic (equivalent of about 9% of total HMA mixture) the stiffness of the granite mastic is double that of fly ash mastic. This demonstrates the potential extended range of use of fly ash in HMA beyond that of traditional mineral filler. The mastic integrity is tested at the same concentrations shown in Figure 2 that also illustrates mastics performance with fly ash and granite. The maximum integrity of the mastic with granite is achieved at 27% volume concentration and at 45% for fly ash. These concentrations correspond to 5% and 8% concentration of HMA by mass. In general, at concentrations more than 10% by volume, the mastic with fly ash outperforms mastic with granite filler, indicating that fly ash enhances bonding strength compared to standard fillers used in the paving industry. It is important to note this performance is duplicated when the same fillers were used with a different binder from a different crude oil source. The range of concentrations reported this study overlap with the ranges of fillers incorporated in Mixtures used for paving. The details of the integrity testing are detailed elsewhere (Faheem *et al.*, 2009).

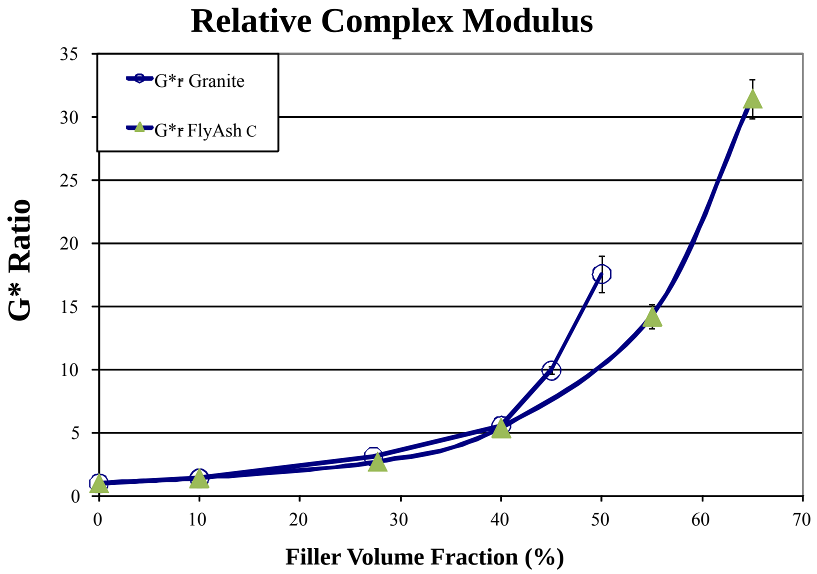


Figure 1. Progression of G* ratio with respect to filler concentration (*after* Faheem et al 2009)

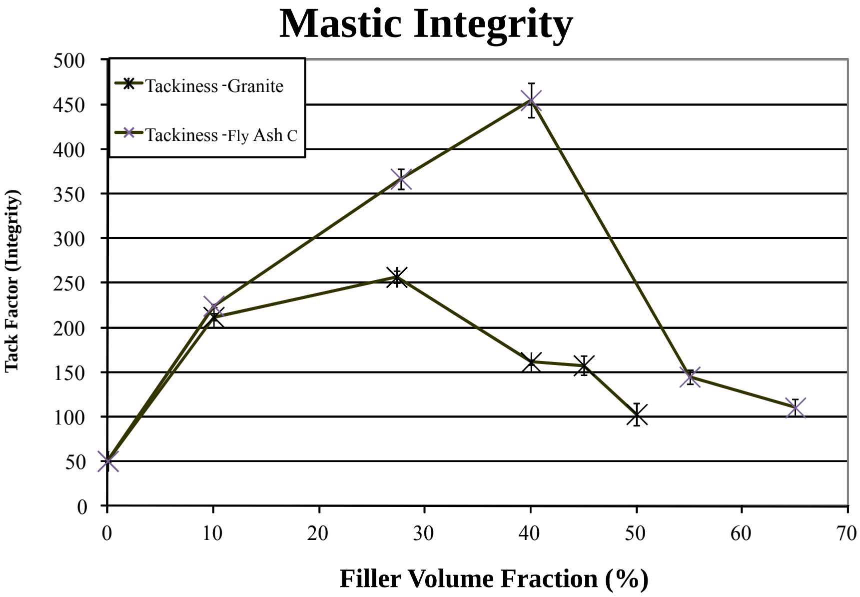


Figure 2. Tack Factor at different filler concentrations (after Faheem *et al* 2009)

Crack-arresting behavior was successfully induced by evenly distributed fly ash particles within the bitumen matrix utilizing microstructural investigations. Sobolev *et al*. (2012) investigated the effect of fly ash addition on rheological behavior and low temperature fracture of asphalt mastics (using Scanning Electron Microscopy – SEM) as demonstrated in Fig. 3.

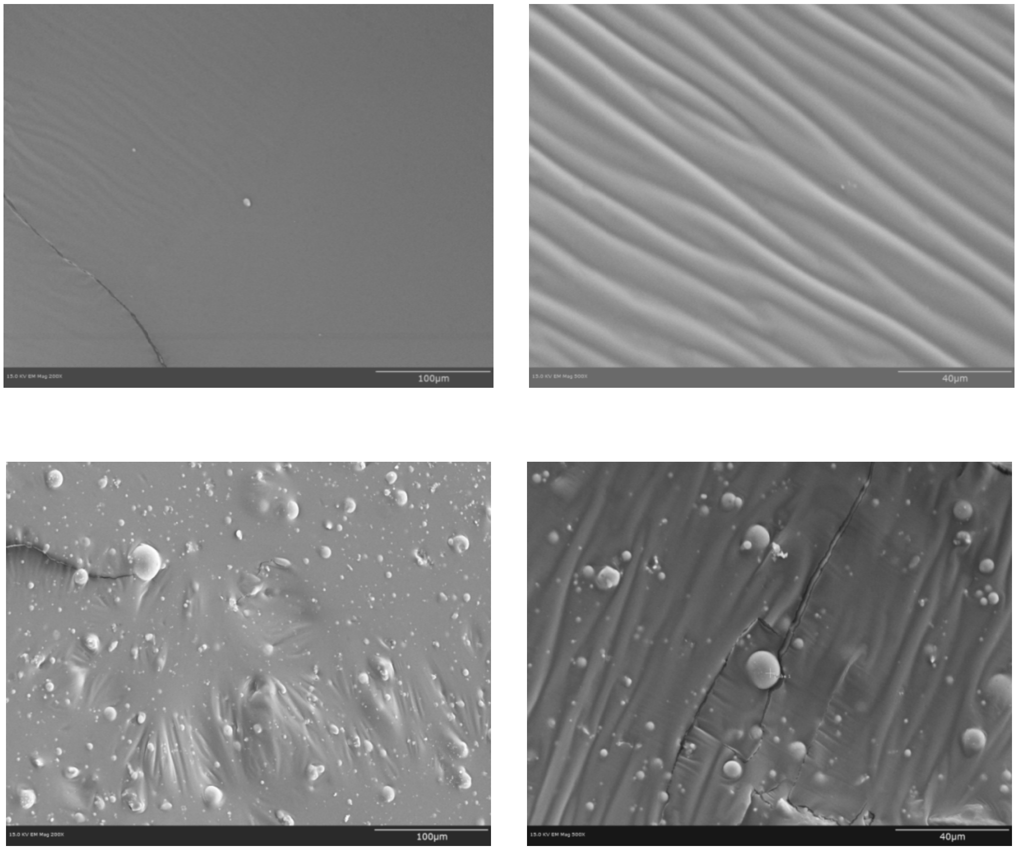


Figure 3. SEM images of low-temperature fractured bitumen/mastic specimens:

Top: brittle failure of plain bitumen (PG-70-22); Bottom: crack pinning and crack deflection in ASHphalt specimens with 60% of fly ash; 200x (left) and 500x (right) magnification

2. Experimental Program

2.1. Materials

Two types of asphalt binders of different grades were used and mixed with different fly ash powders. The binders used were PG-58-28 and PG-70-22M, where PG stands for “Performance Grade” and the first number refers to high temperature during summer and the second number refers to the low temperature during winter. Therefore, the binders used in this study are suitable for temperature ranges from 58°C to -28°C for PG-58-28, and 70°C to -22°C for PG-70-22. The “M” following PG-70-22 binder refers to modification of the asphalt by means of additives to enable utilization over such a wide range of temperatures. These modifications are achieved through blending the asphalt with polymers, although this process significantly increases the price of the asphalt binder.

Class F (FAF) fly ash and Class C (FAC) fly ash from We Energies (WI) were sieved through mesh No. 200 (0.074 mm) prior to use in the experimental program. The chemical and physical characteristics of two types of fly ash are shown in Table 1. X-ray diffraction (XRD) and SEM images of fly ash are shown in Figs. 4 and 5.

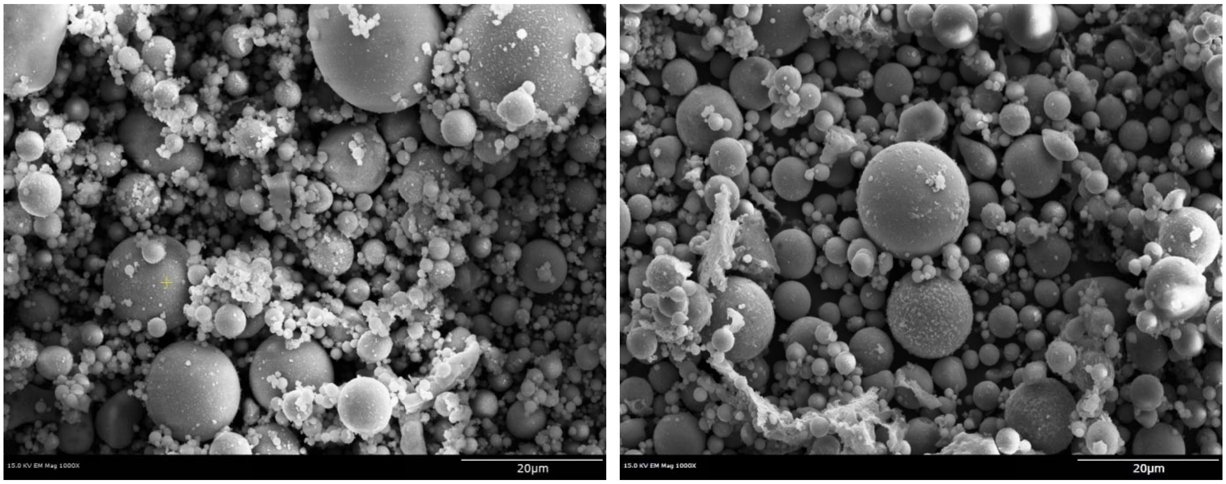
Aggregates used in this study were donated by a local pavement contractor (Northwest Asphalt, WI). The contractor also provided mix design information for generating asphalt mixture specimens that mimic typical mixtures used in Wisconsin highways.

Results shown in Table 1 clearly indicate that the chemical and physical properties of the ash used in this study are different. It appears that Class C fly ash is finer than that of Class F. Figure 5 illustrates the predominant round shape of the ash particles regardless of the Class type.

Table 1. Chemical composition and properties of fly ash Class F and C

Chemical composition, %	Class F	Class C	ASTM C 618 limits	
			Class F	Class C
Silicon Oxide, SiO_2	49.9	32.9	--	--
Aluminum Oxide, Al_2O_3	24.0	19.4	--	--
Iron Oxide, Fe_2O_3	14.4	5.4	--	--
Total, $SiO_2+Al_2O_3+Fe_2O_3$	88.0	57.7	70 min	50 min
Sulfur Trioxide, SO_3	0.88	3.8	5.0 max	5.0 max
Calcium Oxide, CaO	3.23	28.9	--	--
Magnesium Oxide, MgO	0.98	4.8	--	--
Potassium Oxide, K_2O	2.46	0.3	--	--
Moisture Content	0.11	0.8	3.0 max	3.0 max
Loss on Ignition	3.50	0.6	6.0 max	6.0 max
Physical Tests	**Class F**	**Class C**	**ASTM C 618 limits**	
			Class F	**Class C**
Fineness, % Retained on #325 Sieve	25.7	15.9	34 max	34 max
Pozzolanic Activity Index, %	93	79	75 min	75 min
Water Requirement, % of Control	103	89	105 max	105 max
Soundness, Autoclave Expansion, %	0.08	0.11	0.8 max	0.8 max
Specific Gravity	2.30	2.58	--	--

Figure 4. XRD of Class C (FA C) and F (FA F) fly ash



a) b)

Figure 5. SEM images of: a) Class C (FA C) fly ash, b) Class F (FA F) fly ash

2.2. Mastic Preparation

The 0.50 kg specimens of bitumen (PG-58-28 or PG-70-22) were heated for 1.5 h at 163°C and mixed with 0, 5, 15, 30, or 60% of filler (by weight). All fillers were mixed with bitumen using a standard mixer at a low speed (140 ± 5 rpm). After mixing for 1.5 min, the mixture was reheated for 10 min at 163°C. To provide uniform mixing, the procedure was repeated four times to complete 7.5 min of mixing. At the end of the run, the mixture was remixed for an additional 0.5 min. By the end of the procedure, all the materials were mixed for 8 min.

2.3. Rheological Study

AASHTO T 315 standard was used to evaluate the rheological characteristics of the modified asphalt binder using Dynamic Shear Rheometer (DSR). This study evaluated the impact of fly ash on performance asphalt binder and aging. Many pavement failures that include thermal cracking, fatigue cracking and surface raveling are linked to binder oxidative aging. Laboratory testing was thus conducted to measure the change in binder and mastic stiffness before and after simulated aging. Testing using the DSR was conducted at 19°C for PG58-28 and 28°C for PG 70-22. The testing temperature was different for both binders since their grades were different. At these temperatures, the binders are expected to be at the same rheological state, so the test results can be compared.

2.4. Rolling Thin Film Oven (RTFO)

The aging was conducted on both binder and mastic specimens. Test was performed on each sample according to AASHTO standard T 240-09 in order to predict the effect on properties of asphalt binder during conventional batch plant mixing at about 150°C (302°F). The procedure consists of blowing hot air at film of asphalt over a period of time (about 100 minutes) and measuring the changes in viscosity and other rheological properties before and after the sample was placed in the oven. A residue was produced with properties similar to an asphalt binder immediately after the pavement is placed in the field. After the test was completed, the asphalt binders were tested on the dynamic shear rheometer, according to the AASHTO T 315 procedure, to determine the rheological properties of the asphalt binder after simulated aging.

2.5. Bending Beam Rheometer

In addition to the DSR, the testing study also investigated the effect of fly ash on thermal stress relaxation of binders and mastics. This test was only conducted on materials subjected to simulated aging. The specimens were cast into beams of 127 mm x 12.5 mm x 6.25 mm according to ASHTO PP 42. The beams were tested at the low PG temperature according to the reference binder used and the stiffness was calculated from the amount of deflection along the beam. This test helps determine the flexural creep stiffness of the beam at low temperatures as well as its ability to relax built up thermal stresses.

2.6. Compaction of HMA

The Superpave gyratory compactor simulates the compaction of asphalt mix samples to densities achieved under actual pavement climate and loading conditions. These aggregates were used to fabricate two groups of 5 kg specimens of asphalt mixtures. Each group utilized one of the asphalt binders PG-58-28 or PG-70-22. The mixing of aggregate, fly ash, and binder was conducted at 160°C to achieve the uniform coating of aggregate particles with binder and to uniformly distribute the fly ash. Once mixing was completed, the specimens were compacted using the Superpave Gyratory Compactor for a given number of gyrations to mimic the field compaction.

3. Results and Discussion

Two binders with different performance grades were used to determine the percent change in G* after RTFO aging. These binders were blended with the fillers at two concentrations (5% and 60% by weight). It is important to note that G* is used to distinguish between different asphalt binders and their suitability for use in pavements in a given climate zone or under a given traffic load and speed. It is generally undesirable for the G* to significantly increase over time as the pavement ages. This increase is regarded as an indication of potential pavement cracking, as aged asphalt loses its flexibility under different types of loadings. Figure 6 illustrates the percent change in binder and mastic stiffness (G*) after aging. The results for the PG58-28 binder demonstrate, that the stiffness of the binder increased by more than 150%. For PG70-22 the increase is recorded at 132%.

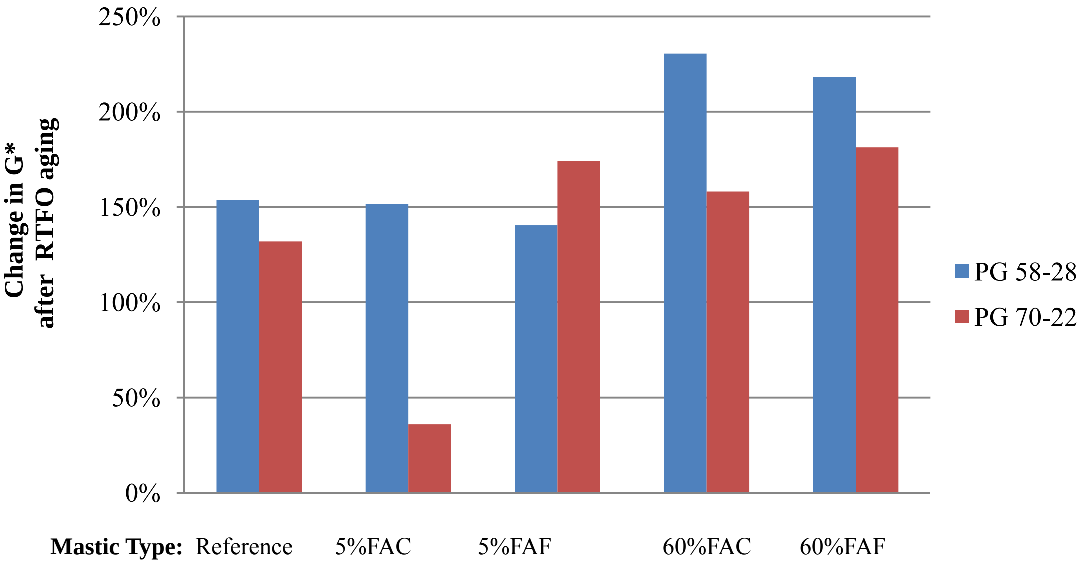


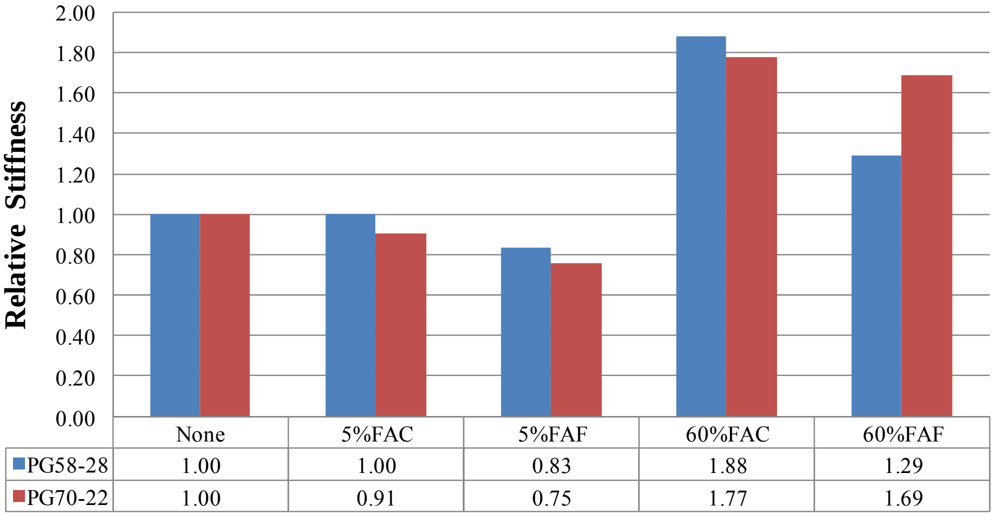
Figure 6. Change in G* after laboratory aging for mastics with fly ash

At 5% concentration of Class C fly ash the percent change value for PG 70-22 is lower than that of the non-fly ash modified binder, a positive outcome indicating there may be a binder polymer-filler synergy that can result in the aging protection effect of the fly ash. For PG58-28 binder the ash shows no effect on aging. For the 5% Class F fly ash mix, the percent change values slightly decreased for PG58-28 and increased for PG70-22 compared to the reference binder. At higher fly ash concentrations (60%), the change in G* for both Class C and Class F fly ash is minor for PG70-22 binder, but much higher for the PG58-28 binder. The optimal dosage of Class C fly ash above 5% and below 60% to reduce aging (in higher grade binders) must be further investigated. The results reported above are for the first phase of testing to establish the optimum range of use for fly ash. The second phase of the research will include testing at more concentrations within the range reported to elaborate the trend of influence to develop a practical mix design protocol. Further testing at fly ash concentrations above 5%, such as 10% and 15% are planned, and may better define the optimum level of ash content for greatest benefit.

In order to evaluate the performance of the aged mastics at low temperatures, the BBR (Bending Beam Rheometer) test was used to quantify the change in stiffness and measure the relaxing coefficient of a binder/mastic at low temperatures corresponding to their performance grade. Figure 7 shows the relative stiffness (S_r) values for the tested specimens, measured by dividing the measured stiffness of specimens by the stiffness of the base asphalt binder.

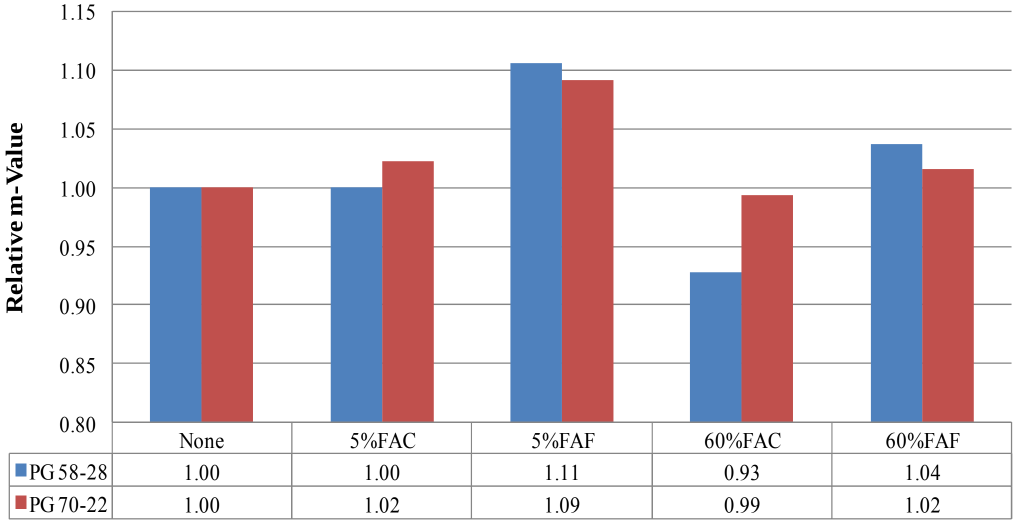
The calculated S_r values show that at low fly ash concentrations, the addition of fly ash reduces the measured low temperature stiffness, except for 5% fly ash class C with PG58-28 binder where no change in stiffness was observed. Class F fly ash shows the most reduction in low temperature stiffness, with a 25% decrease in stiffness for the PG70-22 binder. This indicates that the low temperature stiffening effect due to oxidative aging is reduced by the addition of fly ash at lower ash concentrations. Determining this behavior at ash concentrations above 5% and below 60% in further testing would identify an optimized mix which may further reduce low temperature stiffening. This observation has great implications on the utilization of fly ash in freezing climatic zones.

Figure 8 shows the relative m-values which represent the ability of the tested specimens to relax thermal stresses. An increase in the m-value indicates an improved ability to relax thermal stresses.



	None	5%FAC	5%FAF	60%FAC	60%FAF
🟦 PG58-28	1.00	1.00	0.83	1.88	1.29
🟥 PG70-22	1.00	0.91	0.75	1.77	1.69

Figure 7. Relative low temperature stiffness of aged mastics with fly ash



	None	5%FAC	5%FAF	60%FAC	60%FAF
🟦 PG 58-28	1.00	1.00	1.11	0.93	1.04
🟥 PG 70-22	1.00	1.02	1.09	0.99	1.02

Figure 8. Relative m-value for mastics with fly ash

The results of the m-value show the superiority of the Class F fly ash to improve thermal relaxation of the mastics at lower addition rates. The addition of 5% Class F fly ash provided the greatest improvement for both binders. At the same 5% concentration, Class C fly ash provided some increase in the m-value (2%) for PG70-22, with no change in the m-value for PG58-28. However, additional planned testing for ash contents above 5% (10% or 15%) may provide an improved or optimized m-value for Class C fly ash. The results show that even at a 60% addition, Class F fly ash provided nominally better thermal relaxation compared with the reference binders.

The results for mastic testing show an improvement of aging resistance obtained by using Class C fly ash at intermediate temperatures. At low temperatures, Class F fly ash shows more influence on the ability of the binders to relax thermal stresses. In both cases, fly ash at lower dosages provides improvements to binders' performance.

In this experiment, a standard Wisconsin asphalt mix was evaluated to determine the effect of Class C fly ash on workability of mixes with fly ash. The standard HMA mixtures with 1% fly ash by volume of total mix were compacted and tested. Another set was compacted after replacing 10% of the asphalt binder by mass with fly ash. The objective was to evaluate the ability of fly ash to extend the asphalt binder and thus save on the overall pavement cost, with the understanding that the asphalt binder is the most expensive component of the mixture. Figure 9 shows the percentage of air voids in the mix per number of compaction gyrations. Compactability was evaluated by calculating the number of gyrations to reach 8% air voids in the mix.

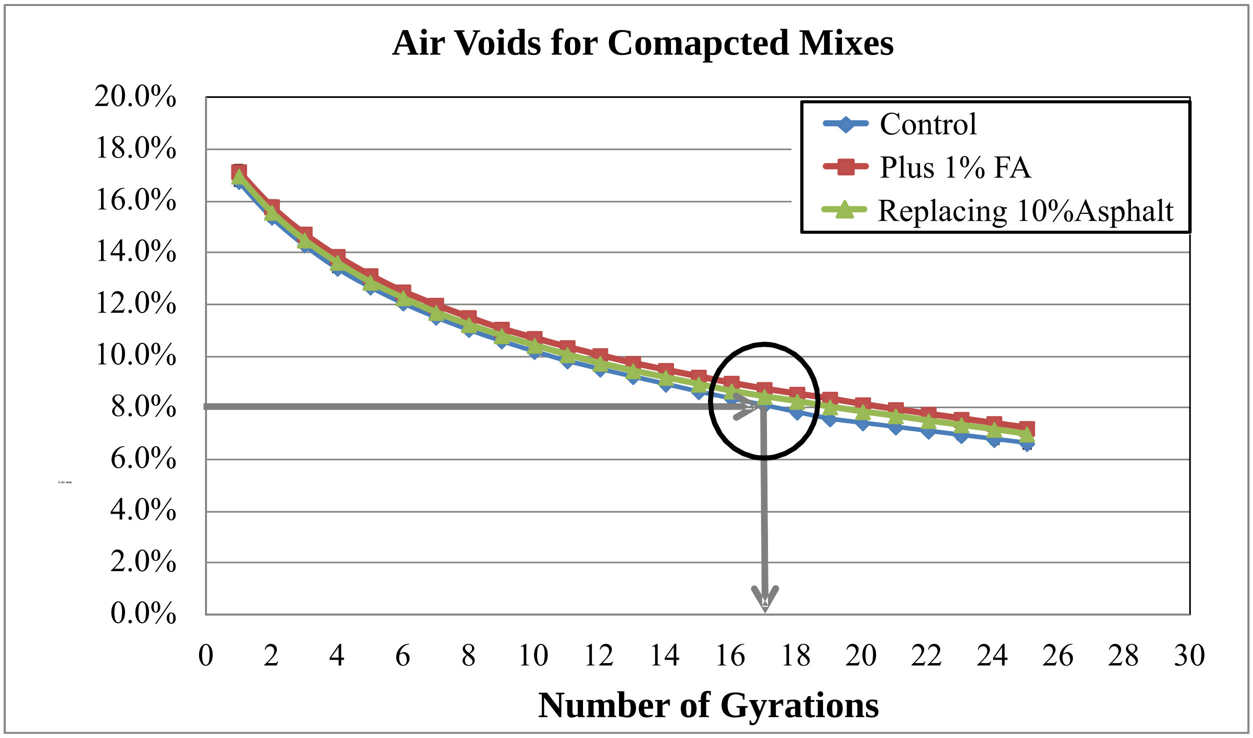


Figure 9. Compactability of HMA/ASHphalt samples

Figure 9 clearly shows a minimal change in the mixture compaction effort for HMA mixtures with fly ash, or even for mixtures with fly ash replacing 10% of the asphalt binder. This indicates fly ash can be successfully used in asphalt without compromising the air void structure, extending or reducing the binder used in asphalt.

4. Implementation of ASHphalt technology

Based on the results of this study, We Energies, the main utility company in Milwaukee, WI decided to construct a private road section at their facility with an asphalt mix using a 10% fly ash replacement rate for bitumen binder. In addition, a control section without fly ash was constructed to provide a reference to a standard mix pavement. The road construction process did not experience any operational changes between the two sections. The field compaction effort exerted on either mixes at the site did not exhibit any difference.

Four months after construction, non-destructive field testing was conducted to measure the field pavement modulus using Falling Weight Deflectometer (FWD). The 1993 AASHTO Guide for Design of Pavement Structures describes FWD testing as a means of evaluating the conditions of existing pavement. The impact load used in this study was approximately 40 kN. The pavement surface deflections were recorded by seven sensors located at 0, 1.0, 1.5, 2.0, 3.0, 4.0, and 5.0 ft from the center of the loading plate and FWD tests were performed at 100 ft intervals. The measured deflection data were used to back calculate the elastic modulus of the pavement layer as well as that of the support layers. According to FWD results, the average modulus for the ASHphalt (ASH1) construction section is compared to standard HMA section in Figure 10.

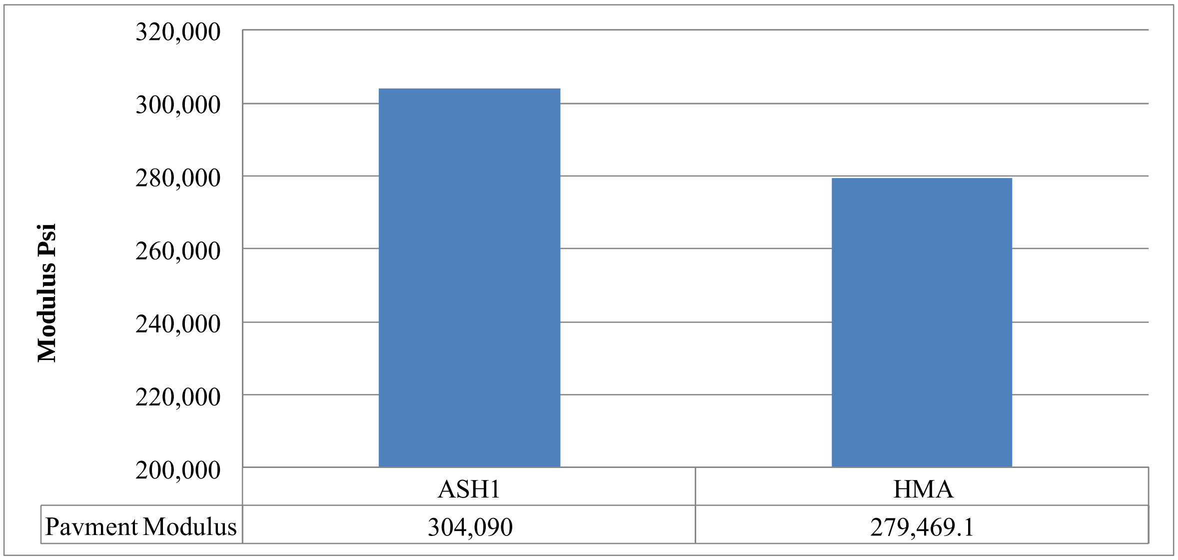


Figure 10. The elastic modulus of pavement based on FWD test

Initial field results show that the modulus of the surface layer is for the ASH section (where 10% of binder is replaced by Class C fly ash) exhibits a modulus value of about 9% higher than the non-ash control section of pavement. Collected asphalt batch samples will be tested in the second phase of this study to evaluate the potential differences in material properties between the two sections. The ultimate goal is to highlight the interaction between fly ash and asphalt binders to optimize the dosage and predict the performance in the field.

5. Conclusions

The feasibility of using fly ash to significantly improve asphalt binder performance was confirmed by testing the performance of blends of asphalt binders with different types of fly ash (ASHphalt). The research results have demonstrated that:

- The addition of fly ash improve the rheological properties of the asphalt mastics and mixtures. These changes can be controlled to changes the mechanical stability of asphalt pavements.
- Fly ash appears to improve the aging resistance of the mastics, thereby increasing the longevity of pavement infrastructure by reducing aging-related cracks.
- The addition of fly ash improves thermal relaxation; therefore, mastics show improved resistance to thermal cracking and ability to relieve internal thermal stress build-up during winter months.
- Microstructural investigation (SEM) of asphalt binders with fly ash demonstrated the crack-arresting effect induced by the fly ash particles at low temperatures.
- The addition of fly ash does not affect the compactability of asphalt mixtures; therefore, the conventional mix design procedures and pavement construction technologies are applicable for asphalt with fly ash; furthermore, the use of round particles of fly ash in asphalt can help reduce mixing and placing temperatures and extend the workability of mixtures for effective placement in the field.
- Fly ash appears to effectively extend the asphalt binder used in the mix, thereby reducing the amount of asphalt binder needed for required performance.

- Utilization of fly ash replacing 10% of the asphalt content in pavement construction shows no change in construction methods or effort to achieve specified placement or compaction.
- Preliminary results show that the field measured average modulus of the pavement section constructed with ASHphalt exhibits a higher modulus value than the traditional asphalt pavement.

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