

Asphalt Concrete Long-term Aging Characterization Using I-FIT Specimens

IAPA Hanley Memorial Scholarship Report

**Prepared for the IAPA Scholarship Board
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Disclaimer

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1. INTRODUCTION

Maintaining an adequate level of serviceability on the highway network is a major industry and research challenge that requires an insightful understanding of the deterioration factors affecting pavement materials. Asphalt Concrete (AC) is the most widely used material for roadway paving due to its low initial construction cost, construction expediency, good surface traction, and durable characteristics. It's also relatively easy to use for rehabilitation and recycling [1]. AC is a mixture of virgin or recycled mineral aggregates, petroleum-based asphalt binder and additives. Although asphalt binder comprises of a relatively small portion of the total AC composition, it has a significant impact on the long-term durability of AC pavements due to its aging characteristics. Fundamentally, asphalt binder is a naturally occurring organic hydrocarbon. Therefore, asphalt is prone to chemical oxidation by reacting with oxygen readily available in the atmosphere [2]. As a consequence, some critical physical properties of asphalt, such as viscoelasticity and adhesive properties, are altered as asphalt ages. As a result of different origins of crude oil and refinery processes, differences in the chemical structure and the compositional makeup of asphalt binder govern the susceptibility to aging [3].

Some of the changes occurring in asphalt binder with aging include the increase in the carbonyl and sulfoxide functionalities. It is well documented that, with aging, there is an increase in the asphaltene fraction while the aromatic portion decreases [4]. The concentration of oxidative products and the speed at which they are produced is a function of time, temperature, oxygen, diffusion flux, and physiochemical characteristics of the chemical species present. Therefore, the change in mechanical and rheological properties such as viscosity and stiffness is a result of the rate at which each specific binder undergoes aging [5].

Increasing amounts of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) in AC mix designs also contribute to the rate of aging [6]. Although RAP and RAS are widely incorporated into AC to reduce materials costs, these materials contain considerable amounts of age-hardened binder which can adversely affect AC by increasing its stiffness and brittleness [7,8].

Along with the natural environmental aging, incorporating high amounts of RAP or RAS may have a detrimental effect on the AC durability as it relates to it may increase the AC cracking potential [9,10]. Cracking is one of the major distresses affecting safety, riding quality, and longevity of AC pavements. The severity and frequency of different modes of cracking is usually a trigger for pavement maintenance and rehabilitation [11]. AC may experience different modes of cracking including fatigue, low temperature, and block cracking; each of which has its own initiation mechanism [12]. There have been multiple studies geared toward improving AC performance and to control cracking; some techniques include binder modification, aggregate gradation changes, using additives (such as rejuvenators), increasing asphalt binder content, and using multiple AC-layers with crack mitigation characteristics [13,14]. Stone matrix asphalt (SMA) was reported to be a mix design option to reduce cracking potential in AC pavements [15].

Understanding how aging evolves in AC mix and its effect on the AC mechanical properties is a key to improving the AC durability. In order to predict AC changes due to aging, there is a need to develop laboratory methods to simulate long-term aging. Although the current long-term aging method (AASHTO R 30) is widely adopted, shortcomings, such as not considering environmental effects and practicability, were reported [16,17,18,19]. In recently completed NCHRP 9-54 study, researchers characterized the long-term aging of AC mixtures using laboratory simulated aging methods with the objective of correlating them to field performance [20].

In this study, efforts were made to evaluate the effects of laboratory-simulated aging and AC mix design parameters on plant-produced and laboratory-produced AC mixes' cracking potential. A recently developed cracking testing procedure known as Illinois Flexibility Index Testing (I-FIT) was used [8,10,21].

2. RESEARCH OBJECTIVE

There are two objectives of this study and they are listed as below:

1. Understand the influence of long-term aging on the cracking potential of AC using I-FIT after laboratory-simulated aging.
2. Understand the effect of AC mix design parameters on the AC aging rate.

3. MATERIALS AND METHODOLOGY

To investigate the impacts of AC mix design parameters, 12 plant-produced and 4 laboratory-designed AC surface mixtures were included in this study and are summarized in Table 1. The 12 plant AC mixtures were obtained from varying districts in Illinois with a combination of different N-designs, mixture type (dense-graded [DG] or SMA), binder type and content, aggregate mineralogy, and the amount of total recycled content. All mixes were sampled in plants after production to ensure they experienced similar aging prior to laboratory aging and/or testing. On the other hand, laboratory AC mixtures were designed to study the effect of various binder sources on aging. The lab AC mixes were composed of same-source aggregates and the asphalt content was 6.4% in all AC mixtures. The lab mixes LM1 and LM2 had no recycled content while the mixes LM3 and LM4 had 20% asphalt binder replacement (ABR). LM1 varied from LM2 in terms of binder source; similar for LM3 and LM4.

Table 1 – Mix Design Details for AC Mixes Used in This Study

ID	N Design	NMAS	VMA	AC %	Binder Grade	ABR	P_{be}	V_{Eff}
PM1	70	9.5	15.2	5.9	68.5-21.6	20.7	5.00	11.28
PM2	90	9.5	15.1	6.2	72.1-23.1	9.2	4.83	11.05
PM3	90	9.5	15.2	6.2	72.8-24.6	9.6	4.81	11.05
PM5	70	9.5	15.5	6.1	59.7-26.4	20.3	5.01	11.60
PM6	70	9.5	15.7	6.2	66.2-28.7	7.9	5.74	12.97
PM7	80	9.5	16.4	6.4	71.6-29.3	30.2	5.65	12.86
PM8	50	9.5	15.0	6.0	74.7-31.4	15.8	4.79	10.99
PM9	70	9.5	15.0	5.7	77.6-28.7	10.2	4.76	11.06
PM10	50	9.5	15.2	6.0	77.9-25.3	10.2	4.85	11.12
PM11	50	9.5	15.4	6.0	61.4-28.8	24.5	4.94	11.33
PM12	70	9.5	15.0	6.0	71.2-29.5	30.0	4.74	10.94
PM13	80	12.5	17.3	6.3	74.7-31.2	26.7	5.70	13.72
LM1	70	9.5	15.2	6.4	68.5-21.6	0	4.71	10.78
LM2	70	9.5	15.2	6.4	66.1-22.3	0	4.71	10.76
LM3	70	9.5	15.2	6.4	59.9-29.6	20.0	4.93	11.30
LM4	70	9.5	15.2	6.4	59.0-28.3	20.0	4.93	11.26

^aN Design = Design number of gyrations required to produce a sample with the same density as that expected in the field after the indicated amount of traffic

^bNMAS = Nominal maximum aggregate size (mm)

^cVMA = Voids in mineral aggregate (%)

^dAC % = Asphalt content by mass (%)

^eBinder Grade = True Superpave® virgin binder grade

^fRAP % = Reclaimed asphalt pavement added by mass (%)

^gRAS = Reclaimed asphalt shingle added by mass (%)

^hABR = Asphalt binder replacement by mass (%)

ⁱP_{be} = Effective asphalt content defined by mass of total mix(%)

^jV_{Eff} = Effective asphalt content defined by volume of total mix (%)

All AC mixes excluding PM13 have a 9.5-mm nominal maximum aggregate size (NMAS). Aggregate gradations for each of these AC mixes are shown in Figure 1. All AC mixes excluding PM7 and PM13 are dense-graded mixes and their gradations are close to each other excluding PM12, which still meets the Illinois Department of Transportation (IDOT) specification. PM7 and PM13 are stone matrix asphalt (SMA) mixes with open aggregate gradation as shown in Figure 1.

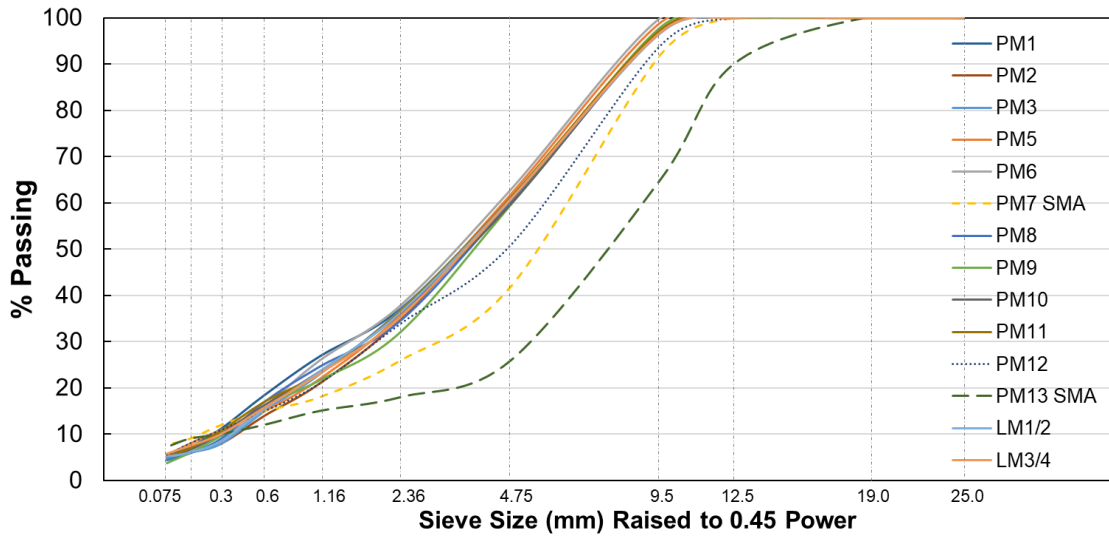


Figure 1 – Aggregate gradations of AC mixes.

3.1. Illinois Flexibility Index Test (I-FIT)

The Illinois Flexibility Index Test (I-FIT), developed at the University of Illinois at Urbana-Champaign, is used to investigate the effects of aging and on AC cracking potential. The flexibility index (FI) parameter is based on fracture mechanics and it has been shown to be helpful for screening AC mixes with different cracking characteristics. Details about I-FIT may be found elsewhere [8,10,21,22]. Standard practice for this test follows AASHTO TP 124 [22]. Figure 2 presents the main outputs of the test. The FI is obtained using Equation 1. Higher values of FI indicate greater resistance to cracking propagation:

$$FI = A * \frac{G_f}{abs(m)} \quad (1)$$

where FI is the flexibility index; G_f is the fracture energy, defined as the area under the load-displacement curve, Joules/m²; m is the post-peak slope, kN/mm; and A is a unit conversion and scaling coefficient taken as 0.01.

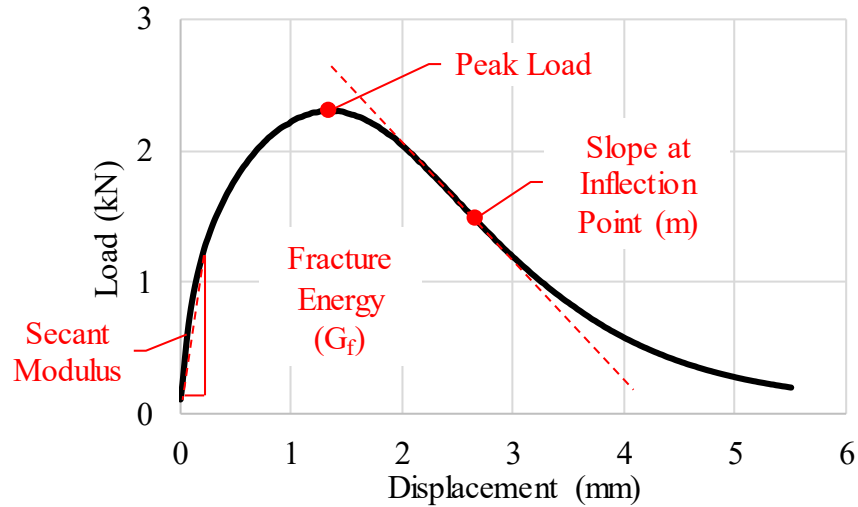


Figure 2 –Outcome of I-FIT [14].

3.2. Aging Method

Since loose mixture aging may introduce more variability when using different material containers and implementing inconsistent stirring process, only aging of compacted specimens was considered in this study. The modified AASHTO R 30, which involves aging semi-circular samples for five days at 85°C, denoted as 5D/85C can mitigate specimen distortion [20]. For practical applications, however, waiting for five days to condition a set of specimens might represent a significant hurdle for its implementation. Therefore, an optimal alternative time and temperature combination were introduced in this study including one day at 95°C denoted as 1D/95C. The above two aging methods were applied to all AC mixes to investigate the influence of AC mix design parameters on aging rate. In addition, in order to fully understand how time and temperature affect aging, PM2 and PM3 were subjected to 12 aging protocols: 1, 3, 5, and 7 days at 75, 85, and 95°C.

Figure 3 shows that the I-FIT specimens were placed in a pan, which was ready to undergo aging conditioning. The aging conditioning was performed using a traditional forced-draft oven at the specified temperature. The oven was calibrated every time before the aging process to ensure that temperature was evenly distributed. The pans were rotated at equally-spaced time intervals.



Figure 3 – Example of test specimens ready to undergo aging conditioning.

3.3. Specimen Preparation

The preparation of the lab-mixed lab-compacted (LMLC) specimens involved the heating of AC materials (binder and aggregates) to the required mixing temperature specified by IDOT, and then using a mechanical stirrer to prepare a loose AC mix. After mixing, the loose material was kept in trays and was subjected to a two-hour conditioning cycle to reach the compaction temperature. AC mixes were compacted to gyratory pills with dimensions of 150 mm diameter and 180 mm height each. The full pills were then cut to achieve the required dimensions of test specimens as specified by AASHTO TP 124 [22]. The final test specimens were then subjected to the designated aging condition. After the aging cycle was completed, the specimens were cooled at room temperature overnight. The samples used for testing were then measured for thickness, notch depth, and ligament length that used in the analysis in accordance with AASHTO TP 124 [22]. The specimens were conditioned in a water bath to achieve the testing temperature of 25°C and were tested in accordance with AASHTO TP 124 [22]. The preparation of plant-mixed lab-compacted (PMLC) specimens was similar to LMLC. The only exception was that instead of heating the raw material, sample canvas bags with the material of approximately 25 kg each were heated for four hours at 135 °C and then split to obtain the targeting compaction weights in accordance with AASHTO R 47 [23].

All of the I-FIT specimens for dense-graded mixes were prepared at an air-void level of $7.0 \pm 0.5\%$, and the specimens for the SMA were prepared at $6.0 \pm 0.5\%$, which is the air-void level at which SMAs are commonly tested [24]. At least six specimens were tested for each set to obtain statistically stable results [25].

3.4. Aging Rate

The FI for the unaged condition was referred to as FI_{unaged} , while for the specific aging condition, it was referred to as FI_{aged} . The effect of aging would result in a change in the FI and was quantified as aging rate. The Aging rate was calculated using equation (2) and it was set up as the response variable (y_i) of equation (3).

$$Aging\ Rate = \frac{FI_{unaged} - FI_{aged}}{FI_{unaged}} \times 100\% \quad (2)$$

where FI_{unaged} and FI_{aged} represent the mean FI of unaged specimens and 1D/95C or 5D/85C aged specimens, respectively.

3.5. Statistical Analysis Methodology

Simple and multiple linear regression techniques were implemented to quantitatively analyze the effect of different mix design parameters on the aging rate of AC mixtures under lab-simulated aging. The regression model has the general form as follows:

$$y_i = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \dots + \beta_p x_{pi} + \epsilon_i \quad (3)$$

where y_i is the value of a continuous variable for observation i , and $x_{1i}, x_{2i}, \dots, x_{pi}$ are the values of explanatory continuous variables. The term ϵ_i is the residual or error for individual i . $\beta_0, \beta_1, \beta_2, \dots, \beta_p$ are the regression coefficients and are generally estimated by least-squares [26]. Normality assumption of residual terms must be satisfied to correctly perform the linear regression analysis. Significance level (α) is 0.1 for all statistical analyses in this study.

4. RESULTS AND DISCUSSION

This section presents the results obtained from the I-FIT for various AC mixes and aging conditions and it contains two parts: the influence of laboratory simulated aging on I-FIT results; and the effect of AC mix design parameters on the aging rate.

PM2 and PM3 were subjected to 12 aging protocols: 1, 3, 5, and 7 days at 75, 85, and 95°C. FI decay curves with aging are shown in Figure 4.

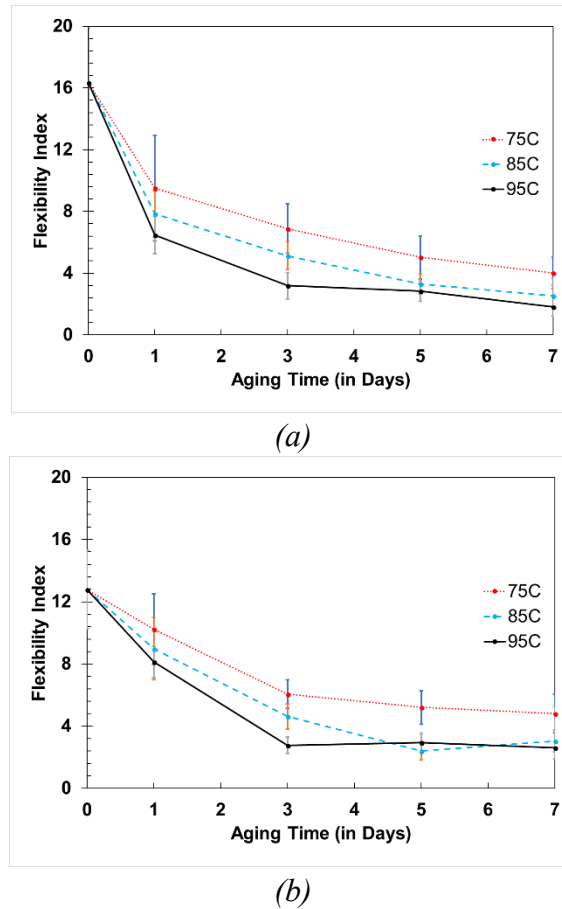


Figure 4 – Flexibility index (FI) decay curves with aging: (a) PM2, and (b) PM3.

It's obvious that AC experienced more aging when it was exposed to a higher temperature and a longer time period, which reduced the FI. FI decay curves with aging are convex functions and they become flatter when aging time increases. Also, it can be noticed that aging temperatures of

85°C and 95°C after five days of aging had no statistically significant effect on FI, especially for PM3.

Interestingly, PM2 and PM3 are similar AC mixes and they have exhibited different aging rates, especially from unaged to one day or three days. This fact raises an important question regarding the effect of AC parameters on aging rate. This is an important relationship for engineers to investigate in order to design more aging resistant AC. Prior to that, the influence of laboratory simulated aging on I-FIT results needs to be fully understood.

Figure 5 presents typical I-FIT load-displacement curves of one representative unaged, 1D/95C and 5D/85C aged specimens each for LM2. There is a clear change in the load-displacement curves after one and five days of aging at 95 and 85 °C, respectively. It was observed that the maximum peak load and pre-peak slope (representing stiffness prior to cracking) significantly increased with aging. Additionally, the post-peak slopes (m) for unaged, 1D/95C and 5D/85C aged specimens varied. The slope of the post-peak curve represents the rate of crack growth. The post-peak slope became steeper with aging consistently indicating the fast and brittle crack growth. The 5D/85C aged specimens had the largest slope and unaged specimens exhibited the smallest slope. In addition, since the displacement rate applied is constant, these curves also imply that 5D/85C aged specimens need the shortest time to reach the peak loads and unaged specimens need the longest.

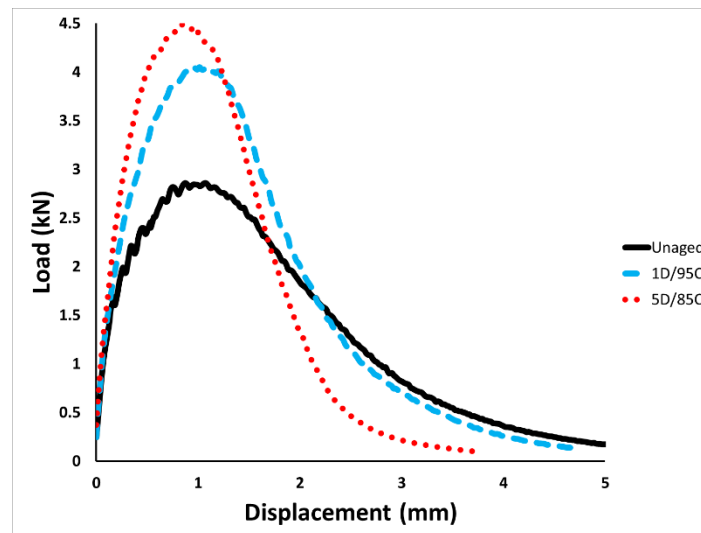


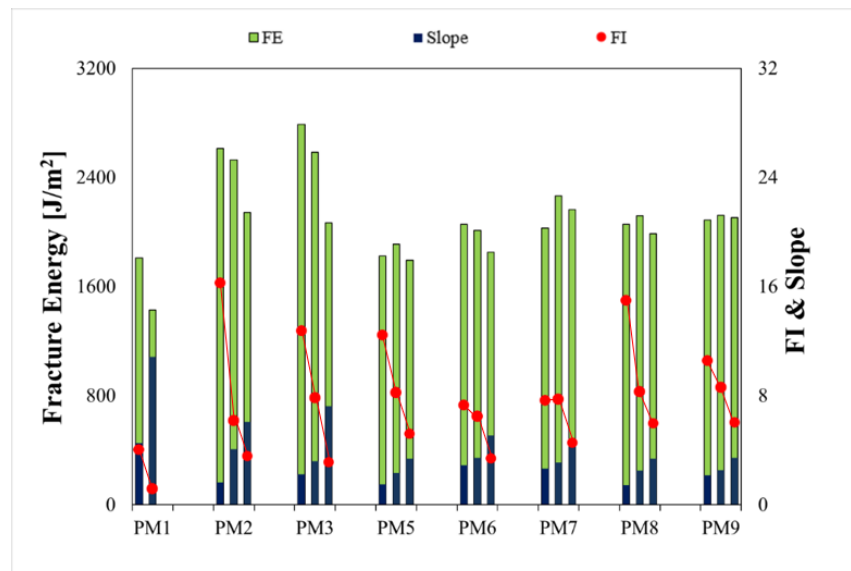
Figure 5 – Loading vs. displacement curves of unaged and aged specimens for LM2.

Fracture energy (FE), slope, and FI were calculated for each AC mix at different aging conditions. Figure 6 illustrates the I-FIT results for all the AC mixes under the three conditions: unaged, 1D/95C, and 5D/85C aging. As shown in the figure, the post-peak slopes (m) became larger after aging, which complies with the observation from Figure 5. 5D/85C-aged specimens always show significantly larger slopes than 1D/95C.

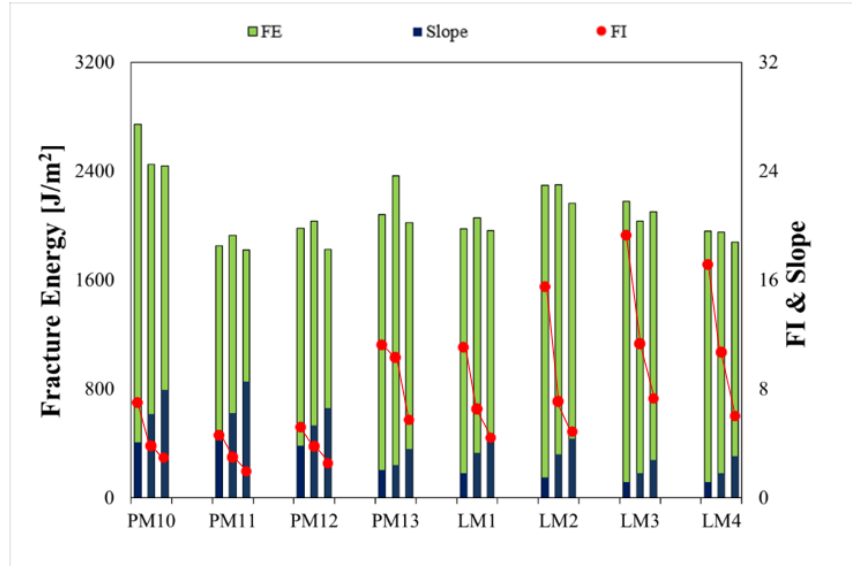
There is no uniform trend for fracture energy (FE) of the AC mixes. Generally, FE decreases after 5D/85C aging, but not all AC mixes show a significant drop. As for 1D/95C aging, some of the AC mixes have smaller FE while others show inverse trends.

As shown in Figure 6, FI decreases with aging for all AC mixes under all aging conditions excluding PM7 (SMA) under 1D/95C. Also, FI drops more significantly under 5D/85C aging compared to 1D/95C. The rate of FI reduction (or aging rates) is dependent upon the AC mixture design parameters and constituents. A detailed statistical analysis is discussed in the next section.

Binder source also plays an important role in affecting aging performance. LM1 and LM2 have the same mix design and the only difference is the binder source. Ultimately, LM2 shows a higher FI under all three conditions: unaged, 1D/95C and 5D/85C. The same observation can be made for LM3 and LM4 since the only difference is also the binder source. There may be two plausible reasons for this. First, although binders have the same PG grade, they have different true grades. To be more specific, binders in LM1 and LM2 have true grades as PG68.5-21.6 and PG66.1-22.3, respectively. Binders in LM3 and LM4 have true grades as PG59.9-29.6 and PG59.0-28.3. Secondly, and appears to be the more appropriate reasoning, binders produced at different oil refineries and from different sources may have a different chemical composition, which will affect the aging development.



(a)



(b)

Figure 6 (a)(b)¹ – I-FIT results for all AC mixes (for each mix from left to right: unaged, 1D/95C aged, 5D/85C aged).

Overall, it was shown that the FI was able to capture AC mixtures' reduction to resist cracking with aging and I-FIT can be a useful test for predicting long-term performance of AC. The increase of the post-peak slope (m) with aging suggests that AC mixture resistance to crack propagation is significantly affected by aging and it depends on the AC mixture design.

4.2. Effect of Mix Design Parameters on Aging Rate

As discussed in the previous section, different AC mixes have different FI deduction rates (or aging rates) due to different mix design parameters. Linear regression was implemented to explore the effect of those parameters on the aging rate of AC mixtures. Mix design parameters namely; N-design value, voids in mineral aggregate (VMA), asphalt content (AC %), asphalt binder high-temperature true grade (high grade), low-temperature true grade (low grade), asphalt binder replacement (ABR), mix type (SMA or dense-graded), effective asphalt content by mass (P_{be}), and effective asphalt content by volume (V_{Eff}) are the mix design parameters considered in this study.

Simple linear regression was conducted first on each of these parameters individually to see whether they are statistically significant and their effect on the aging rate. The residuals normality assumption was validated using a residual-quantile plot. The results for 1D/95C and 5D/85C aging are shown in Table 2. A p-value smaller than 0.1 indicates that the specific term is significantly affecting the aging rate. β stands for parameter estimate, which implies how much the aging rate will change if there is a 1-unit increase on the specific term. The lower and upper limits for parameter estimates using a 90% confidence interval are also helpful for identifying the

¹ The green bar represents FE, which follows the left Y-axis. Post-peak load slope is represented by blue bar and shares the right Y-axis with FI, which is represented by red dot.

significant terms qualitatively and quantitatively. If the 90% confidence interval includes 0 in between, the specific term will be concluded as nonsignificant.

Table 2 – Linear Regression Analysis Results for 1D/95C and 5D/85C Aging

		1D/95C							
	N Design	VMA	AC %	High Grade	Low Grade	ABR	Type ^a	P _{be}	V _{Eff}
p-value	0.738	0.006	0.867	0.598	0.002	0.054	0.005	0.003	0.002
β	-0.143	-20.352	-4.012	-0.431	-4.033	-0.969	-37.013	-37.008	-15.779
90% CI Lower	-0.880	-31.560	-45.561	-1.838	-5.897	-1.782	-56.658	-55.236	-22.816
90% CI Upper	0.595	-9.144	37.537	0.976	-2.169	-0.157	-17.369	-18.781	-8.741
		5D/85C							
	N Design	VMA	AC %	High Grade	Low Grade	ABR	Type ^a	P _{be}	V _{Eff}
p-value	0.324	0.094	0.248	0.420	0.016	0.047	0.048	0.061	0.051
β	0.241	-7.928	16.704	-0.382	-2.124	-0.583	-16.312	-14.888	-6.262
90% CI Lower	-0.176	-15.689	-7.724	-1.193	-3.488	-1.054	-29.535	-27.727	-11.425
90% CI Upper	0.659	-0.168	41.131	0.430	-0.760	-0.112	-3.090	-2.050	-1.099

^aType: stone matrix asphalt (SMA) and dense-graded (DG) were coded as 1 and 0, respectively, since linear regression does not accept a categorical variable.

From the analysis results in Table 2, VMA, low-temperature true grade, ABR, mix type, and effective asphalt content (P_{be} and V_{Eff}) are the significant terms affecting the aging rate for both 1D/95C and 5D/85C at a significance level of 0.1; details are discussed in the following sections.

4.2.1. Effect of Low-Temperature True Grade

If a low-temperature true grade decreases by 1, the aging rate will decrease by 4.03% and 2.12% for 1D/95C and 5D/85C, respectively. This indicates that a softer binder does not only increase the AC flexibility; but also enhances its ability to resist long-term aging in the field. Hence, more likely to maintain flexible pavement serviceability.

4.2.2. Effect of Asphalt Binder Replacement (ABR)

For 1D/95C and 5D/85C, if ABR increases by 1%, the aging rate will have a decrease of 0.97% and 0.58%, respectively. Higher ABR means more aged asphalt binder, which is less likely to be aged further compared to virgin binder and that's why the aging rate decreases as the ABR increases. It should be noted that although adding more recycled materials may lower the aging rate, it is not a sound approach to design aging resistant mixes because mixes with high-recycled content generally result in low flexibility.

4.2.3. Effect of Mix Type

SMA shows a significantly lower aging rate than dense-graded mixes for both 1D/95C and 5D/85C and there might be two plausible reasons. First, SMA always has higher asphalt content. Second, SMA uses high-quality aggregate with less absorption, which induces higher effective asphalt content by both mass (P_{be}) and volume (V_{Eff}). However, since not enough SMA has been investigated in this study, the significant terms cannot be concluded here. As additional SMA mixes are added to the testing matrix, a more reliable statistical analysis can be conducted.

4.2.4. Effect of Effective Asphalt Content (P_{be} and V_{Eff})

For 1D/95C and 5D/85C, if P_{be} increases by 1%, the aging rate will have a significant decrease of 37.01% and 14.89%, respectively. If V_{Eff} raises by 1%, the aging rate will drop by 15.78% and

6.26%, respectively. Higher effective asphalt content means thicker binder film. Hence, it is difficult for the binder film to be thoroughly aged. In addition, it can be noticed that effective asphalt content has less impact on the aging rate when AC experiences more aging.

4.2.5. Effect of Voids in Mineral Aggregate (VMA)

For 1D/95C and 5D/85C, if the VMA increases by 1%, the aging rate will have a decrease of 20.35% and 7.93%, respectively. The VMA is positively self-correlated to effective asphalt content (P_{be} and V_{Eff}), which implies that the impact on the aging rate is not really coming from the VMA.

When putting all the non-highly correlated significant terms as the predictors into a multiple regression model with the aging rate at 1D/95C as the response variable, the final model is significant since its p-value is 0.004. It can also capture 72.5% of the variance of the aging rate among all the AC mixes included in this study. When putting all the non-highly correlated significant terms as the predictors into a multiple regression model with aging rate at 5D/85C as the response variable, the final model is significant since its p-value is 0.058. It can also capture 64.5% of the variance of the aging rate among all the AC mixes. Both regression models show acceptable goodness-of-fit.

In summary, as illustrated in Table 3, VMA, low-temperature true grade, ABR, mix type, and effective asphalt content (P_{be} and V_{Eff}) are the significant mix design parameters affecting the aging rate for both 1D/95C and 5D/85C. Since a wide range of AC mixes was investigated in this study, the statistical analysis is reliable, and the findings could be extended to general AC surface mixtures.

Table 3 – Summary of the Effect of Mix Design Parameters on Aging Rate

Mix Design Parameters	Trend ^b	Absolute Value ^c	Trend	Absolute Value
	1D/95C		5D/85C	
VMA	Decrease	20.35%	Decrease	7.93%
Low-Temperature True Grade	Increase	4.03%	Increase	2.12%
ABR	Decrease	0.97%	Decrease	0.58%
Mix Type ^a	Decrease	37.01%	Decrease	16.31%
P_{be}	Decrease	37.01%	Decrease	14.89%
V_{Eff}	Decrease	15.78%	Decrease	6.26%

^aType: stone matrix asphalt (SMA) and dense graded (DG) were coded as 1 and 0, respectively since linear regression does accept a categorical variable.

^bTrend: aging rate increases or decreases when the specific mix design parameter increases.

^cAbsolute Value: change of aging rate (%) when the specific mix design parameter increases by one-unit.

As shown in Table 3, the significant AC mix design parameters and the trends of aging rate are the same for 1D/95C and 5D/85C. 1D/95C is found to be better than 5D/85 in distinguishing between different AC mixes. Although 1D/95C may not cause the same aging level as that by 5D/85C, it can be used as a predictor of AC long-term aging. This would help engineers detecting problematic AC mixes at an earlier stage. Hence, 1D/95C may be applied as a

reasonable and practical alternative long-term aging protocol for Illinois Flexibility Index Test (I-FIT).

5. FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

This study presents a qualitative and quantitative analysis to assess the influence of long-term lab-simulated aging on the Illinois Flexibility Index Test (I-FIT) results of asphalt concrete (AC) mixtures, and the effect of AC mix design parameters on the mix aging rate. The following are the findings of this study:

- The decrease of the Flexibility Index (FI) after aging mainly resulted from a significant increase in the post-peak load slope (m), which represents the rate of crack growth.
- Because of different true grades and chemical compositions, binder source can significantly affect the I-FIT results for both unaged and aged conditions.
- VMA, low-temperature true grade, ABR, mix type, and effective asphalt content have a statistically significant impact on the aging rate of AC mixtures.
- The increase of each or all of ABR, effective asphalt content, and VMA, and a decrease of low-temperature true grade induce a decrease in the aging rate of AC.
- Stone mastic asphalt (SMA) shows a significantly lower aging rate than dense-graded mixes.
- Although 1D/95C may not result in the same AC aging level as that of 5D/85C, it could be used to predict AC long-term aging performance trend.

The following conclusions are drawn from this study:

- The I-FIT is a valid and effective approach to capture AC aging.
- Two effective methods may be used to improve the AC aging resistant: using a softer binder having a relatively low low-temperature true grade and/or increasing the effective binder content.
- 1D/95C can be a reasonable and practical alternative long-term aging protocol for I-FIT to predict aging behavior of AC.

The followings are recommended for future research:

- The effect of chemical compositions of binder on AC long-term aging needs to be investigated.
- Additional AC mixes, including variation in composition sources, and long-term field performance validation should be considered in future studies.

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