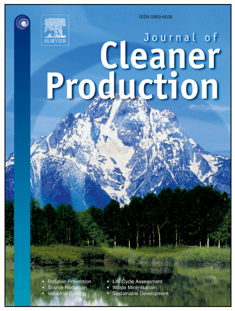

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Kinetics-Based Aging Evaluation of In-Service Recycled Asphalt Pavement

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ABSTRACT

Reclaimed asphalt pavement (RAP) is a type of material that already suffers long-term aging in the field, so its aging characteristics become prominent since they are closely related to premature distresses and longevity of recycled pavements. While most of investigations of RAP mixtures are carried out in the laboratory, this study focuses on in situ aging of asphalt pavements with RAP overlays. A kinetics-based aging modeling approach is proposed to analyze and quantify long-term field aging of RAP overlays using the Falling Weight Deflectometer (FWD) data and climate data. The kinetics-based approach contains a modulus aging model with kinetic parameters (e.g. aging activation energy) for asphalt mixtures. Eight asphalt overlays are selected with different mixtures (RAP and virgin), thickness (50 mm and 125 mm), and surface preparation (milling and no milling). An asphalt pavement with an overlay has a composite aging process since the aging speeds of different asphalt layers are different. Thus an approach to separate the FWD modulus is developed in order to obtain the actual aging behaviors and properties of the overlay. By applying the kinetics-based modeling to the separated FWD moduli, the aging activation energies of both the overlays and old asphalt layers are determined. It is found that the RAP overlay has the highest aging activation energies and slowest aging rates among the RAP overlay, virgin overlay, and old asphalt layer for the selected pavements. It also reveals through the aging activation energy that the thick overlays age slower than thin ones, and the overlays on milled pavements age slower than those placed without milling. The findings in terms of the aging activation energy can be used to explain the difference in the field performance of overlay pavement sections.

Keywords: RAP; FWD; aging; kinetics-based modeling; aging activation energy; overlay

1. Introduction

The use of reclaimed asphalt pavement (RAP) has become a common practice in pavement structural rehabilitations due to its symbiotic environmental and economic benefits. RAP refers to pavement materials generated when an asphalt pavement is removed for reconstruction or resurfacing. The general benefits of using RAP include reduction in energy consumption and emission generation, conservation of natural resources, and savings in rehabilitation cost (Robinette and Epps, 2010; Ding et al., 2018). However, concerns have also arisen about premature distresses and the longevity of recycled pavements. This is because RAP is a type of material that already suffers long-term aging in the field. Aging is known to have a significant effect on pavement performance and has been investigated with numerous efforts. An asphalt pavement is inevitably aged when loss of volatile oils and oxidation occur in the field. The aged asphalt pavement becomes more brittle and is prone to cracking, such as fatigue cracking, reflection cracking, longitudinal cracking, etc.

The most common way to evaluate aging of RAP is to examine the results of binder or mixture testing in the laboratory. For example, Mohammad et al. (2003) used the extraction and recovery technique to obtain asphalt binder from an eight-year old polymer modified pavement. The field aged binder was characterized by binder tests. It was found that extensive age hardening occurred and changes in both chemical and rheological properties were noted. Hamzah and Shahadan (2011) performed a physico-chemical analysis on RAP. They obtained recovered asphalt binder from RAP and incorporated into virgin asphalt with the percentages of 15% and 30%. The RAP modified binders were subjected to different aging conditions and tests to measure the physical and chemical properties. They concluded that the RAP modified binders were further aged as the measured properties distinctly changed. Tarbox and Daniel (2012) prepared four plant-produced mixtures containing different percentages of RAP (0%, 20%, 30%, and 40%), which were aged long-term in the laboratory oven. The dynamic modulus test was conducted on each mixture. The results showed that the oven aging had less effect on dynamic modulus when the content of RAP increased. Compared to the virgin mixtures (0% RAP), the mixtures with RAP stiffened at slower rates in terms of the change of the dynamic modulus. Besides, Colbert and You (2012) and Poulikakos et al. (2014) also utilized laboratory aging procedures and testing methods to quantify the effects of short-term and long-term aging on chemical, physical, and mechanical properties of RAP materials. Clear evidence of aging was observed in terms of the increase of the oxidized products, viscosity, and modulus. In the laboratory tests to evaluate performance like low temperature behavior, fatigue or rutting, the test results showed that a well-designed mixture with 40% RAP produced similar trend with the mixture with virgin materials (Poulikakos et al., 2014).

As recycling techniques mature, pavement analysts and engineers become more and more interested in using high percentages of RAP. An asphalt mixture containing RAP above 25 percent is considered to be a high RAP content mixture. To design such a mixture, an appropriate procedure is needed to address the key issues like selection of rejuvenators and determination of heating methods. Knowing aging characteristics of high RAP content mixtures plays an important role in making these decisions. Rejuvenation of aged asphalt means restoring the performance of the binder. Ali and Mohammadafzali (2015) identified five different recycling agents to rejuvenate recycled asphalt binders, and studied their long-term aging behaviors through extended Pressure Aging Vessel (PAV) aging and the Superpave Performance Grade (PG) test. The level of aging was represented by the high temperature PG. A significant difference was observed in the aging rates of the samples recycled with different rejuvenators.

Another example about high RAP content asphalt mixtures is the process of heating, which prepares RAP samples for mix design and characterization tests. A recent study on incorporating RAP in the Superpave mix design recommended that heating RAP should be minimum to avoid changes in material properties due to aging (McDaniel and Anderson, 2001). In another study about improved mix design of hot mix asphalt (HMA) with high RAP content (West et al., 2013), the heating experiment was designed to evaluate how different heating times and temperatures affected the properties of RAP samples. After heating and mixing, the RAP binder samples were extracted, recovered, and graded. The true grade reflected the extent of aging induced by heating. They found that additional aging of the RAP binder occurred when heating more than three hours.

2. Motivation and objectives

A brief review of existing literature above demonstrates the important role of aging in applying RAP in pavement rehabilitations. It also reveals that most of the studies of RAP aging are carried out in the laboratory on asphalt binders. In addition, a process of binder extraction and recovery is usually involved. There are some concerns raised from these approaches. First, laboratory aging conditions are certainly different from those in the field. Secondly, aging of asphalt binders differs from that of asphalt mixtures due to the existence of air voids and aggregates. In particular, air voids exert a notable influence on aging behaviors of asphalt mixtures (Mirza and Witczak, 1995; Luo et al., 2015). The chemical interaction of aggregates and asphalt binders also alter the mixture's susceptibility to aging (Sosnovske et al., 1993; Moraes and Bahia, 2015). Thirdly, it has been reported that the binder extraction and recovery techniques could change the properties of the recovered asphalt binder (Burr et al. 1993).

Considering these issues, this study aims at proposing a kinetics-based approach to evaluate field aging of in-service pavements containing RAP through common asphalt mixture properties. A similar approach for HMA pavements has been presented in a previous study (Luo et al., 2017). The kinetics-based approach contains a modulus aging model with kinetic parameters (aging activation energy and pre-exponential factor) and field aging temperatures for asphalt mixtures. The modulus in the model is the field modulus measured by the Falling Weight Deflectometer (FWD), a widely used nondestructive test for asphalt pavements. The field aging temperature is determined by a pavement temperature model on the basis of heat transfer fundamentals to account for various sources of heat transfer at the pavement surface. In this study, the FWD moduli of asphalt pavements containing RAP over a long aging period are used in this kinetics-based approach.

The paper is organized as follows. The next section briefly reviews the kinetics-based approach to evaluate long-term field aging of asphalt mixtures using the FWD modulus. Then the methods to collect field modulus data and climate data are introduced to provide inputs for the kinetics-based modeling. After that the characteristics of the FWD modulus of asphalt overlays are discussed in order to separate the modulus of the old asphalt layer and that of the overlay. The overlay materials contain both RAP and virgin materials. With separated moduli for old and new asphalt layers, the results of kinetic parameters of different materials in different asphalt overlays are presented. The last section summarizes the main findings of this study.

3. Kinetics-based aging modeling with FWD for asphalt pavements

This section aims at explaining the methodology used in this study to evaluate the field aging of in-service asphalt pavements. More specifically, the following two aspects are discussed:

1) The concept and formulation of kinetics-based aging modeling of asphalt mixtures that are developed in the previous work (Luo et al., 2015; 2017); and
2) The factors that affect the validity of the proposed method as well as the actions to mitigate the influence.

3.1 Kinetics-based aging modeling of asphalt mixtures

This section briefly introduces the kinetics-based aging modeling for asphalt mixtures that are developed in the previous studies (Luo et al., 2015; 2017). The kinetics-based aging modeling refers to simulating the process of aging of asphalt mixtures by a model containing Arrhenius equations that describes both fast-rate and constant-rate periods. The long-term aging of an asphalt pavement is mainly oxidative aging. The oxidative aging of asphalt mixtures has two distinct stages: fast-rate period initially followed by a constant-rate period. The aging speed changes rapidly in the fast-rate period, and then it maintains a constant value in the constant-rate period. Such a trend is also observed for RAP materials. For instance, Huang and Turner (2014) studied the rheological properties of RAP blended asphalt binders. Two asphalt binders were blended with 15% and 50% extracted RAP binders. The complex moduli of the RAP blends were measured and plotted against the aging time. The figures demonstrated that the modulus increased significantly at the beginning and then leveled off as the aging time increased.

The mathematical formulation of the kinetics-based aging model is:

$$E = E_i + \left(E_0 - E_i\right)\left(1 - e^{-k_f t}\right) + k_c t \tag{1}$$

in which
$$k_f = A_f e^{-\frac{E_{af}}{RT_a}} \tag{2}$$

$$k_c = A_c e^{-\frac{E_{ac}}{RT_a}} \tag{3}$$

where E is the modulus of an asphalt mixture; E_i is the initial modulus of an asphalt mixture in the unaged condition; E_0 is the intercept of the constant-rate line of the modulus; k_f is the fast-rate reaction constant; k_c is the constant-rate reaction constant; t is the aging time in days; A_f is the fast-rate pre-exponential factor; E_{af} is the fast-rate aging activation energy; A_c is the constant-rate pre-exponential factor; E_{ac} is the constant-rate aging activation energy; R is the universal gas constant; and T_a is the aging absolute temperature.

When using Equation 1 to evaluate pavement field aging, besides the FWD modulus, the other essential input is the field aging temperature. The pavement temperature model used to determine the field aging temperature is based on heat transfer fundamentals (Han et al., 2011). It considers three types of sources of heat transfer at the pavement surface: 1) solar radiation and reflection of solar radiation; 2) absorption of atmospheric downwelling long-wave radiation and emission of long-wave radiation; and 3) convective heat transfer between pavement surface and air, enhanced by wind. The model has three components: a surface boundary condition, a thermal diffusion function for heat transfer in the pavement, and a bottom boundary condition. The inputs for the temperature model include the hourly solar radiation, hourly air temperature, and hourly wind speed. Moreover, the model needs some site-specific pavement parameters like albedo, emissivity, absorption coefficient, thermal diffusivity, etc. More details of the model formulations and calculations can be found in Han et al. (2011). The outputs of the model are the hourly pavement temperatures for the entire aging period. The field aging temperature in Equation 1 is then taken as the harmonic mean of these temperatures (Luo et al., 2017).

Given the FWD moduli at different aging times and the corresponding field aging temperatures, the procedure to determine the kinetic parameters (aging activation energies and pre-exponential factors) is as follows with the aid of Figure 1:

1) Plot the FWD modulus (dots in Figure 1) versus the aging time, and then fit the curve with a power function.
2) Divide the fitted modulus curve into several segments and start from the last segment to determine the boundary of each segment. Note that the number of segments varies depending on the length of aging time and features of the material.
3) Determine the boundary of the last segment (i.e. Segment 6 in Figure 1). Select three data points in Segment 6 (triangles in Figure 1): starting, middle, and end.
    a. Assign the end of aging time as the end of Segment 6.
    b. Fit the three points in this segment with a linear model.
    c. Adjust the starting point until the R-squared value of the linear model is almost 1. Then the starting point is identified.
4) Repeat Step 3 to determine the boundaries of the rest of the segments. Normally the time interval decreases from Segment 6 to Segment 1.

5) Calculate the slope of the linear model for each segment in the constant-rate period. These slopes are the constant-rate reaction constants in Equation 3.
6) Calculate the field aging temperature of each segment in the constant-rate period.
7) Plot the slopes of the linear model versus the field aging temperatures, and determine the constant-rate aging activation energy and pre-exponential factor from this plot according to Equation 3 as follows:

$$\ln k_c = -\frac{E_{ac}}{RT_a} + \ln A_c \tag{4}$$

8) Substitute the fitted FWD moduli in the fast-rate period and associated field aging temperatures into Equations 1 and 2. Solve for the fast-rate aging activation energy and pre-exponential factor.

The FWD modulus versus aging time curve needs to be divided into several segments, especially in the constant-rate period. According to the definition of this period, the rate of the change of the FWD modulus is a constant. When the aging time is very long, it must be divided into several time intervals so that the rate of the modulus change can be close to a constant value. Following the steps above, both the constant-rate and fast-rate aging kinetic parameters are obtained for an asphalt mixture given its FWD and climate data. More details about this procedure can be found in Luo et al. (2017).

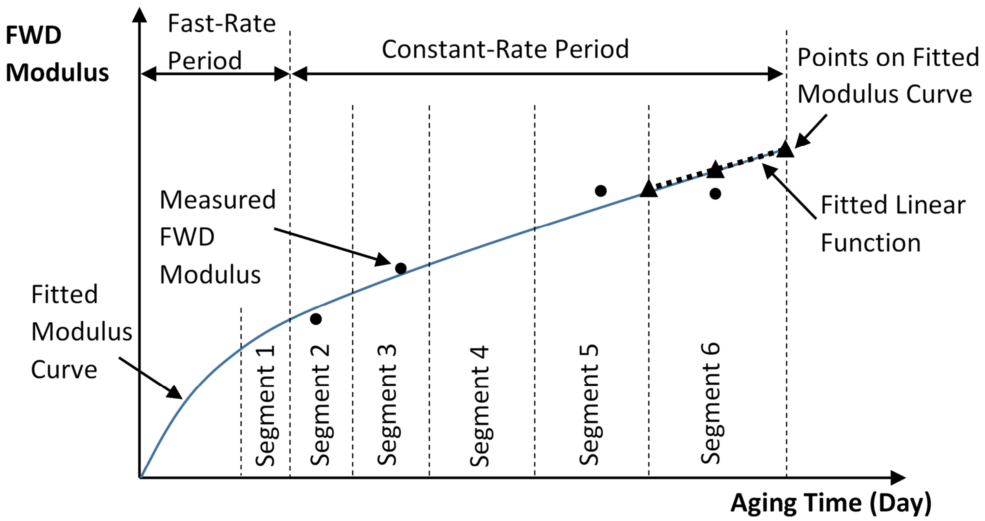


Figure 1. Illustration of determination of aging kinetic parameters using FWD data of asphalt mixtures

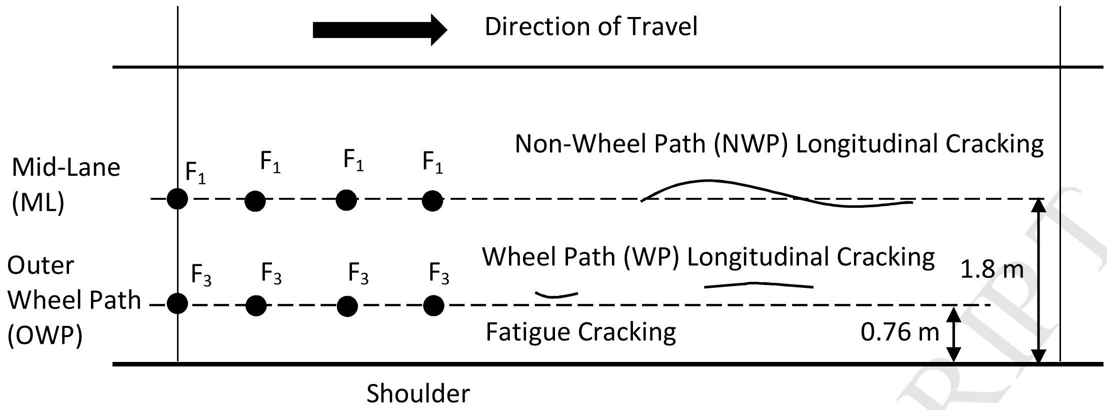
3.2 Validity of kinetics-based aging modeling with FWD modulus

It is known that the FWD modulus is affected by many factors. Aging is one of these many factors that makes the FWD modulus increase with time. For example, the compaction quality has a significant impact on the layer modulus. The FWD modulus varies with the change of the air void content of asphalt mixtures in the surface layer. The influence caused by the variation of material composition and compaction quality can be accounted for using the average values of the multiple FWD measurements at different locations. For the FWD data collected in this study, there are normally eight to nine consecutive FWD passes for a given test section. Over forty deflection basins are generated in each FWD pass. Therefore, using the mean of the collected FWD moduli helps reduce the errors due to material and compaction variations.

Pavement deterioration due to traffic and environmental loading conditions is another type of influence that changes the FWD modulus. For example, fatigue cracking, thermal cracking and moisture intrusion in the pavement cause a decrease of the FWD modulus, while densification due to permanent deformation leads to an increase of the modulus. Note that pavement densification usually occurs in the first few years when the pavement is open to traffic. In the long run the modulus of asphalt mixtures decreases as permanent deformation develops to further severe stages (Zhang et al., 2012). As a result, such a deterioration in the structural integrity of the pavement is demonstrated by a reduction of the FWD backcalculated layer moduli. These effects are considered in this study by examining the performance data and selecting the appropriate location of the FWD measurements, which are elaborated in the next paragraph.

The test plan of the FWD measurements on the selected pavement sections is sketched in Figure 2, which is according to the Long-Term Pavement Performance Program (LTPP) manual for the FWD measurements (Schmalzer, 2006). The FWD data collected herein are from two test locations: one is mid-lane (ML) and one is outer wheel path (OWP). F1 is the lane specification for ML and F3 is the lane specification for OWP. The locations of the distresses including fatigue cracking and longitudinal cracking are also illustrated in Figure 2 according to the LTPP distress manual (Miller and Bellinger, 2003). As an example, the FWD moduli on a specific test date and performance data on eight survey dates are given in Figure 2 for a selected pavement section. The average modulus is the average of backcalculated moduli for a FWD pass at a given test date. It is clear that the moduli obtained from OWP are larger than those from ML. To further exhibit this difference, the mean value is taken for the four modulus values at ML and mean for the rest four values at OWP. The two means are then compared for the eight pavement sections chosen in this study and the examples of the results are presented in Figure 3. Detailed descriptions of the selected pavement sections can be found in the next section and Table 1 below. The two means are close when the aging time is around seven hundred days. The means at ML deviate from those at OWP with the increase of the aging time. The majority of the mean moduli at OWP is larger. With respect to the distresses, fatigue cracking at OWP and wheel path (WP) longitudinal cracking are much less than non-wheel path (NWP) longitudinal cracking for the pavement section in Figure 2. Similar trend is also observed for other selected pavement sections. This fact explains that most of the mean moduli at ML are smaller than those at OWP in later aging time, the observations from Figure 3. In other words, pavement deterioration more heavily affects the FWD moduli at ML for these pavement sections. When fatigue cracking is none or minor, it is acceptable to neglect the influence of pavement deterioration on the FWD moduli at OWP and utilize them to study field aging. If fatigue cracking recorded in the LTPP increases moderately on the last one or two FWD test dates, the corresponding modulus data are not used to analyze aging of asphalt pavements.

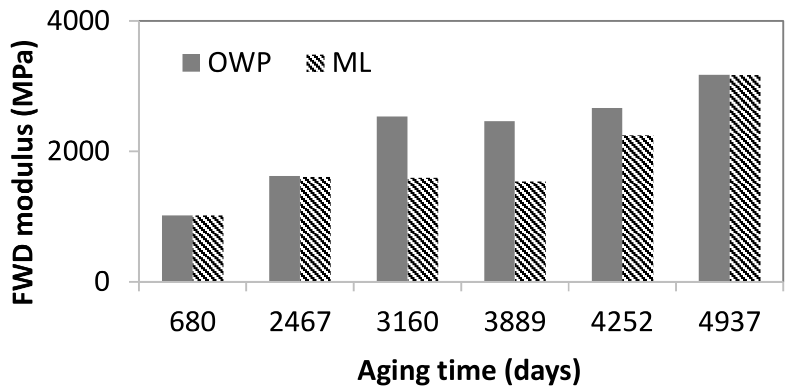
Based on the FWD data in the authors' previous work (Luo et al., 2017) and in this study, it is found that the FWD moduli exhibit a clear increasing trend as the in-service time increases. Figure 4 shows the FWD modulus data used in the previous study on HMA pavements and the ones collected here for RAP pavements. In the legend of the figure, for example, "RAP #1" and "RAP #2" refer to two RAP pavement sections respectively. A power function is fitted to each curve with the R-squared value. Such a relationship is then used to determine the kinetic parameters so as to evaluate the long-term field aging of asphalt pavements with RAP. In the next section the sources to collect necessary data for the kinetics-based modeling are presented.



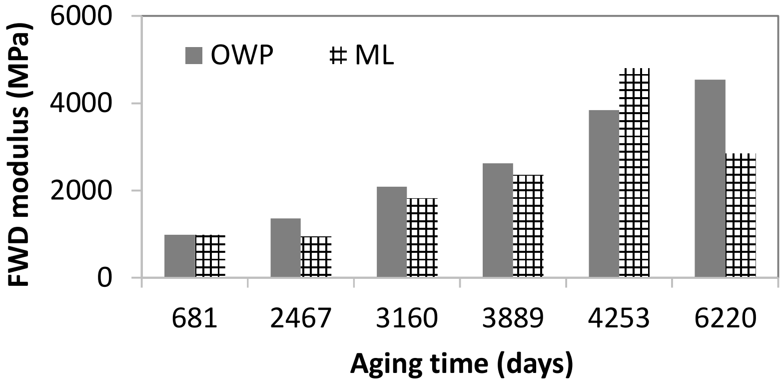
FWD Modulus and Performance Data of 48-A502

FWD Pass on 4/25/2002	Lane Spec.	Avg. Modulus (MPa)	Survey Date	Fatigue Cracking (m^2)	WP Longitudinal Cracking (m)	NWP Longitudinal Cracking (m)
49	F1	1456	1/28/1992	0	0	0
50	F1	1481	8/10/1993	0	0	0
51	F1	1618	6/29/1995	0	0	0
52	F1	1615	6/3/1998	0	0	261.8
53	F3	2356	4/26/2000	0	1.6	323.8
54	F3	2536	4/4/2002	0	5.1	326.6
55	F3	2447	4/23/2003	0.7	9.9	334.7
56	F3	2509	3/8/2005	1.1	2	335.5

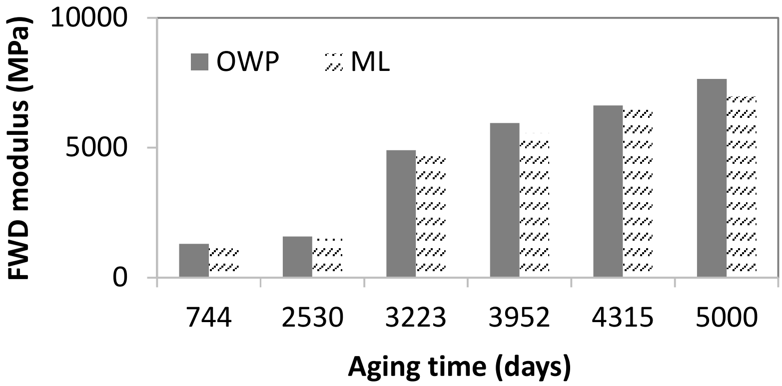
Figure 2. FWD test plan with modulus and performance data for a selected LTPP pavement section



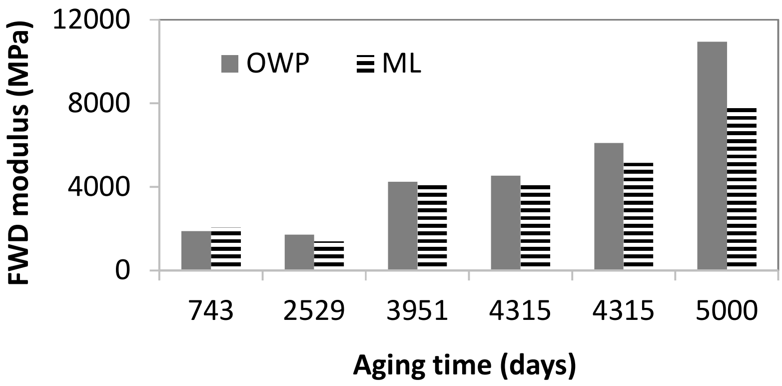
(a) 48-A502



(b) 48-A503



(c) 48-A507



(d) 48-A508

Figure 3. Comparison of the FWD moduli at OWP and those at ML

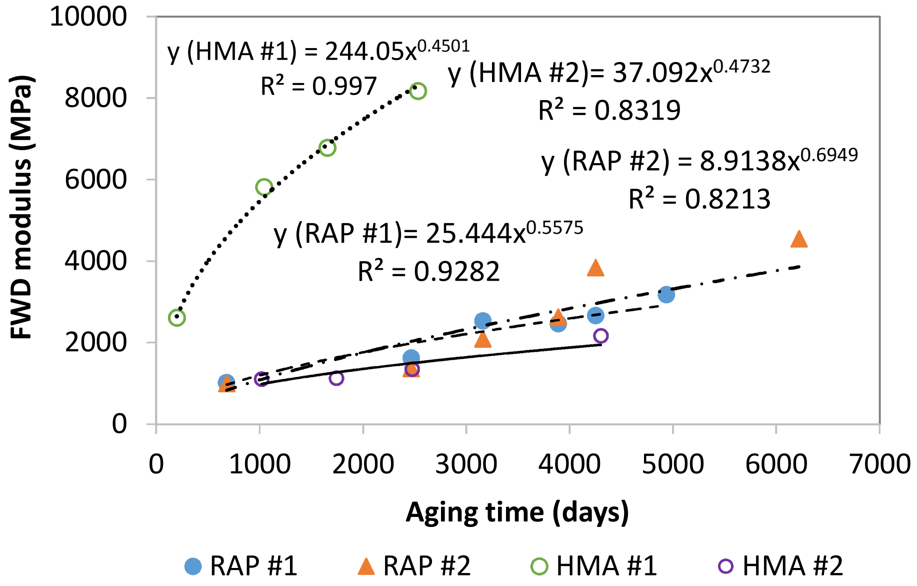


Figure 4. Plots of FWD backcalculated moduli versus aging time

4. Collection of field deflection and climate data

The LTPP database is utilized to collect the FWD data and part of the climate data. Eight pavement sections in Texas are chosen from the SPS-5 (rehabilitation of asphalt concrete pavements) of the LTPP, an experiment to examine the effects of existing pavement condition, traffic, and climate on pavements rehabilitated by different methods with overlays. The sections are located on US highway 175. Details of these sections are given in Table 1 in terms of overlay material, surface preparation, and overlay thickness (Hong et al., 2010). Half of the sections are constructed with virgin materials for the overlay; the others with 35% RAP. The asphalt binder in the virgin mixtures is AC10 modified by 3% latex. A softer asphalt binder, AC5, is used in the RAP sections. Half of the sections are milled with a thickness of 50 mm, while the other half has no milling. The milled part is backfilled with the overlay material. There are two overlay thicknesses: 50mm and 125 mm. For those milled sections, the total thickness of the backfilled layer and overlay is 100 mm or 175 mm. The pavement structures before and after overlay are shown in Figure 5. Before overlay, the pavement consists of an asphalt layer, lime-treated base course, lime-treated subbase, and natural subgrade.

For each pavement section, the FWD data are collected from the LTPP database in the module of “Deflection-Backcal Data”. The values in the “Deflection-Backcal Data” are backcalculated moduli converted to the standard condition: 25˚C and 100 millisecond loading time (EVERSERIES©, 2005). The following data are extracted:

- Average modulus: the average of backcalculated moduli at a test date, from the worksheet of "BAKCAL_MODULUS_SECTION_LAYER".
- Test date: the date when the FWD test is performed, from the worksheet of "BAKCAL_PASS". The test duration covers a long aging period from 1992 to 2008.
- Layer thickness: the layer thickness assigned for backcalculation, from the worksheet of "BAKCAL_STRUCTURE_LAYERS".

In addition to the FWD data, the climate data must be collected in order to calculate the field aging temperature of the pavement. As mentioned above, they include hourly climatic data and site-specific pavement parameters. The hourly climatic data (solar radiation, air temperature, and wind speed) are collected from the National Solar Radiation Database (NSRDB), National Climatic Data Center (NCDC), and LTPP database. The site-specific pavement parameters are detailed in Han et al. (2011). All of these data are imported to the MATLAB software and the pavement temperature model is solved numerically by a finite-difference approximation method. The 20-year field aging pavement temperatures are calculated for the Texas SPS-5 sections. The field aging temperatures used in determining the layer aging properties are the computed surface temperatures.

After obtaining both the field modulus and aging temperature data, the next step is to using the kinetic-based aging model (Equations 1-3) to examine field aging of the Texas SPS-5 pavement sections.

Table 1. Overlay design of SPS-5 sections used in this study

LTPP ID	Overlay material	Surface preparation	Overlay thickness (mm)	Group No.
48-A502	35% RAP	No milling	50	A
48-A503	35% RAP		125	
48-A504	Virgin		125	B
48-A505	Virgin		50	
48-A506	Virgin	50 mm milling	50	C
48-A507	Virgin		125	
48-A508	35% RAP		125	D
48-A509	35% RAP		50	

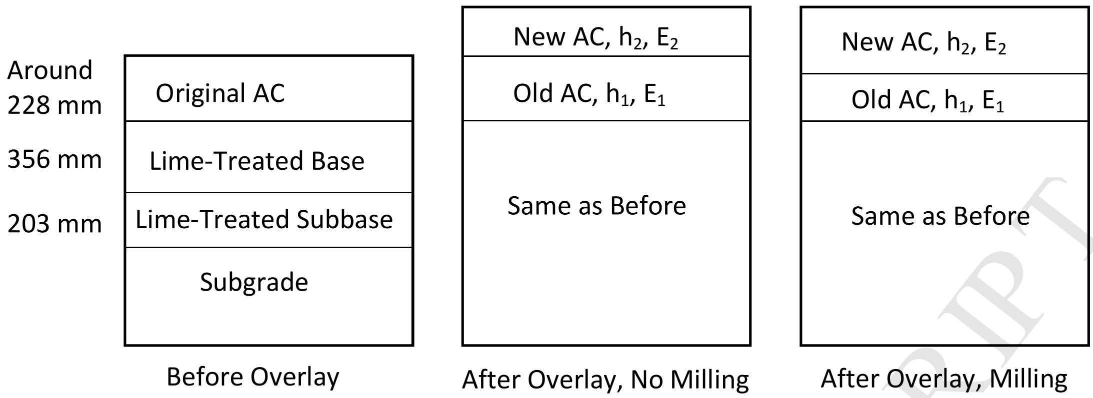


Figure 5. Pavement structure before and after overlay

5. Separation of FWD modulus for asphalt overlays

A rehabilitated pavement with overlay exhibits a unique aging feature since it consists of several asphalt layers with different aging speeds. The original asphalt layer has a slower or faster aging rate than the asphalt overlay depending on the nature of overlay materials. However, the FWD modulus is a single value that represents the net effect of mechanical responses of all asphalt layers. When the FWD modulus is used to evaluate aging, it indicates the net effect of aging speeds of all asphalt layers, which cannot differentiate aging behaviors of different materials. Therefore, in order to apply the kinetics-based modeling to evaluate aging in asphalt overlays, the FWD modulus of an asphalt pavement with overlay must be separated to obtain the modulus for each asphalt layer. Then the modulus of each layer is utilized in Equation 1 to determine the aging kinetic parameters of this particular layer.

The Odemark's assumption is used herein to facilitate the modulus separation process. It states that the deflections of a multi-layered pavement can be represented by that of a single layer. The thickness of this equivalent single layer is expressed as (Lytton, 1989):

$$H = \sum_{i=1}^{m} Ch_i \left(\frac{E_i}{E_H} \right)^{\frac{1}{3}} \tag{5}$$

where H is the thickness of the equivalent single layer; E_H is the modulus of the equivalent single layer with a thickness of H; h_i is the thickness of each layer in a multi-layered pavement; E_i is the modulus of each layer in a multi-layered pavement; and C is a constant around 0.8 to 0.9.

According to the data of the layer thickness collected from the LTPP, there are two thicknesses assigned to backcalculate the moduli of the Texas SPS-5 sections: one before overlay and the other after overlay, as listed in Table 2. Thus the asphalt concrete surface is divided into two layers: one is the original asphalt concrete layer, called the old AC layer, and the other is the asphalt overlay, called the new AC layer, as shown in Figure 5. When there is no milling, the thickness of the old AC layer is equal to the original AC layer. When there is milling, the milled part is backfilled with overlay materials so that aging of the milled part is the same as the overlay. Therefore, the thickness of the old AC layer become the difference between the original AC layer thickness and milling thickness. Under this circumstance, Equation 5 becomes:

$$H\left(E_{FWD}\right)^{\frac{1}{3}} = Ch_1\left(E_1\right)^{\frac{1}{3}} + Ch_2\left(E_2\right)^{\frac{1}{3}} \tag{6}$$

in which $H = h_1 + h_2$ (7)

$$h_1 = \begin{cases} h_{orig} & \text{no milling} \\ h_{orig} - h_m & \text{milling} \end{cases} \tag{8}$$

where H is the value of the AC thickness after overlay obtained from the LTPP database; E_{FWD} is the FWD modulus after overlay obtained from the LTPP database; h_1 is the thickness of the old AC layer; h_2 is the thickness of the new AC layer; h_{orig} is the thickness of the original AC layer; h_m is the milling thickness; E_1 is the modulus of the old AC layer; and E_2 is the modulus of the new AC layer. The values of H, h_1, and h_2 are given in Table 2.

Table 2. Asphalt layer thickness in backcalculation and Odemark's equation

LTPP ID	Backcalculation Data from LTPP		Layer Thickness in Odemark's Equation		
	AC thickness before overlay (mm)	AC thickness after overlay (mm)	H (mm)	h_1 (mm)	h_2 (mm)
48-A502	236	290	290	236	53
48-A503	239	371	371	239	132
48-A504	226	353	353	226	127
48-A505	239	292	292	239	53
48-A506	218	290	290	168	122
48-A507	224	366	366	174	192
48-A508	241	394	394	191	203
48-A509	226	307	307	176	131

After determining the thicknesses in Equation 6, the next is to determine the moduli of the two asphalt layers for the Texas SPS-5 pavement sections. In order to calculate E_1 and E_2 based on the FWD data by Equation 6, the following procedure is proposed:

1) Divide the eight pavement sections into four groups, as shown in Table 1. The sections in the same group have the same overlay materials and surface preparation methods. The only difference is the thickness of the overlay.
2) The FWD moduli of the two pavement sections in each group at the first test date are substituted into Equation 6 to solve for E_1 and E_2 at this date. Take Group A for example:

$$H_{A502}\left(E_{FWD,A502,1}\right)^{\frac{1}{3}} = Ch_{1,A502}\left(E_{1,1}\right)^{\frac{1}{3}} + Ch_{2,A502}\left(E_{2,1}\right)^{\frac{1}{3}} \quad (9)$$

$$H_{A503}\left(E_{FWD,A503,1}\right)^{\frac{1}{3}} = Ch_{1,A503}\left(E_{1,1}\right)^{\frac{1}{3}} + Ch_{2,A503}\left(E_{2,1}\right)^{\frac{1}{3}} \quad (10)$$

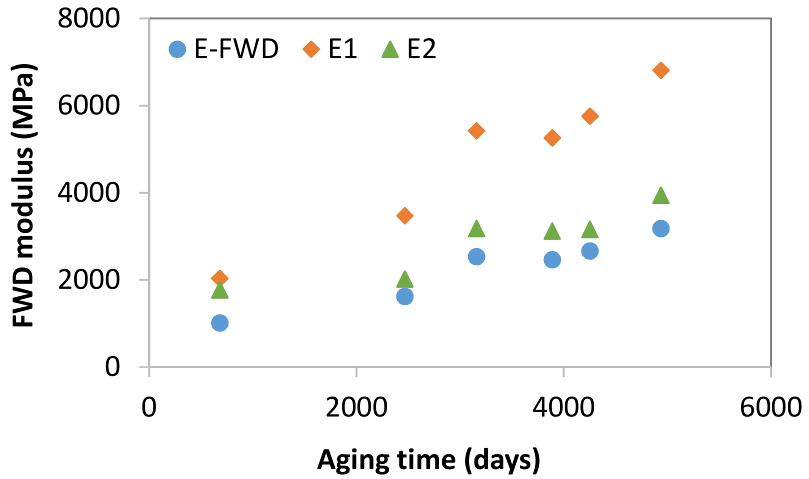
in which the subscripts "A502" and "A503" in Equations 9 and 10 stand for the section 48-A502 and 48-A503 respectively; $E_{FWD,A502,1}$ is the FWD moulus of the section 48-A502 at the first test date; $E_{FWD,A503,1}$ is the FWD modulus of the section 48-A503 at the first test date; $E_{1,1}$ is the modulus of the old AC layer at the first test date; $E_{2,1}$ is the modulus of the new AC layer at the first test date; and the value of C is 0.8. The only unknown variables in Equations 9 and 10 are E_1 and E_2. Thus combining these two equations gives the moduli of the old AC layer and that of RAP in new AC layer.

3) Use E_1 and E_2 at the first test date as the seed values for the second test date to solve for them at the second test date based on Equation 6. The Solver function in the Excel is employed to perform the calculation. Similarly, the moduli at the following test dates are determined using the moduli at the previous date as the seed values according to the following equation:

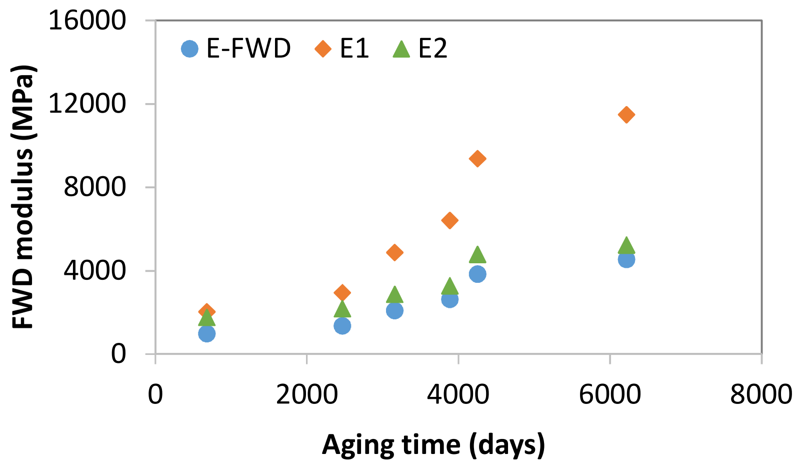
$$H_{A502}\left(E_{FWD,A502,i}\right)^{\frac{1}{3}} = Ch_{1,A502}\left(E_{1,i}\right)^{\frac{1}{3}} + Ch_{2,A502}\left(E_{2,i}\right)^{\frac{1}{3}} \qquad i = 2,3...7 \quad (11)$$

4) Repeat Steps 2 and 3 to obtain E_1 and E_2 for all pavement sections in Table 1 at all test dates.

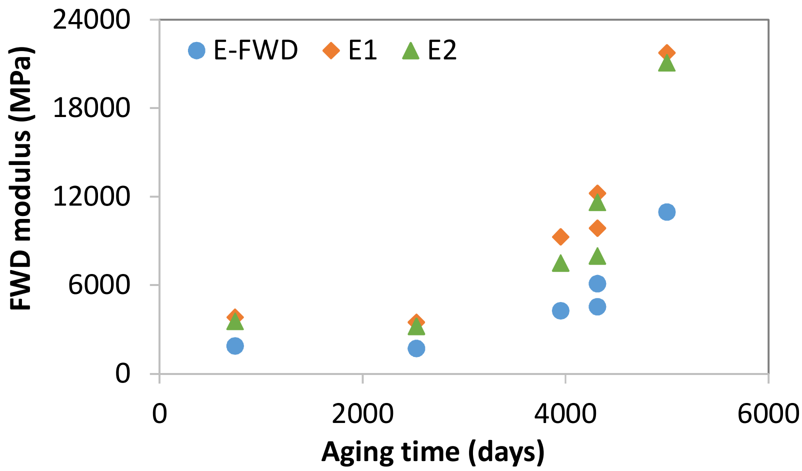
The results of separating the FWD modulus for each pavement section are obtained, and several examples are presented in Figure 6. In some cases, significant variations exist among the FWD moduli and separated moduli. This is due to the nature of the raw data that are collected from the LTPP database. The modulus of the old AC layer can be larger or smaller than that of the new layer, depending on the nature of the materials and associated aging behaviors.



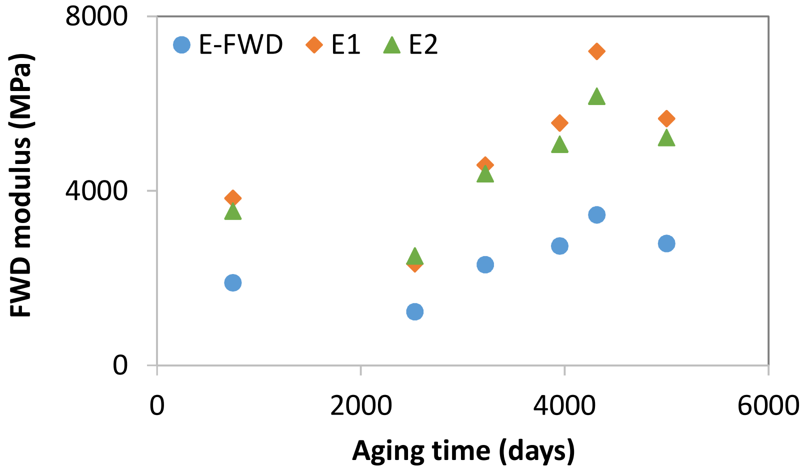
(a) 48-A502



(b) 48-A503



(c) 48-A508



(d) 48-A509

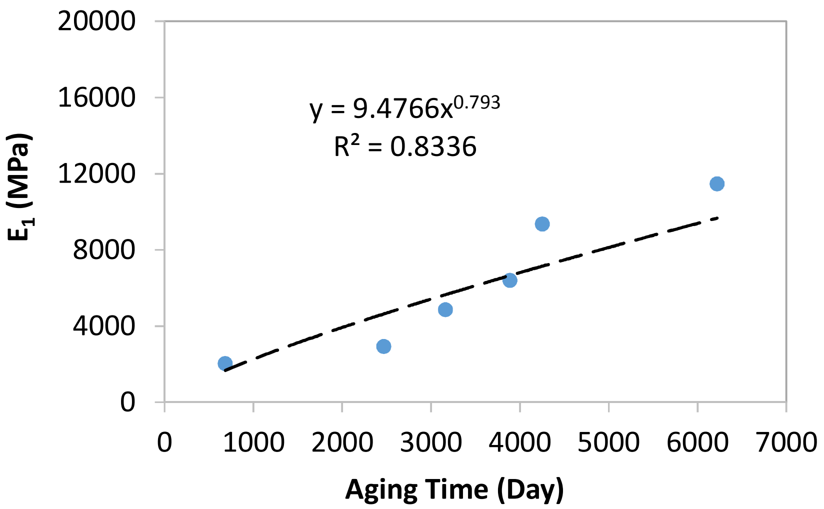
Figure 6. Examples of separated FWD moduli for old AC layer and new AC layer (overlay)

6. Aging characteristics of asphalt overlays

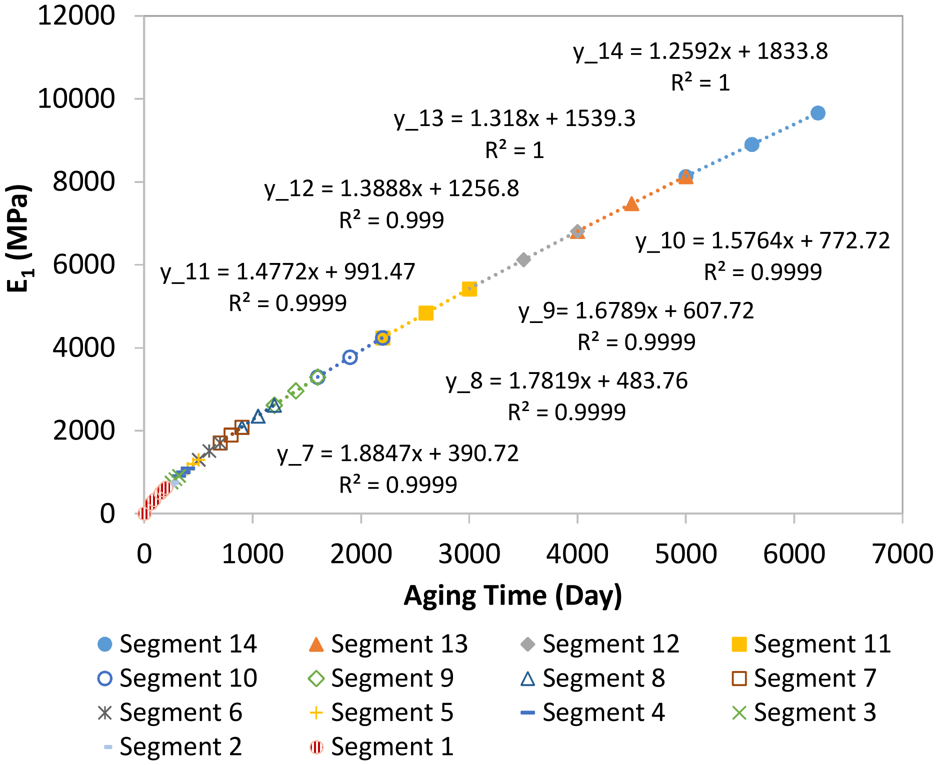
After separating the FWD modulus, the kinetics-based model can be applied to the moduli of each asphalt layer to determine the aging kinetic parameters.

6.1 Determination of aging kinetic parameters

Take the section 48-A503 as an example to explain the procedure for determining the aging kinetic parameters listed in the section entitled "kinetics-based aging modeling for asphalt mixtures". The modulus of the old AC layer (E_1) is plotted against the aging time, as shown in Figure 7a. Fit the curve with a power model, and then plot the fitted modulus versus aging time as shown in Figure 7b. The fitted modulus curve is divided into fourteen segments in this case. Segment 14 to Segment 2 are belonged to the constant-rate period, and Segment 1 is the fast-rate period. In Segments 14 to 2, the R-squared values of the linear models are all around 1.



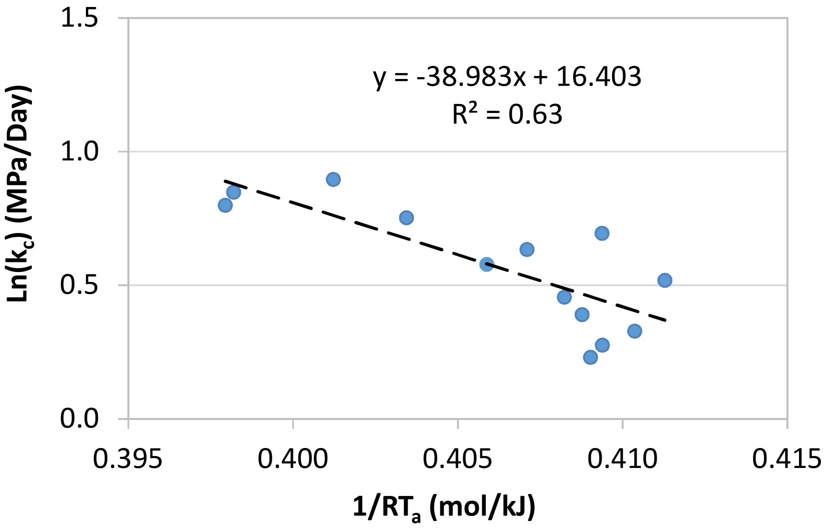
(a) E_1 separated from FWD measurements with fitted power model



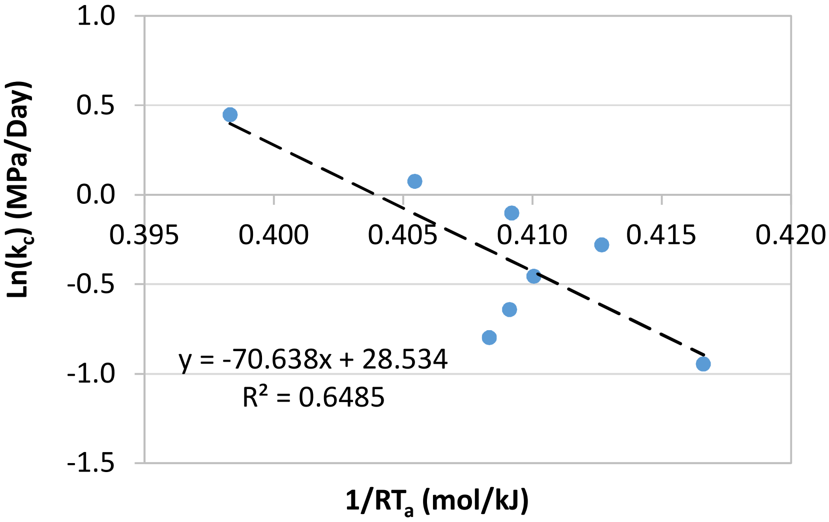
(b) E_1 fitted by power model with different segments

Figure 7. Fitting of the curve of FWD moduli versus aging time

The slope of the linear model of each segment in the constant-rate period is determined, which is denoted k_{cs}. The values of k_{cs} are plotted versus the field aging temperatures for Segments 14 to 2, as shown in Figure 8a. The constant-rate aging activation energy and pre-exponential factor are determined from Figure 8a based on Equation 4. Then the fitted moduli in the fast-rate period and associated field aging temperatures are substituted into Equations 1 and 2 to solve for the fast-rate aging activation energy and pre-exponential factor. Similarly, the constant-rate/fast-rate aging activation energies and pre-exponential factors are determined for new AC layer (i.e. overlay) of the section 48-A503 (Figure 8b); also for the old and new AC layers of the other pavement sections. Figure 9 presents the constant-rate/fast-rate aging activation energies for the old and new AC layers of the eight Texas SPS-5 pavement sections. Higher aging activation energy indicates that the material has a smaller aging rate, or it is harder to be aged.

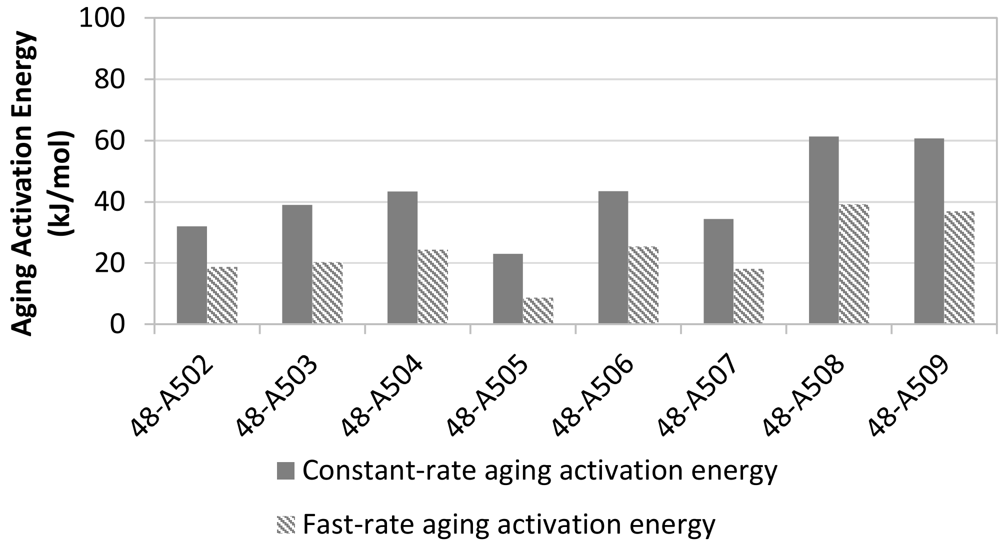


(a) E_1 of the old AC layer

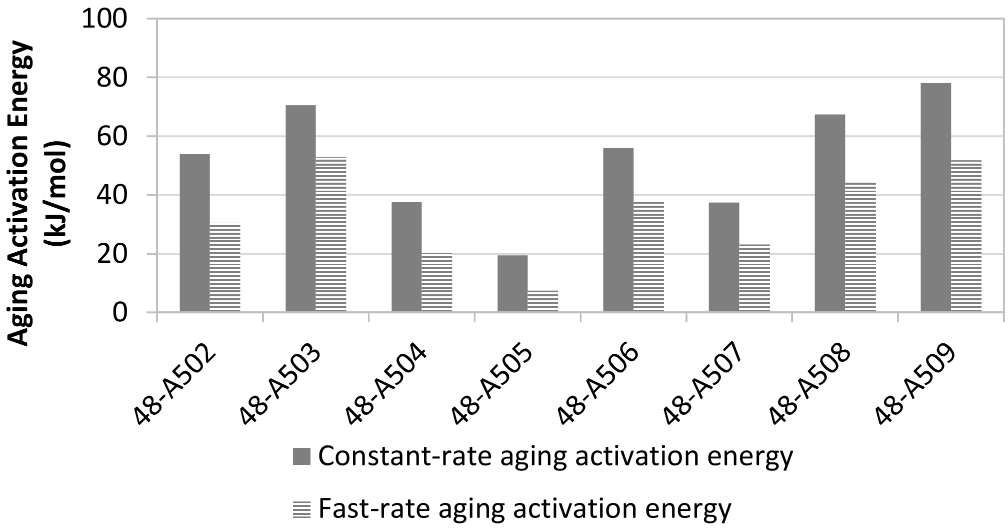


(b) E_2 of the overlay

Figure 8. Arrhenius plot of constant-rate reaction constant for Section 48-A503



(a) Old AC layer



(b) New AC layer (overlay)
Figure 9. Calculated aging activation energies for all Texas SPS-5 sections

6.2 Effects of material type, thickness and milling

Figure 10 shows the constant-rate and fast-rate aging activation energies for different types of materials. The aging activation energies of the "Old AC" are the averages of those of old AC layers of all eight pavement sections. The aging activation energies of the "New RAP" are the averages of those of new AC layers of the four RAP sections, i.e. four RAP overlay sections. The aging activation energies of the "New Virgin" are the average of those of four virgin overlay sections. It shows that the constant-rate/fast-rate aging activation energy of the RAP overlay is larger than that of the old AC layer, and that of the virgin overlay is smallest.

Aging activation energy of an asphalt mixture in a pavement structure is affected by the binder type, aggregate type, air voids, and location (Sosnovske et al., 1993; Mirza and Witczak, 1995; Luo et al., 2015; Moraes and Bahia, 2015). This means that the aging activation energy of an asphalt pavement is a net result of all these factors. The asphalt binder is clearly a significant factor, which has the same two aging stages and fast-rate and constant-rate aging activation energies (Jin et al., 2011). Aggregates have been proven to influence both short-term and long-term aging and apparent mitigating effect of some aggregates on aging was observed. The may be related to the chemical interaction between aggregates and asphalt binder, a larger adhesive bonding helping mitigate aging (Sosnovske et al., 1993). In addition, it was found that the adsorption of asphalt components on to aggregates could help reduce the impact of oxidative aging (Moraes and Bahia, 2015). Air voids of an asphalt mixture and its location in a pavement structure affect aging in terms of the amount of oxygen available for the oxidation process.

Based on these understandings, the results in Figure 10 have the following indications. The overlay with the virgin asphalt mixtures has a smaller aging activation energy than the old AC layer, which means that the virgin overlay ages faster. This is because the virgin overlay has more oxygen available as the top layer. The overlay with RAP has a larger aging activation energy and ages slower than the old AC layer. Compared to the virgin overlay, the virgin binder in the RAP overlay is different and probably the RAP aggregates are different from those in the virgin mixture, which would cause a change in the aging activation energy. Besides, a change of the adhesive bonding and/or a different adsorption mechanism between RAP aggregates and asphalt binder due to aging probably changes the aging activation energy of the RAP overlay. In the process of recycling, the RAP-binder aging is accelerated due to the increase of exposure of the binder surface to the atmosphere. The process of crushing of an existing asphalt layer into RAP increases the aging rate (De Lira et al., 2015). Moreover, at a higher temperature the molecular diffusion rate and range are larger (Sun et al., 2018); then the elevated temperature during the recycling process contributes to further aging of the RAP material (Hassan, 2009). It is found that aging affects the adhesion of an asphalt-aggregate system based on the measurements of adhesive bond energy at different aging levels. Depending on the source of binder and aggregates, the adhesion may increase or decrease (Cheng, 2002; Aguiar-Moya et al., 2015; Kassem et al., 2016). Furthermore, aging may change the chemistry of the asphalt-aggregate interface of RAP materials, which results in a different adsorption mechanism between asphalt and aggregates. Therefore, the aggregate-binder interaction in the RAP is different from that in the virgin mixture and that in the old AC, which significantly affects the aging activation energy.

Figures 11a and 11b show the difference in aging activation energies between the thin overlays (50 mm) and thick overlays (125 mm). The phrases “Old AC_RAP Overlay” and ““New AC_RAP Overlay”” represent the old and new AC layers of the RAP overlay sections respectively; “Old AC_Virgin Overlay” and “New AC_Virgin Overlay” stand for the old and new AC layers of the virgin overlay sections respectively. The aging activation energies in Figures 11a and 11b are the averages of the two sections with the same overlay material and thickness. It is found that the aging activation energy of the thick overlay is always larger than that of the thin overlay. This is because a thicker asphalt layer requires more oxygen for the aging process, so under the same environmental conditions the oxidation reaction rate is slower. In other words, the aging speed is slower so the aging activation energy is larger in thick overlay sections.

Figures 12a and 12b show the difference in aging activation energies between the milled overlay sections and those without milling. The aging activation energies in Figures 12a and 12b are the averages of the two sections with the same overlay material and surface preparation. It is seen that milling results in higher aging activation energies in both old and new AC layers for both RAP and virgin overlays. This is probably because the milled pavement part is backfilled with the overlay material. Even though the milling thickness is not counted in the overlay design, it causes the same effect as increasing the thickness of the asphalt layer in terms of aging.

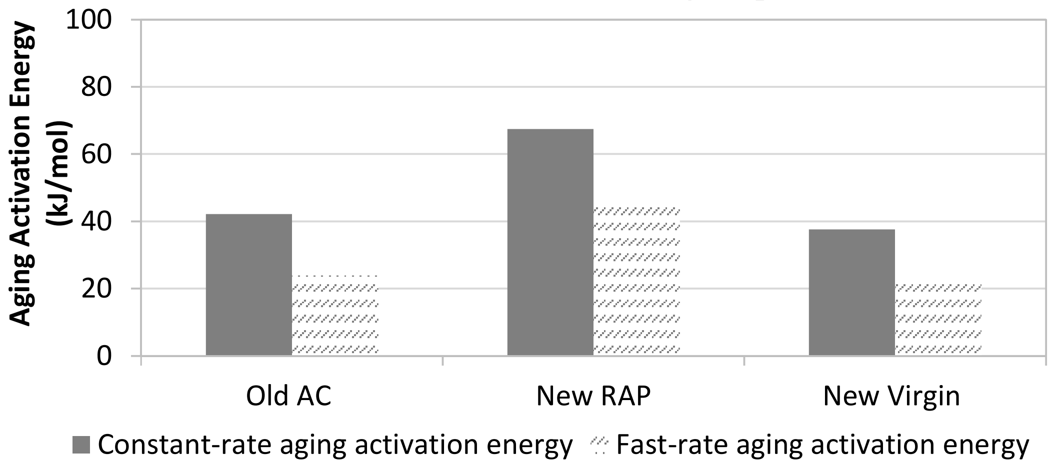
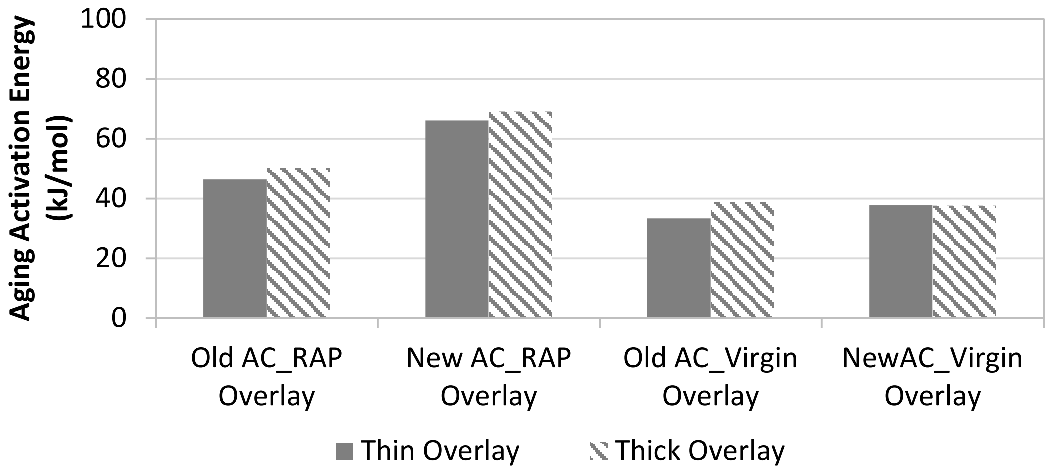
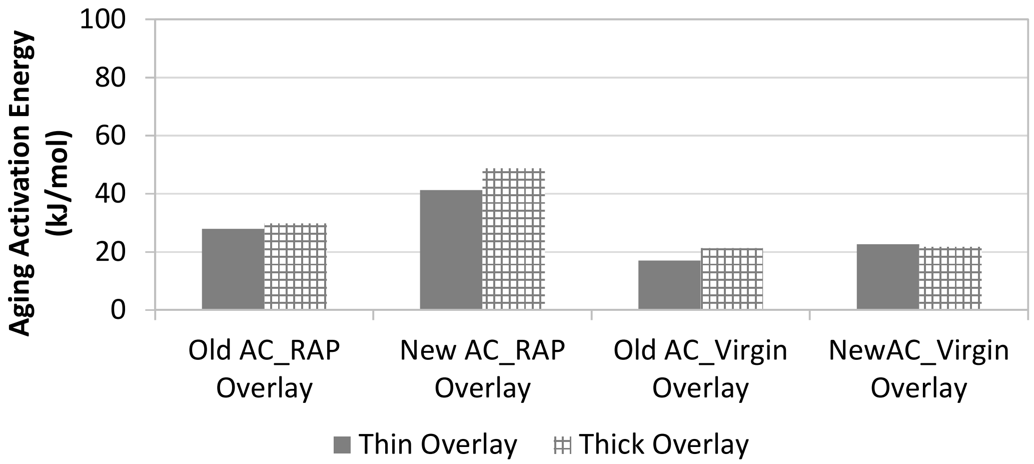


Figure 10. Comparison of aging activation energies for different asphalt mixtures

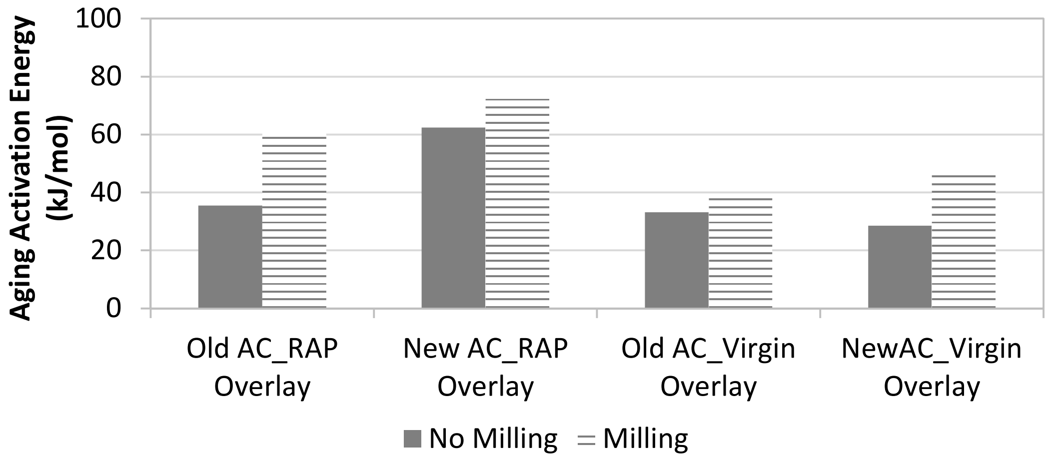


(a) Constant-rate aging activation energies

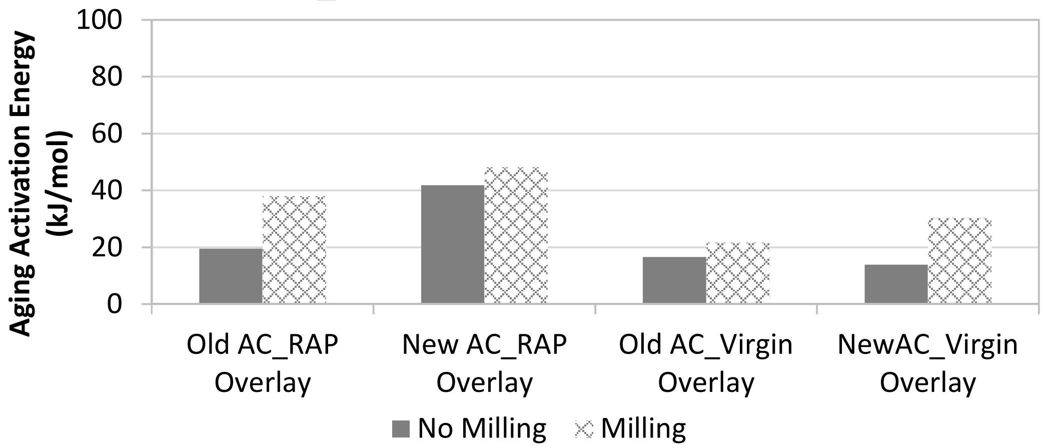


(b) Fast-rate aging activation energies

Figure 11. Comparison of aging activation energies for the effect of layer thickness



(a) Constant-rate aging activation energies



(b) Fast-rate aging activation energies

Figure 12. Comparison of aging activation energies for the effect of milling

6.3 Comparison with field performance

The findings observed from Figures 10 to 12 in terms of material type, asphalt layer thickness and milling are compared with a study on SPS-5 pavement performance (West et al., 2011). This study used SPS-5 performance data to investigate the effects of overlay rehabilitation. The data from 18 projects within the United States and Canada (each project has 8 test sections and 1 control section) were collected. The statistical analysis was performed on the paired sections shown in Table 3. There are totally 72 comparisons of RAP with virgin mixtures for each of the distress measurements. Take fatigue cracking, transverse cracking, and longitudinal cracking for example, which are closely related to aging. For these three types of cracking, the statistical analysis yields the same result with respect to the amount of cracking:

RAP>virgin; 50-mm overlay>125-mm overlay; no-milling overlay>milled overlay

Table 3. Paired sections in West et al. (2011) to compare pavement performance of 30% RAP and virgin mixtures

Paired Sections (RAP and virgin)	Description
502 and 505	No milling, 50 mm
503 and 504	No milling, 125 mm
509 and 506	Milled, 50 mm
508 and 507	Milled, 125 mm

Compare this result with the findings from Figures 10 to 12. Figure 10 indicates that the RAP overlay has higher aging activation energies than the virgin overlay, which means that the modulus of the RAP overlay increases slower than that of the virgin overlay. However, the RAP overlay might have a larger modulus because it contains a high percentage of already-aged materials, or it may have a different aggregate gradation and/or asphalt binder content. All of these factors contribute to the resistance of the RAP overlay to cracking (Luo et al., 2016). Figure 11 reveals that the 125-mm overlay sections have higher aging activation energies and slower aging rates than the 50-mm overlay sections. For the same overlay materials, thus, the 50-mm section ages more and fractures more easily than the 125-mm section. Figure 12 demonstrates that the milled overlay sections have higher aging activation energies than the overlay sections without milling. Therefore, for the same material type, the overlay section without milling is more prone to aging and cracking.

In sum, the observations from Figures 10 to 12 in terms of the aging activation energy can be used to explain the findings based on the field performance data of the SPS-5 sections.

7. Conclusions and future work

This study aims at investigating aging characteristics of in-service recycled asphalt pavements using field backcalculated modulus and climate data. The kinetics-based aging modeling approach developed in the authors' previous studies is applied to RAP materials herein. The following findings and conclusions are drawn:

- An asphalt pavement with overlay has a composite aging process since the aging speeds of different asphalt layers are different. The FWD modulus of an asphalt overlay must be separated into the moduli of its component layers in order to obtain the actual aging behaviors and properties of the overlay.
- The Odemark's assumption is successfully applied to separate the FWD modulus of the entire asphalt layer into a modulus for the overlay and a modulus for the old asphalt layer.
- With the separated FWD moduli and field aging temperatures from the pavement temperature modeling, the kinetics-based aging modeling approach is able to determine the aging properties (e.g. aging activation energy) of both the overlay and old asphalt layer for the selected eight RAP and virgin pavement sections.
- The overlays with RAP have higher aging activation energies than the old asphalt layers and the overlays with virgin mixtures. The aging activation energy of an asphalt mixture in a pavement layer is affected by the binder type, aggregate type, air voids, and location in a pavement structure.
- The thick overlay sections (both overlay and old asphalt layer) have higher aging activation energies than the thin overlay sections, so the thick overlay sections exhibit slower aging rates.
- The milled pavement sections (both overlay and old asphalt layer) have higher aging activation energies than the sections without milling. The milled sections that have a thicker overlay age slower.
- The comparisons of aging behaviors based on the aging activation energy can be used to explain the difference in the field performance of overlay pavement sections.

It is worth mentioning that the conclusions above are based on the analysis of the SPS-5 overlay sections in Texas. The SPS-5 in the LTPP database also contains similar data for other locations in the United States and Canada. It is planned that the data from various locations will be collected and analyzed to gain a better understanding of aging characteristics of recycled asphalt materials.

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