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16. Abstract

Binder oxidation in pavements and its impact on pavement performance has been addressed by numerous laboratory studies of binder oxidation chemistry, reaction kinetics, and hardening and its impact on mixture fatigue. Studies also have included some work on binder oxidation and hardening in pavements and the effectiveness of maintenance treatments. Yet more such studies are needed to better understand the fundamentals of pavement performance as a function of climate and pavement parameters.

Based on these reports in the literature, an experimental design has been developed to meet three objectives and to provide four products. The objectives are: 1) to develop and calibrate a laboratory test to assess binder aging during the production process and during the field service of the pavement; 2) to incorporate aging for use in a HMA mix design system to produce mixtures that provide adequate resistance to fatigue cracking, including guidelines to optimize resistance of HMA to aging; and 3) to evaluate the use of maintenance treatments to reduce the aging of asphalt pavements starting at early ages. The products: 1) a new test procedure to characterize binder aging, and predict service life for different applications; 2) an HMA mix design component that incorporates aging and its effect on resistance to fatigue cracking; 3) guidelines for optimizing HMA mixture resistance to aging; and 4) guidelines for the best maintenance treatments to reduce the aging of binders.

The experimental design includes measurements of binder oxidation and hardening at various stages of binder service, fundamental studies of binder oxidation and hardening kinetics, developing a transport model of binder oxidation in pavements, measurements of field oxidation and hardening rates, measurements of mixture fatigue decline as a function of binder oxidative hardening in both the field and laboratory, and measurements of maintenance treatment effectiveness at retarding binder oxidative hardening.

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LIST OF ABBREVIATIONS AND SYMBOLS

ω	Angular Frequency
$\eta'(\omega)$	Dynamic Shear Viscosity
$G'(\omega)$	Elastic (storage) Dynamic Shear Modulus
$G''(\omega)$	Viscous (loss) Dynamic Shear Modulus
$G^*(\omega)$	Complex Dynamic Shear Modulus
$G'/(\eta'/G')$	DSR Function
r_η	Binder Hardening Rate
r_{CA}	Binder Oxidation Rate (Rate of Carbonyl Area Formation)
N_i	Number of Load Cycles to Crack Initiation
N_f	Fatigue Life or Number of Load Cycles to Fatigue Failure
N_p	Number of Load Cycles to Crack Propagation
R_L	Pavement Loading Rate
SF_a	Shift Factor due to Anisotropy
SF_h	Shift Factor due to Healing Effects
CMSE	Calibrated Mechanistic with Surface Energy Measurements
TS	Tensile Strength Test
RM	Relaxation Modulus Test
RDT	Uniaxial Repeated-Direct Tension Test
σ_t	Tensile Strength of HMA Mixture (psi)
ε_f	Failure Tensile Strain at Break under Tensile Loading (in/in)
E_1	HMA Elastic Relaxation Modulus at 1 s Reduced Loading Time (psi)
m	Stress Relaxation Rate of the HMA Mixture
b	Rate of Fracture Damage Accumulation under Repeated Direct-Tension Test

CHAPTER 1

INTRODUCTION

Evidence is mounting that asphalt binders oxidize in pavements and that this oxidation has a negative impact on pavement durability, contrary to historical assumptions and practice. That binders oxidize in pavements has not been a well or universally accepted proposition, partly because of a lack of compelling data that show oxidation occurs, but also because of arguments that below the immediate surface, temperatures are moderated and surely the availability of oxygen is reduced. Both of these situations would reduce binder oxidation. Furthermore, the notion that binder oxidization is limited to a maximum value of viscosity has been accepted, historically. In fact, all three of these binder oxidation hypotheses have been incorporated into the mechanistic-empirical design guide (MEPDG), resulting in the assumptions that: 1) binders do not oxidize below about the top inch of pavement, and 2) binder hardening in that top inch advances only to a maximum, limiting viscosity (AASHTO, 2004). Furthermore, concerning the impact of binder oxidation on mixture (pavement) performance, the design guide assumes that binder oxidation does not fundamentally affect the fatigue decline of mixtures as a function of loading cycles.

Chapter 2 details recent literature findings that support the notion that binder oxidation may occur in pavements and significantly below the top inch of the pavement. Reports that this oxidation has a negative impact on mixture and thus pavement fatigue also are cited. Furthermore, the notion of a limiting viscosity has not been born out, either by laboratory studies of binder oxidation or by aged binders recovered from aged pavements. In short, all of the assumptions of the design guide with respect to binder oxidation and hardening in pavements, and its impact on pavement performance, appear to be incorrect.

With an improved appreciation of the extent of binder oxidation in pavements and its importance to pavement durability, a better quantitative understanding of this phenomenon becomes essential to cost-effective pavement design and maintenance planning. This improved understanding will include a better knowledge of the progression of binder oxidation in pavements through pavement milestones such as: hot mix plant processing, placement, the early (fast-rate) period oxidation, and the later (constant-rate) period oxidation. (Fast-rate and constant-rate period oxidation periods refer to binder oxidation kinetics at constant temperature and not to what actually occurs in pavements at non-constant temperature. Chapter 2 provides more detail on the reaction kinetics periods.) Also needed is an ability to predict, for each binder as it moves through these milestones, how it will respond to pavement service. To achieve this understanding, further development of binder tests, coupled with calibration with field binder aging data, will be important.

For example, while the rolling thin-film oven test does a good job of quantifying the extent of binder oxidation and hardening that takes place in the hot-mix process, tests that go beyond this point are problematic. The pressure aging vessel procedure oxidizes binders to a significantly more extended level over a 20 hour period; however, how this level corresponds to in-service aging time is unknown and variable, depending on climate and binder kinetics, plus mixture parameters such as air voids. In addition, how binder hardening in service affects performance has not been adequately quantified. Some mixtures show less decline of mixture fatigue resistance in response to binder oxidative hardening than others and there is little understanding about why. Binders can easily be aged to a particular level in the laboratory. The questions always have been "How does such aging correspond to in-service aging?" and "What is its relevance to pavement performance?" Thus, calibration of laboratory aging to field aging is essential.

The effectiveness of maintenance treatments is another issue that is not well understood and as such, the optimal time of placement is unknown. A prime question that needs to be addressed is how well treatment binders prevent oxidation by sealing the surface of the pavement. Actually, this is a two-part question. First, do treatments seal the surface and second, if they do, is this surface sealing sufficient to prevent oxidation. It may well be that oxygen can still find a way to reach the binder from below the surface.

This report provides a literature summary plus details of an experimental plan to address the issues discussed above. Chapter 2 is a literature review of binder oxidation kinetics and hardening, in both controlled laboratory conditions and in pavements; the effect of binder hardening on mixture fatigue resistance; and maintenance treatments. Also, two surveys of Texas Department of Transportation (TxDOT) districts on their use of maintenance treatments are summarized. Chapter 3 presents details of an experimental plan that is designed to meet the objectives and provide the products of this research project.

The three objectives are:

- development and calibration of a laboratory test to assess binder aging during the production process and during the field service of the pavement;
- incorporation of aging for use in a HMA mix design system to produce mixtures that provide adequate resistance to fatigue cracking, including guidelines to optimize resistance of HMA to aging; and
- evaluation of the use of maintenance treatments to reduce the aging of asphalt pavements starting at early ages.

The four products are:

- a new test procedure to characterize binder aging, and predict service life for different applications;
- an HMA mix design component that incorporates aging and its effect on resistance to fatigue cracking;
- guidelines for optimizing HMA mixture resistance to aging; and 4) guidelines for the best maintenance treatments to reduce the aging of binders.

CHAPTER 2

LITERATURE REVIEW AND MAINTENANCE TREATMENT SURVEYS

LITERATURE REVIEW

Although evidence that binder oxidation in pavements occurs, that it occurs beyond the near-surface of the pavement, that it is ongoing throughout the life of the pavement, and that it has a very profound effect on pavement durability is mounting and gaining acceptance, important implementation questions remain. Understanding how best to design mixtures in a way that takes binder oxidation into account to achieve maximum pavement durability is a very complex but important issue. A second, related issue is the use of maintenance treatments to impede or reduce binder oxidation in pavements.

A new TxDOT project (0-6009) is designed to provide information on these issues so as to achieve significant improvements to pavement durability, at significant life-cycle cost savings to TxDOT. The discussion that follows presents a background and literature survey of key issues that impact the major concern of this project, long-term pavement performance. Of specific interest are binder oxidation and hardening in pavements, their impact on pavement design and performance, and maintenance treatments.

Binder Oxidation and Hardening

Important questions concerning binder oxidation and hardening have been studied over the years:

- What are the reactions involved in binder oxidation?
- How fast does it occur in controlled reaction conditions and in pavements?
- What is the impact of oxidation binder physical properties?
- What is the mixture response in terms of fatigue resistance to binder oxidation?

The first three questions are considered further in this section and the last question is addressed in the next section.

Oxidation Chemistry

Perhaps the most fundamental issue impacting binder hardening in pavements is the basic binder oxidation chemistry. This issue has been explored rather extensively in significant reports by Lee and Huang (1973), Lau et al. (1992), Petersen et al. (1993) and others. A general observation of these reports is that carbonyl compounds form as a result of oxidation and that, while the exact nature of the carbonyl compounds and the formation rates as a function of temperature and oxygen partial pressure may vary from asphalt to asphalt, the common factor is that for each asphalt the carbonyl content can be used as a surrogate for total oxidative changes. Qualitatively the carbonyl growth varies linearly with total oxygen increase, even though the quantitative dependence varies from asphalt to asphalt (Liu et al., 1998b).

Oxidation Kinetics – the Constant-Rate Period

A second aspect of binder oxidation is the oxidation kinetics of an asphalt, studied and reported by Petersen et al. (1993), Liu et al. (1996), and others. The basic carbonyl reaction rate can generally be described using an Arrhenius expression (Equation 2-1) for temperature variation and pressure dependence:

$$\frac{d\text{CA}}{dt} = r_{\text{CA}} = AP^{\alpha}e^{-E/RT} \qquad (2\text{-}1)$$

where A is the frequency (pre-exponential) factor, P is the pressure, α is the reaction order with respect to oxygen pressure, E is the activation energy, R is the gas constant, and T is the absolute temperature. Values of A, E, and α are very asphalt dependent, though A and E are generally correlated (Liu, et al., 1996). Recent studies by Domke et al. (2000) show that the activation energy, E, is also pressure dependent for many asphalts, and this dependence is a function of asphaltenes.

Lau et al. (1992) reported results for 10 asphalts in which they determined values for E, α and A. In general, the reaction rates of asphalt binders undergo an initial rapid rate period that declines over time until a constant rate period is reached and the reaction rate given in the equation above describes this constant rate period. The early time, faster rate, period has been variously described as the "initial jump" by Lau et al. (1992), or the "initial spurt" by Petersen (1993). The point is that while the parameters of the oxidation rates vary from one asphalt to another, the basic form of the reaction rates are essentially the same. Kinetic parameters have been determined for a number of different asphalts including the SHRP core asphalts and others. Glover et al. (2005) report many of these results.

Oxidative Hardening

A third facet of binder oxidation is the impact that the oxidation has on the binder's physical properties. Fundamentally, the oxidation of the binder creates carbonyl compounds, primarily by oxidizing aromatic compounds in the naphthene aromatic, polar aromatic, and asphaltene fractions. These more polar carbonyl groups result in stronger associations between asphalt components, which increase the asphaltene fraction, and in turn lead to a stiffening of the binder in both its elastic modulus and its viscosity. Results have been reported in terms of the low shear rate limiting viscosity, and it has been observed that this viscosity increases in direct proportion to the carbonyl band infrared carbonyl growth (Martin et al., 1990). The proportionality factor has been termed the hardening susceptibility (Lau et al., 1992; Domke et al., 1999).

More recently, a DSR function (G'/(η'/G') measured at 44.7 °C, 10 rad/s and time-temperature shifted to 15 °C 0.005 rad/s) has been defined that includes both elastic and viscous properties and at more mid-range test conditions (frequency and/or temperature) than are represented by the low shear rate limiting viscosity (which, by definition, is at very low frequency or, equivalently, at high temperatures). This DSR function also increases linearly with carbonyl content, and the slope of this relationship is termed the DSR function hardening susceptibility. Glover et al. (2005) report the DSR function hardening susceptibility for a number of asphalts.

For either of these hardening functions, one can develop kinetics equations, just as can be done for carbonyl formation kinetics in that the hardening rate can be expressed in an Arrhenius rate form, thereby bypassing the carbonyl kinetics. Equivalently, the hardening susceptibility can be multiplied by the oxidation reaction rate to obtain the hardening rate, again, after the initial jump period has been passed, with the reaction rate constant at a fixed temperature.

Oxidation Kinetics – a Broader View

The oxidation kinetics discussion above was restricted to the constant-rate period of binder oxidation. Binder oxidation is somewhat more complicated, involving a fast, but declining rate period leading up to the constant-rate period. Equation 2-2 includes the various mechanisms by which hardening occurs, in the absence of oxygen diffusion resistance:

$$\ln\eta_t = \ln\eta_o + \Delta(\ln\eta_{ot}) + \Delta(\ln\eta_j) + r_\eta \cdot t \qquad (2\text{-}2)$$

where η_o is the original viscosity, η_t is the viscosity at time t, $\Delta(\ln \eta_{ot})$ is the hardening in the hot mix plant simulated by an oven test, $\Delta(\ln \eta_j)$ is the hardening that occurs in an early rapid "initial jump" stage, and r_η is the subsequent constant rate of hardening. This sequence is shown in Figure 2-1 in which η_{ot} is the viscosity after the oven test and η_j is the viscosity after the initial jump defined by the intercept of the constant-rate line. Region A will be defined as the time for the initial jump, and region B is a constant-rate region. Equation 2-2 is valid for time long enough to carry the process past region A. If there is diffusion resistance, this rate will decline as the asphalt hardens. Equation 2-2 and Figure 2-1 are expressed in terms of zero-shear viscosity η_o* but hardening in terms of other properties (such as the dynamic shear rheometer, [DSR] function G'/(η'/G'), discussed above and in the next section, follow the same hardening kinetics.

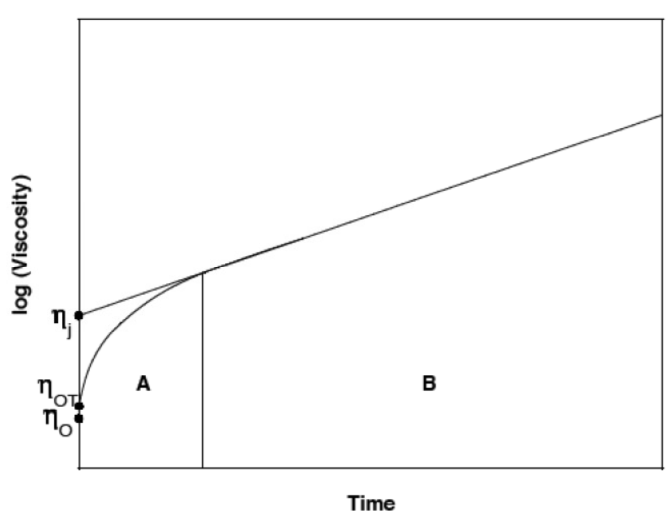

Figure 2-1. Typical Hardening Response of an Unmodified Asphalt Binder to Oxidation.

Asphalt oxidative hardening is almost entirely caused by asphaltene formation (Lin et al., 1995, 1996 and 1998), and the rate can be expressed as follows:

$$r_\eta = \frac{\partial \ln \eta}{\partial t} = \frac{\partial \ln \eta}{\partial \mathrm{AS}} \cdot \frac{\partial \mathrm{AS}}{\partial \mathrm{CA}} \cdot \frac{\partial \mathrm{CA}}{\partial t} \qquad (2\text{-}3)$$

where $\partial \ln \eta/\partial \mathrm{AS}$ is the impact of asphaltene (AS) increase on increasing viscosity and is affected by asphaltene size, which in turn is affected by maltene solvent power; $\partial \mathrm{AS}/\partial \mathrm{CA}$ is the extent to which increases in carbonyl area (CA) produce asphaltenes; and $\partial \mathrm{CA}/\partial t$ is the rate of CA formation. The increase of CA correlates linearly with oxidation (Liu et al., 1998b). Equation 2-4 can be simplified as:

$$r_\eta = \mathrm{HS} \cdot r_{\mathrm{CA}} \qquad (2\text{-}4)$$

where HS is the combination of the first two terms in Equation 2-3. This combination is remarkably constant as oxidation proceeds and is independent of oxidation temperature below about 100-110 °C. It has a characteristic value for each asphalt except that it is pressure dependent. This term is called the hardening susceptibility (Lau et al. 1992; Domke, 1999). The rate of carbonyl formation is given above as Equation 2-1 (Lin et al., 1996; Lin et al., 1998; Liu et al., 1997).

The following equation summarizes these results where [P] or [T,P] or [P] indicates that the property is a function of temperature or temperature and pressure, or just pressure:

$$\ln \eta_t = \ln \eta_{ot} + \Delta(\ln \eta_j)[P] + r_{\mathrm{CA}}[T,P] \cdot \mathrm{HS}[P] \cdot t \qquad (2\text{-}5)$$

As only one term is multiplied by time, this means that the relative rankings of asphalts from any accelerated aging procedure will change with the length of the test as well as with the temperature and pressure. Note that particularly relevant hardening rate parameters are the initial jump (η_j), the hardening susceptibility (HS), and the oxidation rate, r_{CA}.

The Fast-Rate Reaction Period

Figure 2-1 showed binder reaction kinetics, in terms of binder rheology, separated into an initial fast-rate (initial jump) period and a second, constant-rate period. Accurately representing binder oxidation in pavements requires understanding the relative amount of time spent by the binder in each of these different periods during the course of a pavement's life. The following discussion addresses literature reports of these two reaction periods and the fast-rate period reaction kinetics.

The Fast-Rate Period in Pavements. While the reaction kinetics of binder oxidation during the constant-rate period (described above) has been studied extensively, the early-time, fast-rate period reaction kinetics has been studied much less, providing a source of error in comparisons of field and laboratory binder oxidative hardening. Though we can assure, in the laboratory, that the fast-rate period of oxidation has been passed, it is more difficult to tell when it ends in the field, due to the lower field temperatures and the cyclical nature of temperatures in pavements. Using constant-rate period kinetics to assess field aging without knowing if the fast-rate period has been passed may contribute considerable error and uncertainty to the results and conclusions. Thus, an improved understanding of oxidation kinetics during the fast-rate period is important.

Recovered binders from field cores from Texas and Minnesota (MnROAD) were measured for rheological properties, and then aged further in a 60 °C environmental room for up to eight months (Woo et al., 2007). Figure 2-2 shows the stiffness (in the form of the DSR function) of each of the extracted and recovered binders (zero months ER aging), plus increases that occur with further ER aging (2, 4, 6, and 8 months ER aging). If the binder, as recovered from the core, together with its subsequently-aged samples all form a single straight line, then they are all past the fast-rate (initial jump) period. However, if the binder, as recovered from the core, lies below a straight line formed by its subsequently-aged samples, then the core sample was not past the initial jump. From the figure, it seems clear that the binder recovered from the Texas pavements had past the fast-rate period after two to three years aging in the pavement, whereas the MnROAD AC 120/150 binder was still within this period, even after 12 years of field aging. From these data, it seems that the fast-rate period of aging is not as important for Texas pavements, relative to long term pavement aging, as it is for Minnesota.

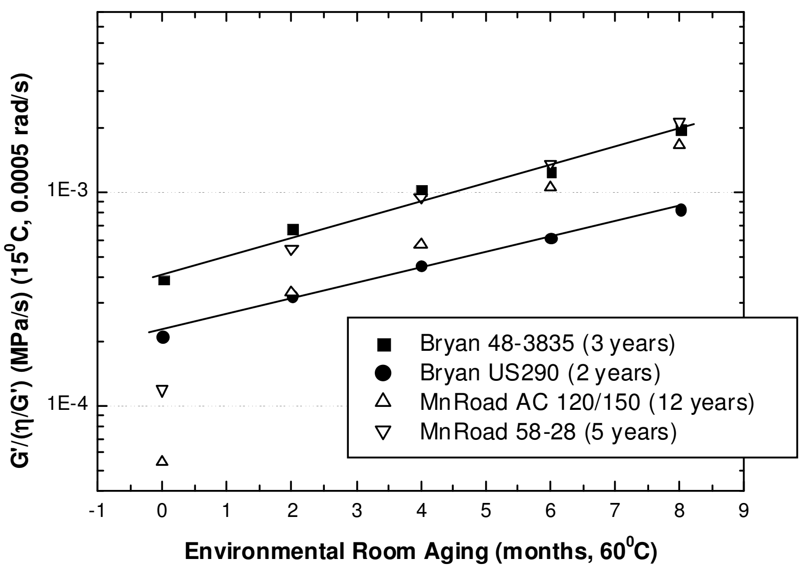

Figure 2-2. DSR Function Growth of Recovered Binders from Texas and Minnesota Aged in Environmental Room (60 °C). (Data from Woo et al., 2007)

Fast-Rate Period Reaction Kinetics. Dickinson and Nicholas (1949) investigated oxygen absorption by tar oils. Two parallel reactions were suggested, one a first order reaction with respect to phenol and the other a zero order reaction with respect to aromatics. The combined effect of these two reactions produced an early time fast (but declining) rate period of oxygen absorption, followed by a later-time constant-rate period after the first reaction terminated due to depletion of phenol, the limiting reactant. The reaction kinetics model they proposed for tar oil was:

$$M = k \cdot t + M_2 \cdot [1 - \exp(k_2 \cdot t)] \qquad (2\text{-}6)$$

where M is total amount of oxygen absorbed by the tar oil, k and k_2 are reaction constants for the constant-rate and fast-rate reactions, respectively. The constant-rate reaction constant k is temperature and oxygen pressure dependent according to $k = A \cdot P^{\alpha} \cdot \exp(-E_a / RT)$ and k_2 is independent of temperature and pressure for tar oil. M_2 is the maximum oxygen absorption due to the first reaction, which depends linearly on oxygen pressure, $M_2 \propto P$.

A similar model was observed for oxygen absorption by asphalt. Van Oort (1956) measured oxygen absorption by seven-micron thin films of asphalt at 22 °C and atmospheric pressure. Seven different asphalts were aged for 50 weeks. From the oxygen absorption versus time relation, a fast increase of oxygen absorption was observed during the first 10 weeks; however, the rate of absorption decreased until a constant rate was reached after about 30 to 40 weeks.

Viscosity changes with time showed a trend similar to oxygen absorption, but had the apparent advantage of being able to be determined more precisely. This observation suggests that viscosity change, rather than oxygen absorption might be a better indicator of the beginning of constant rate period, as viscosity is closely related to binder performance. In addition, viscosity change is mainly due to oxidation which leads to carbonyl area (CA) growth, while oxygen absorption not only leads to the formation of CA, but also leads to products that have no apparent effect on viscosity. Thus, the study of CA and viscosity would seem to be the better variables for the understanding of fast-rate aging period.

Despite the obvious similarity of kinetics between asphalt and tar oil, three possible differences should be explored. First, it is quite possible that k_2 for asphalts is temperature and pressure dependent. Second, M_2 may be a non-linear function of oxygen pressure. Finally, neat binders have a finite (non-zero) initial viscosity or carbonyl area.

The Importance of Oxidative Hardening to Mixture Performance

Impact of Binder Oxidation on Mixture Fatigue

The above discussion has addressed the issue of binder oxidation reaction and kinetics and the resulting binder hardening. A fourth issue regarding binder oxidation is "So what?" Assuming binders oxidize in pavements, what is the importance of this oxidation to pavement performance? For example, to what extent is the fatigue life of a pavement impacted by binder oxidation? This is a question that has recently been addressed by Walubita et al. (2005, 2006a and 2006b, 2006c). These results indicate that binder oxidation in pavements can have a very significant negative impact on pavement fatigue life (fatigue resistance). While the mechanism of this fatigue life decline with oxidation is not yet well understood, early data indicate that it is a very important phenomenon and that there can be significant differences between different mixture designs as shown in Figure 2-3. The reasons for these differences need to be understood.

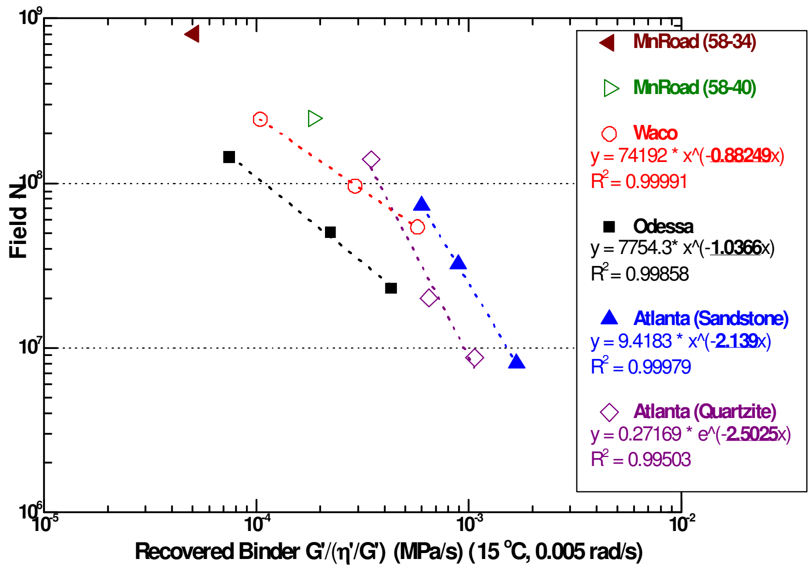

Figure 2-3. Impact of Binder Oxidative Hardening on Mixture Fatigue Resistance.

Specific results from this recent multi-year research project that impact directly the experimental plan presented in Chapter 3 include:

- Fatigue life decreases significantly primarily as a result of aging due to binder oxidation and its subsequent effect on mixture properties.
- The decrease in fatigue life is a function of more than just the binder stiffening due to oxidative aging. Thus mixture parameters that may be controlled during the mix design process are important to ensure adequate fatigue resistance.
- Different mixtures show unique declines in fatigue life due to aging.
- The CMSE approach is valid for understanding the different mixture responses to aging.
- Two different methods show promise in capturing the effects of aging on fatigue life. One method is more empirical but practical, and the second facilitates greater understanding of the aging mechanism.

So, the decline of mixture fatigue resistance under controlled-strain conditions is an important phenomenon that varies from mixture to mixture. Unknown, however, are the quantitative contributions of each of the various mixture parameters (air voids, binder content, binder composition, aggregate type, aggregate gradation) to the differences in decline of mixture fatigue life with binder oxidation. Quantitative assessment of these differences is essential. Also, assessing pavement durability as it is influenced by binder oxidation and traffic loading, and in light of laboratory conclusions on the effect of binder aging on mixture fatigue resistance, will require monitoring pavement fatigue resistance over time.

Further Analysis of Fatigue Resistance Decline

As discussed above, previous work reported fatigue tests on a number of mixtures (Walubita et al., 2006b; Woo et al., 2007). The resulting data showed that the fatigue resistance of mixtures declines significantly with binder oxidative hardening and that the rate of decline can vary significantly from one mixture to another. The reasons for the differences were undetermined.

In an effort to better understand this decline of mixture fatigue resistance, the data of these reports have been extensively reviewed as part of this report. The eleven mixtures that were tested in those two projects are described in Table 2-1; important mixture parameters are listed in Table 2-2.

A dimensionless group analysis technique was employed and nine dimensionless groups were constructed from the twelve mixture parameters and they also are listed in Table 2-2. Correlations of the fatigue life decline rates to mixture parameters and dimensionless groups, and their combinations were then examined.

Table 2-1. Mixtures Studied for Key Mixture Parameter Identification.

Mixture	Aggregate	Mixture Type	Binder PG	Binder Content (%)
Odessa	Rhyolite	Coarse Matrix High Binder F	70-22 (SBS)	7.3
Waco	Igneous	Superpave_19mm	70-22 (SBS)	5.3
Altanta 1	Sandstone	Superpave_12.5mm	76-22 (SBS)	5
Altanta 2	Quartzile	Superpave_12.5mm	76-22 (SBS)	5
Bryan	Limestone	TxDOT Type C	64-22	4.4
A1	Gravel	Superpave_12.5mm	64-22	5
A2	Gravel	Superpave_12.5mm	64-22	5.5
B1	Gravel	Superpave_12.5mm	76-22 (SBS)	5.3
B2	Gravel	Superpave_12.5mm	76-22 (SBS)	5.8
C1	Gravel	Superpave_12.5mm	76-22 (TR)	5.2
C2	Gravel	Superpave_12.5mm	76-22 (TR)	5.7

Table 2-2. Mixtures Parameters and Dimensionless Groups Studied.

Mixture Parameters	Symbol	Unit	Dimensionless Groups
Film Thickness	T_f	L	$N1=T_f/(SA_{agg})^{0.5}/M_b$
Binder Mass	M_b	M	$N2=T_f/b/SE(\Delta G_f)$
Aggregate Surface Area	SA_{agg}	L^2/M	$N3=SE(\Delta G_f)/SE(\Delta G_h)$
Air Void	AV	N/A	$N4=\sigma_t/b$
Surface Energy (Fracture)	$SE(\Delta G_f)$	M/T^2	$N5=\sigma_t*m/E_i$
Surface Energy (Healing)	$SE(\Delta G_h)$	M/T^2	$N6=(T_f)^3/AV/M_b$
Rate of Dissipated Energy	b	$M/(LT^2)$	$N7=P_b$
Maximum Tensile Strength	σ_t	$M/(LT^2)$	N8=AV
Critical Tensile Strain	ε_t	N/A	$N9=\varepsilon_t$
Elastic Modulus in RM Test	E_i	$M/(LT^2)$	N10=m
Stress Relaxation Rate (RM)	m	N/A	
Binder Content	P_b	N/A	

In Figure 2-4, the rates of mixture fatigue life decline with binder oxidative hardening are compared to binder content (P_b), film thickness (T_f), and two dimensionless groups constructed from these parameters plus the rate of fracture damage accumulation (b) and binder and aggregate surface energies. The correlations are weak, but suggest that these may be contributing parameters. Further experimental work is required to better understand this phenomenon.

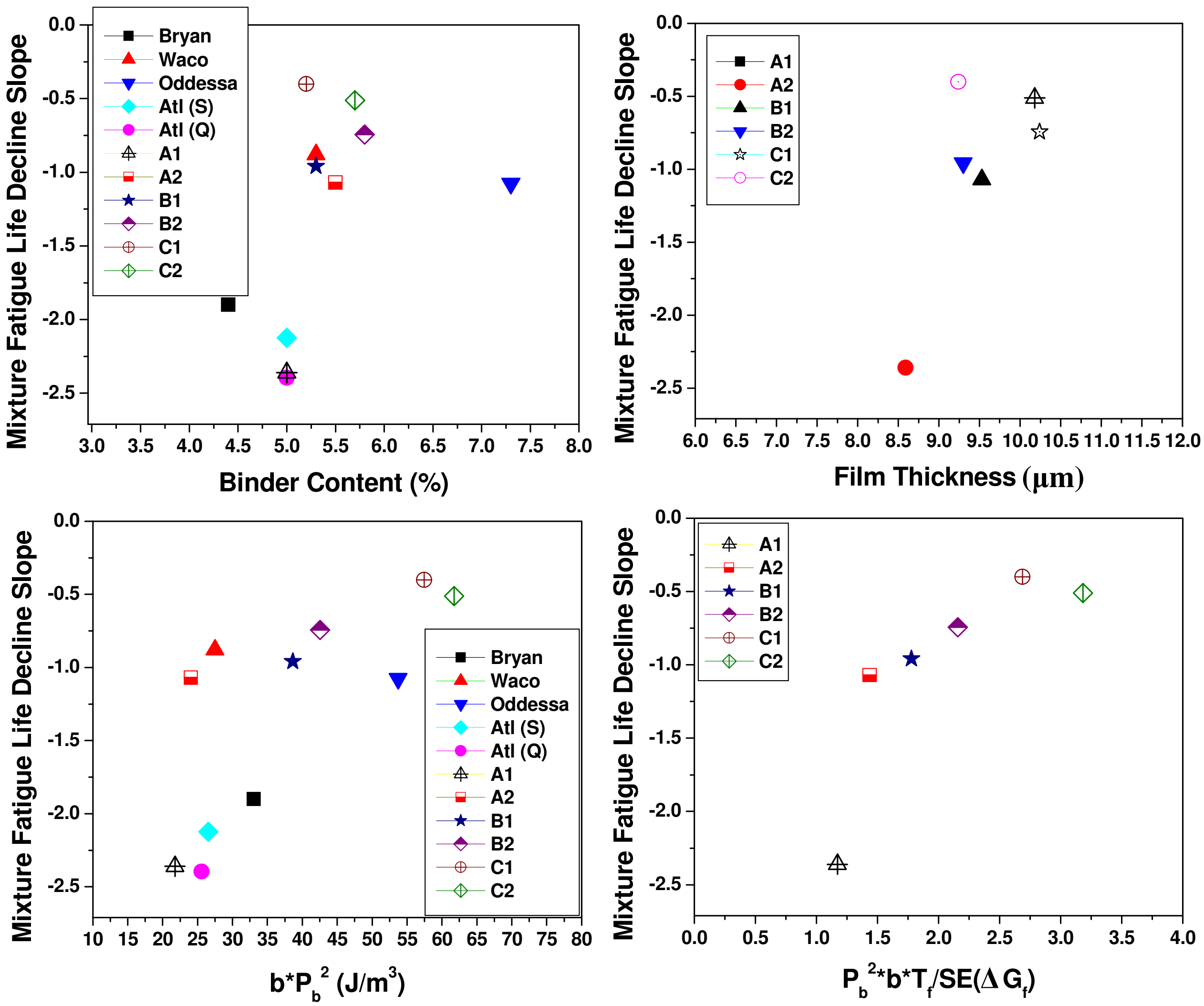

Figure 2-4. Analysis of the Correlation between Mixture Parameters and Parameter Groups to Mixture Fatigue Life Decline Rates.

Oxidation in Pavements

The final issue of binder oxidation in pavements is the question of whether, in fact, binders oxidize in pavements at all, in the face of presumed reduced temperatures and restricted oxygen transport to the binder below the surface. The work discussed above showed that binders harden as a result of oxidation, that the kinetics of oxidation and the hardening that results from oxidation are quite well known (or can be measured) and can be described quantitatively in terms of oxidation temperature and pressure. The work discussed above also indicates that if binders oxidize in pavements, the impact on pavement fatigue performance can be profound. All of these factors, however, will be moot if binder oxidization does not occur in pavements, and the question of whether this oxidation occurs has no clear answer in the literature. In fact, a very well cited and accepted literature report concludes that binder oxidation occurs only in the top inch of the pavement and that below the top inch, the binder is left virtually unaffected by years of use and years of environmental exposure (Coons and Wright, 1968). Their conclusion is formalized in a recently developed mechanistic empirical pavement design guide (AASHTO, 2004) that assumes in its calculation that binders oxidize only in the top inch. Parenthetically, calculations performed using the MEPDG under TxDOT Project 0-4468 suggest that binder oxidation and the consequent increase in pavement stiffness (and the presumed decrease in deformation under load as a result of this stiffness) actually have a *positive, beneficial* impact on pavement fatigue life.

Contradicting the work of Coons and Wright and the assumptions of the pavement design guide are the extensive data reported in Glover et al. (2005) in which a large number of Texas pavements were cored, the binder extracted and recovered, and then tested to determine binder stiffness as a function of age in the pavement. The results of this work indicate rather strongly that in fact binders can age in pavements well below the surface and that the hardening of binder in the pavement is virtually unabated over time. These data also are reported in a recent paper by Al-Azri et al. (2006).

A Simple Model of Binder Oxidation in Pavements

More recent work provided significant new results on binder hardening in pavements that relate both to modeling binder oxidation and to calibration with binders recovered from pavements (Woo et al., 2007). The discussion of this model is presented in some detail below because this simple model provides the basic concepts and results of more detailed models that will be explored in this project.

The model considers the pavement to behave as a semi-infinite slab with an imposed periodic temperature at the pavement surface. The periodicity occurs daily because of daytime and nighttime temperatures swings, and yearly due to seasonal variations of temperature. Such a model is used extensively in geology to estimate the temperature of the earth's crust as a function of time and depth and it is now considered whether such a model is applicable for HMA pavements (U.S. Geological Survey, 2006). Such a model of temperature in the pavement as a function of time and depth below the surface follows the well-known thermal diffusion model given by Equation 2-7 in which $\Theta(x,t) = (T(x,t) - T_{avg})$ is the temperature deviation from (oscillation about) an average temperature, t is time, and x is depth below the surface into the pavement.

$$\frac{\partial \Theta}{\partial t} = \kappa \frac{\partial^2 \Theta}{\partial x^2} \qquad (2\text{-}7)$$

In this equation, κ is the thermal diffusivity, which is equal to $k/(\rho C)$, where k is the thermal conductivity, ρ is density, and C is the heat capacity of the solid material. This model assumes no temperature variation parallel to a pavement's surface, so it is an unsteady-state, one-dimensional model.

It is assumed the pavement is initially at uniform temperature (T_{avg}) and that at the surface there is imposed a temperature oscillation (of amplitude A, frequency ω and phase shift ε). These conditions provide initial and boundary conditions according to Equations 2-8.

$$\text{I.C.: } \Theta(x,0) = 0$$
$$\text{B.C.: for } x = 0 \text{ and } t > 0,\ \Theta(0,t) = A\cos(\omega t - \varepsilon) \tag{2-8}$$

The asymptotic, periodic solution to this problem is given by Equation 2-9 (Carslaw and Jaeger, 1959).

$$\Theta = Ae^{-x(\omega/2\kappa)^{1/2}} \cos\left[\omega t - x\left(\frac{\omega}{2\kappa}\right)^{1/2} - \varepsilon\right] \tag{2-9}$$

Thus, according to this model, the temperature, after a sufficiently long period of time persists as a periodic temperature profile that is attenuated in amplitude according to the depth below the surface, and also, shifted in phase according to the depth below the surface.

Measured temperature profiles are available from SHRP program long-term pavement performance (LTPP) site measurements and allow estimates of the thermal diffusivity independently from both the amplitude attenuation and from the phase shift. As an example, temperature amplitude data from Refugio, Texas (LTPP site 48-1060) provided an estimate of thermal diffusivity of 0.010 cm^2/s and the phase shift data provide an estimate of 0.0092 cm^2/s. This is very good agreement between these two estimates. Note also that the model says that the temperatures at various depths should oscillate about the same average temperature.

Comparisons to Field Aging. Using this model for pavement temperature as a function of time and depth, and using known asphalt binder oxidation kinetics parameters while also assuming that the transport rate of oxygen to the binder does not limit the oxidation rate, estimates of binder oxidation in Texas SH 21 were calculated. By neglecting the effect of oxygen diffusion resistance we obtain an upper limit estimate of the binder oxidation rate.

The same procedure was followed for a pavement that was part of the MnROAD controlled study. Original binder was not available, so binder oxidation kinetic parameters were determined experimentally by aging binder that was recovered from a core in the laboratory in 1 mm thick films and at 60 °C, 75 °C, and 95 °C.

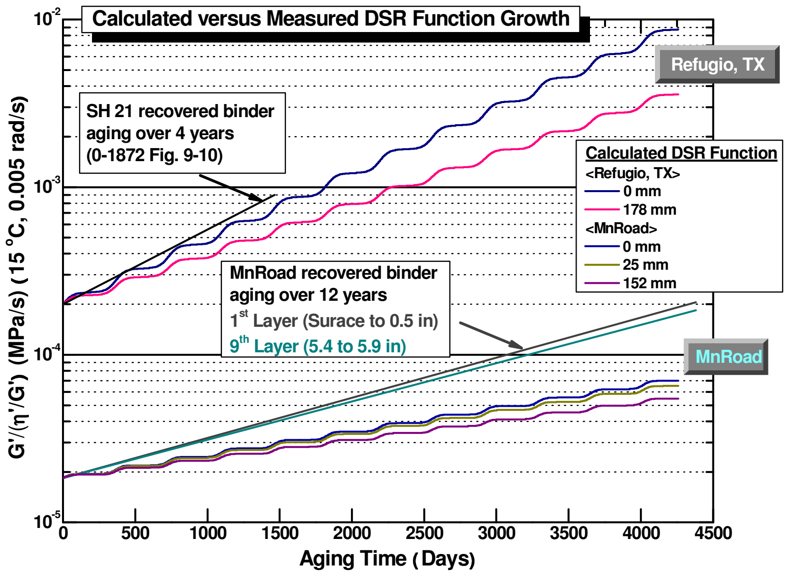

Figure 2-5. Calculated Versus Measured DSR Function Growth.

Figure 2-5 shows the binder hardening over time expressed in terms of the DSR function for both the SH 21 and MnROAD pavements. Note that calculations are made for the surface and 178 mm (7 in) below the surface. According to the model, while greater depths provide different rates, they do not provide grossly different rates compared to zero. Figure 2-5 also shows lines that represent the actual measured hardening rate of the binder in both the SH 21 and MnROAD pavements. The agreement between the actual pavement hardening rates and the corresponding calculated hardening rates based upon the temperature model and the binder oxidation kinetics is quite good and suggests that for these pavements, the assumption of good oxygen availability to the binder is acceptable. In the calculated carbonyl and DSR function oxidation curves, the near-zero hardening rates during the winter months versus the much higher hardening rate during the summer months is evident in the stair-step calculations.

Note that in Figure 2-5, the measured hardening of binder in the pavement in Minnesota occurs at a significantly lower rate than the hardening rate of binder in Texas Highway 21. The MnROAD values are approximate average hardening rates for the MnROAD pavement, based on the 1st and 9th layers of the Cell 1 core. The 1st and 9th layers both appear to have ample access to oxygen (accessible air voids of from 3 to 5 percent) and aged at essentially the same rate. Thus, it is those rates that are depicted by the slopes of the two lines together with the stair-step calculations.

Note also that for the binder recovered from the MnROAD cell, the binder hardening rates are higher than for the stair-step model calculations, and a couple of reasons seem possible. First, an initial pavement value was not measured and an error in estimating this value would affect the rate. Second, binder aging over most of the service life of the pavement may well have occurred during the initial jump portion of binder aging kinetics, and therefore at a higher aging rate than would be calculated from the measured constant-rate period kinetic parameters. This probably is the more likely explanation, based on recovered binder initial jump measurements.

Accelerated Binder Oxidation Test. As a final observation using binder oxidation model calculations, the issue of whether measurements of laboratory aging rates at a single elevated temperature, albeit near pavement aging temperatures, can provide accurate relative rankings of binder aging in pavements is reviewed. Because pavement aging occurs over a range of temperatures whereas the ER aging occurs at a single temperature, the nonlinear effect of temperature on reaction rates through the Arrhenius equation, in principle, can result in reversals in the order of the rankings. Calculations of (model) pavement binder aging rates were reported for seven SHRP asphalts, plus two others, and compared to calculated 60 °C hardening rates (Woo et al., 2007). Some reversals were seen in these calculations. Specifically, AAB-1 ranked with the second highest rate in the ER at 60 °C but was tied for sixth by the pavement calculation. Also, ABM-1 was fourth at 60 °C but second in the "pavement."

So, the reported conclusion was that the only correct method for estimating (annual average) reaction rates in pavements is to measure rates at several temperatures, from these measurements calculate reaction parameters, and then use an appropriate model to calculate expected pavement hardening rates based on these parameters (Woo et al., 2007). On the other hand it was noted that the range of the ratio of laboratory (60 °C) hardening rates to field (pavement, near the surface, annual average) hardening rates is only from 13 to 19, perhaps not so large a range for an engineering estimate. Stated differently, for all of these various binders, one month of aging in the laboratory at 60 °C was equivalent to from 13 to 19 months in the pavement, at the location considered by their model.

Of course, the issue always comes down to accuracy of the measurement versus time to make the measurement. The calculations of the nine binders described above provided 60 °C to "pavement" hardening rate ratios that varied by up to 46 percent. Similar calculations for single-temperature laboratory rate measurements of 40, 80, and 100 °C gave high ratio (lab to field) values that exceeded low ratio values by 35, 72, and 109 percent. The tradeoff in time was that a one-day test at 100 °C would correspond (roughly) to five days at 80 °C, one month at 60 °C, and six months at 40 °C.

The conclusion is that developing an accelerated binder aging test that ranks asphalts the same as pavement aging is challenging at best and fundamentally impossible at worst because of the different effects of time, temperature, and pressure on different materials.

Measurements of Binder Aging in Pavements

Hardening of various binders in pavements in the form of the DSR function was reported by Woo et al. (2007) and is summarized in Figure 2-6. This figure shows DSR function values for binders recovered from pavements versus the corresponding pavement service age. Both Texas pavements and the MnROAD pavements are summarized. Both unmodified and modified binders appear in the figure. The bulk of the binders reported were modified.

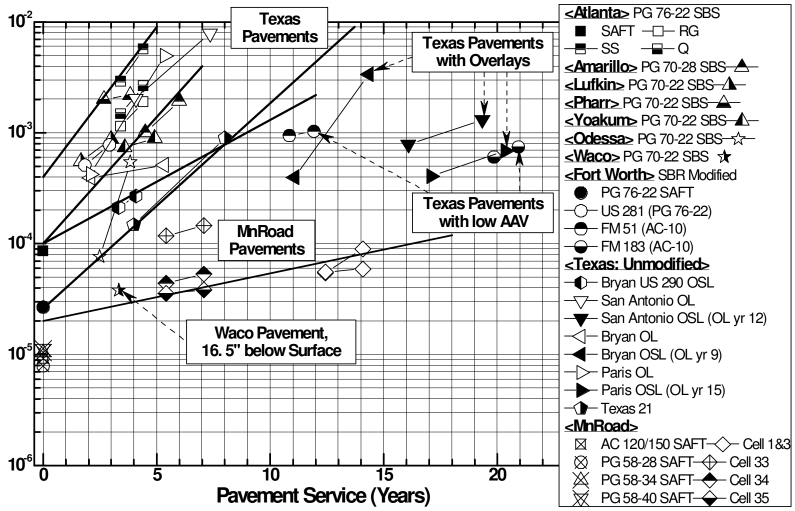

Figure 2-6. DSR Function Hardening with Pavement Service Time in Texas and MnROAD Pavements.

Based upon the above data a number of conclusions were reported concerning modified and unmodified binder aging in pavements in Texas.

- Texas pavements constructed from both modified and unmodified binders, age and harden at comparable rates given sufficiently high accessible air voids. The rate is largely determined by the temperature as a function of time and position (depth) in the pavement provided the accessible air voids are sufficiently high (four percent or greater). This temperature function is established solely by the climate conditions.
- This dominant impact of temperature notwithstanding, there is considerable evidence that when the accessible air voids in pavements are sufficiently low (2 percent or less) the hardening rate of binders in Texas pavements can be significantly reduced, thereby prolonging the service life of the pavements to 15 or 20 years or more.
- Some of the Texas pavements appear to be under aged relative to the other binders, perhaps due to the application of a chip seal and/or overlay one to three years before coring the pavement. This phenomenon has been observed before and these data may be an indication again that the right kind of treatment during a pavement's service might well soften the binder and rehabilitate it, thus providing an extended pavement life.
- If a binder with an inherently low hardening rate (slow oxidation kinetics and minimal physical response to the oxidation) is used in a pavement, and if a low enough level of accessible air voids can be achieved (in the range of 2 percent or less), then the pavement has a real chance of providing service over a very extended period of time.
- Binder DSR function hardening rates in Texas are about twice the rate for the corresponding binder in Minnesota at comparable air void conditions.
- In order to estimate pavement binder hardening rates, values of the binder reaction kinetics parameters are required. Approximating the rate with measurements at 60 °C may give a rate from which a rough estimate can be calculated, but the nonlinear activation energy effect can cause significant error (discussed just before "Measurements of Binder Aging in Pavements").

- Calculations from the pavement oxidation model and known binder reaction kinetics parameters indicate that 60 °C hardening rates range from 13 to 19 times the calculated pavement binder aging rates as discussed previously.

The Importance of Accessible Air Voids

As noted above, low levels of accessible air voids appear to relate to binder oxidation. Figure 2-7 shows data for four pavements, where low accessible air voids appear to affect binder aging rates. Each dashed line connects data for successively deeper 0.5 in slices of a single core, starting at the pavement surface ("1st"). In Figure 2-7, the binder DSR function is shown layer-by-layer versus the accessible air voids of that layer. Cell 1 is particularly instructive as a strong DSR function versus accessible air voids correlation is seen both near the surface (slices 1 and 2) and also in the deepest part of the core (slices 6 through 9). While these specific data are from the MnROAD sites (used because of the 6 inch core thicknesses), the results appear to reflect aging in Texas pavements also (Figure 2-6, Fort Worth FM 51 and SH 183).

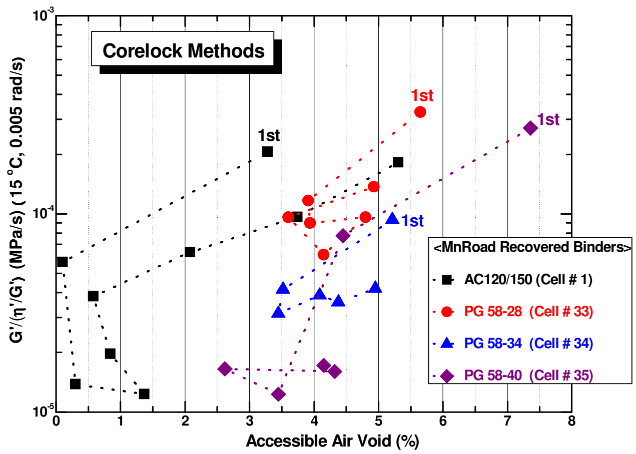

Figure 2-7. Binder Hardening Related to Local Pavement Accessible Air Voids.

More Realistic Models of Thermal and Oxygen Transport in Pavements

From the above discussion, it is clear that while a simplified model of binder oxidation in pavements may perform reasonably well in some cases, improved temperature calculations and estimates of oxygen transport that account for restricted air voids are needed in many others. Improved methods for estimating pavement temperatures are reported in the literature; by contrast, improved methods for estimating oxygen transport are embryonic. Both of these topics are discussed further, below.

Improved Models for Calculating Temperature in Pavements. Accurate calculations of binder oxidation in pavements require accurate pavement temperatures, over both time (daily and seasonally) and position (depth) and as a function of climate (site location). In recent years, considerable research has been conducted to establish suitable methods of modeling and calculating pavement temperatures. While this work primarily has been used to estimate changes in pavement properties with temperature as well as for the purpose of materials selection, it also provides a foundation for calculating binder oxidation in pavements and subsequent changes in binder properties that result from this oxidation.

In early development of pavement temperature calculation methods, interactions between climatic conditions and pavement temperatures were correlated using either empirical equations or simple mathematic models (Barber, 1957; Rumney and Jimenez, 1969). Following these initial efforts, Solaimanian et al. (1993) developed an advanced analytical approach to calculating maximum pavement temperatures. Their method employed heat and energy transfer fundamentals, but used the problematic assumption of a steady-state thermal energy balance over the entire pavement slab, from the pavement surface to a specific (but not stated in the article) subgrade depth. Most recently, Diefenderfer et al. (2006) proposed an empirical equation that derived from linear regression techniques to predict pavement maximum and minimum temperatures from known maximum and minimum ambient air temperatures, pavement location, and depth below the pavement surface. This method, though providing good results at the pavement surface, failed to predict pavement temperatures accurately below the surface because they also inaccurately assumed that pavement temperature is a linear function of depth.

In general all of these methods, developed using either empirical equations or analytical approaches, have focused primarily on determining the yearly maximum and minimum pavement temperatures for the purpose of binder selection. As such they are unable to provide accurate calculations of temperature as a function of both time and depth, due to model shortcomings in capturing fundamental aspects of heat transfer processes in the pavement.

Fundamental thermal energy balance models for pavements have been discussed by a number of authors (Dempsey, 1970; Solaimanian and Kennedy, 1993). The heat transfer process is depicted in Figure 2-8. The most significant heat source at the pavement surface is shortwave solar radiation directly from the sun. Both the pavement surface and air act like blackbodies to emit long-wave radiation to each other as up-welling and down-welling long-wave radiation. Additionally, heat transfer occurs by convection at the pavement surface by convection. The net heat flux received by the pavement surface by those four mechanisms then propagates into and through the pavement by conduction.

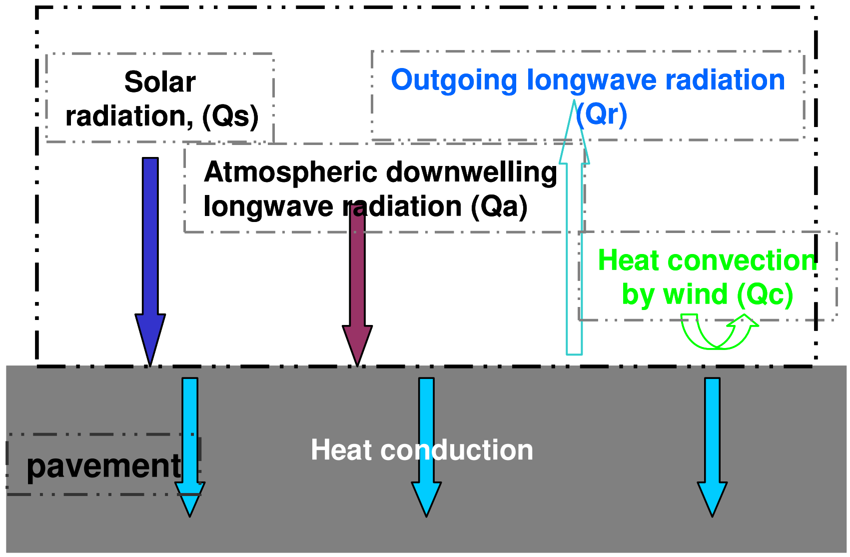

Figure 2-8. Schematic Representation of Pavement Heat Transfer.

Incorporating these fundamental processes, a one-dimensional heat simulation model, the climatic material structure model (CMS) was proposed to calculate continuous pavement temperature profiles numerically (Dempsey, 1970). The model was later integrated into the enhanced integrated climate model (EICM) (Lytton et al., 1989) and was further incorporated in the current prevailing pavement design guide (MEPDG). This model divides the pavement into different layers and applies a finite difference approximation method to numerically calculate pavement temperatures at each layer as a function of time and depth. This model also assumes a steady-state thermal energy balance over the entire pavement/subgrade from the surface to a depth ranging from 9 to 18 m (depending on location), where a constant temperature (equal to the water table temperature) was used as a boundary condition. Within the pavement, the heat conduction process was modeled with the Fourier's law thermal diffusivity equation. With known required climatic input data including solar radiation, ambient temperature, and wind speed in hourly format and with assumed constant model parameters including albedo, emissivity, and thermal diffusivity, the model can be solved numerically to obtain the temperature in each pavement layer.

Although this EICM model can be used to predict continuous real-time pavement temperature profiles for the needs of general pavement design, rather inaccurate results have been reported (Ahmed et al. 2005), when compared to measured pavement temperatures, especially at pavement layers close to the surface (Figure 2-9). Those differences are most likely caused primarily by the assumption of a steady-state thermal energy balance over a finite layer of pavement and subgrade. This assumption must be questioned because there is no fundamental reason that the energy flux at the pavement surface should equal that due to conduction at some depth below the surface. Other possible sources of error are the inaccuracy of climatic input data (especially hourly solar radiation), the assumption of a constant temperature bottom boundary condition, and the assumption that model parameters are constant and universal. In fact, model parameters such as albedo, emissivity, and absorption coefficient are site-specific and their values are highly sensitive to environmental conditions.

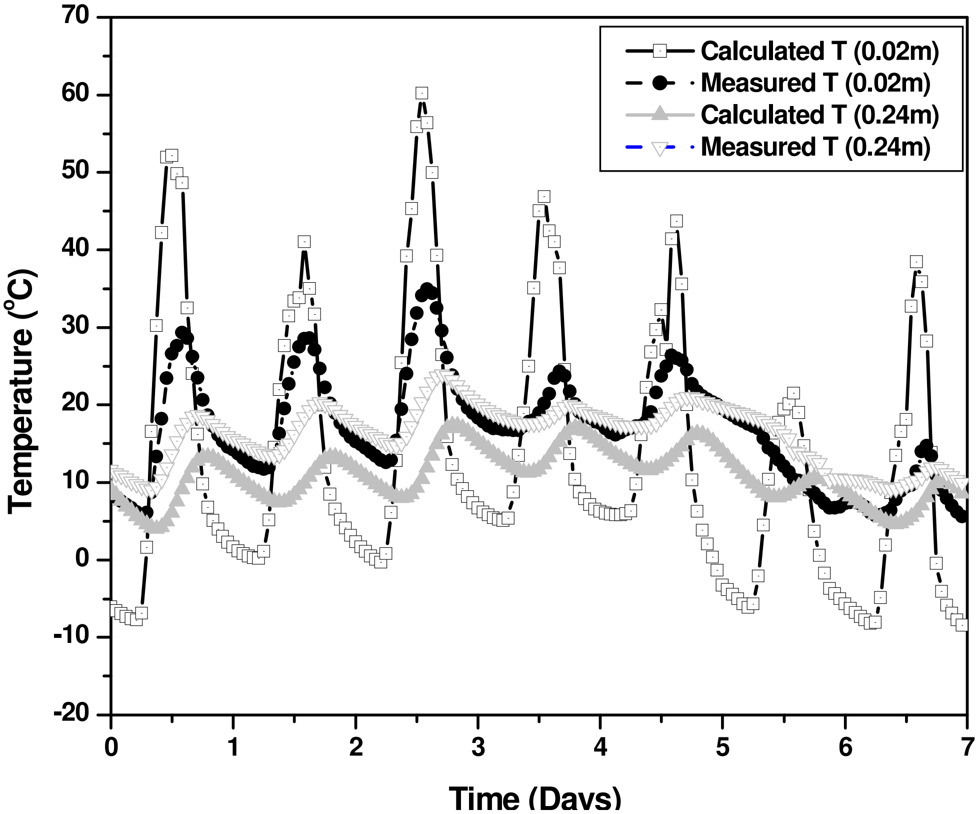

Figure 2-9. Sample Calculation of Pavement Temperatures Using the EICM Method at 48-1068, TX (Mar-03-1994 to Mar-09-1994), Compared with Field Measurements.

Models having significant improvements in temperature prediction accuracy and consistency have been reported recently by several authors (Hermasson et al., 2000, 2004; Gui et al., 2007). These models, compared to the EICM model, employ an unsteady-state thermal energy balance at the pavement surface, thereby avoiding the steady-state assumption over a finite thickness of the pavement. Measurements of hourly climatic input data and site-specific model parameters, estimated from field pavement temperature measurements were used as input to the model. Hermansson used a fixed temperature (an approximation of the annual mean temperature) as the bottom boundary condition at 5 m; Gui et al. used a fixed temperature of 33.5 °C at a depth of 3 m. A comparison of model calculations to field measurements is shown in Figure 2-10. Clearly, great improvement has been achieved with this unsteady-state balance at the pavement surface.

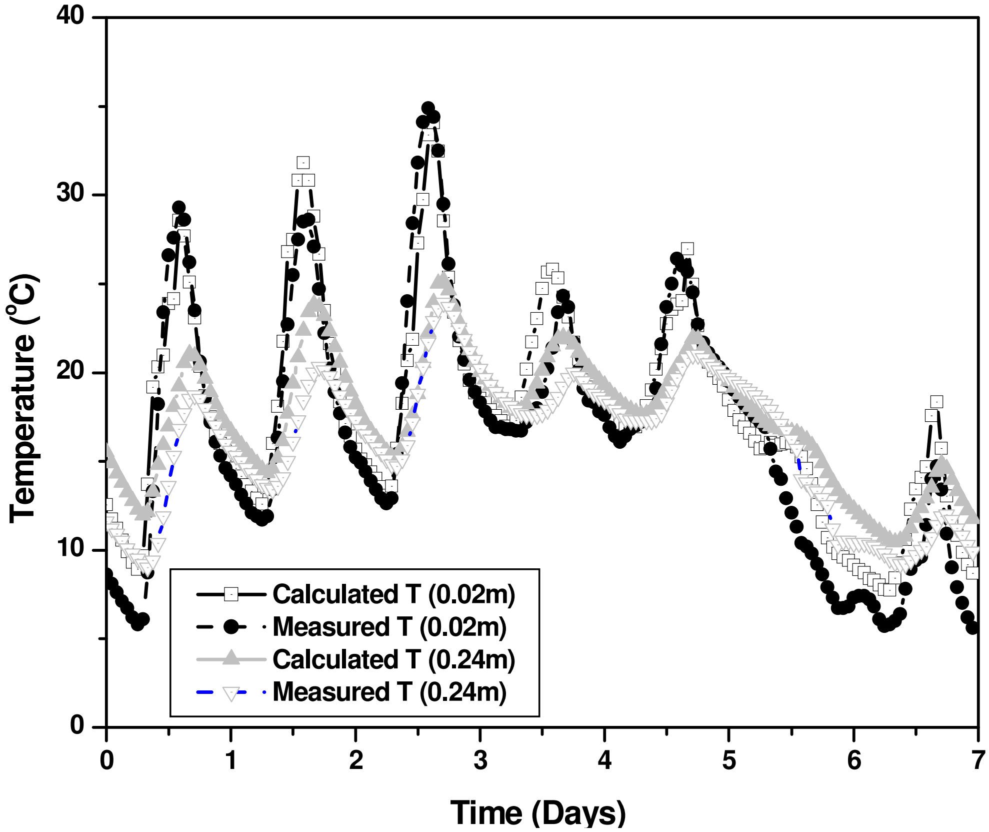

Figure 2-10. Sample Calculations of Pavement Temperature Using Enhanced Numerical Model Principle at 48-1068, TX (Mar-03-1994 to Mar-09-1994), Compared with Field Measurement.

Despite their success in model accuracy and consistency, applications of these enhanced models were limited to a relatively short time scale and specific pavement sites, and are highly dependent on the availability of hourly climatic input data and of site-specific model parameters. How to obtain accurate hourly climatic data and site-specific model parameters at any given pavement site have become key issues to be addressed.

Modeling Oxygen Transport in Pavements. Efforts to include the effect of oxygen transport into pavements and through binders are practically non-existent. Lunsford (1994) developed a one-dimensional, flat, thin-film model and performed calculations for approximate cyclical pavement temperature variations to estimate the effect of diffusion on oxidation. As binder oxidized, he estimated changes to the binder viscosity, based on approximate experimental data, and the resulting change to binder diffusivity. Thus the model accounted for the effect of oxygen diffusion on binder oxidation and vice versa. However, the model was very approximate in that the geometry was for flat films and the calculations were done for film thicknesses of the order of 1 mm, which probably were not representative of actual field conditions. Trial calculations were made for various film thicknesses and compared to binder oxidation in a small number of pavements.

The air void characteristics of each pavement depend on several factors including the degree of compaction, method of compaction, aggregate gradation and shape, and binder content (Consuegra et al., 1989; Sousa et al., 1991). It is important to understand how these variables impact the internal structure of asphalt concrete. By using imaging processes and non-destructive techniques, researchers are able to characterize the materials based on their distribution in the asphalt core samples (Danison et al., 1997; Masad et al., 1999a, b).

The x-ray computed tomography (CT) and image analysis methods have been used to study the air void distribution in asphalt specimens. Typically, it is found that a higher amount of air voids exists at the top and the bottom portions of a pavement lift while there is a smaller amount of voids in the middle (Masad et al., 2002). A study of the internal structure of the pavement core suggests that there is a connectivity of void channels vertically within the core (Al-Omari et al., 2002). X-ray CT scanning with a resolution of 0.1 mm per pixel was used in these studies (Masad et al., 2005). In addition, recent X-ray CT analysis shows that with 0.1 mm per pixel resolution, typical permeable friction course samples having a total air void 15 to 20 percent have an average void radius of 2-3 mm, whereas dense-graded mixtures having total air voids less than 10 percent have an average void radius of 1 mm. There is a possibility that higher resolution X-ray CT imaging may reveal additional smaller air voids in pavement core samples which would provide a more accurate interpore spacing that for a pavement oxidation transport model discussed in the next section.

Oxygen transport limitations are important to establishing binder hardening rates in pavements. If the interconnected (or accessible) air voids are sufficiently low, then delivery of oxygen to the binder is hindered. Therefore, an improved model of binder oxidation in pavements that includes oxygen transport needs to be developed.

An improved pavement oxidation transport model should be based on three interlinked processes:

- diffusion of oxygen into the asphalt binder mastic in the pavement;
- heat transfer into the pavement that results in temperature variations with depth and time; and
- asphalt binder oxidation, which is a function of oxygen concentration and temperature in the binder.

A fourth issue that affects the oxygen transport and concentration is the air voids distribution in the mixture because it affects the availability of oxygen to the binder. The diffusion process is coupled to both temperature and oxidation because both of these factors affect oxygen diffusivity.

The concept of approximating the binder film in the pavement as a thin film is probably reasonable for high air voids content where there are a large number of pores passing through the pavement so that the distance from any pore to the binder, even to the farthest binder away, is not very far. According to results from X-ray CT analysis, a more realistic model for a reduced number of air voids might be a cylindrical model that assumes that the oxygen diffuses from the pore in a radial direction into a cylindrical shell of binder. In this case, the relevant parameter would be the thickness of this cylindrical shell, relative to the diameter of the pore containing the air. The smaller the air voids, the greater the ratio of this binder shell to the pore diameter and thus the more time required for oxygen to diffuse through the binder. A similar approach was also used in the study of oxygen diffusion in engineered cardiac tissue (Radisic et al., 2005).

To obtain oxygen partial pressure profiles in the pavement oxidation models, the governing PDE system will be solved for the oxygen partial pressure as a function of time and distance away the from air void-binder interface in a cylindrical coordinate system. In principle the oxygen partial pressure profile can be used to calculate CA and viscosity profiles and histories in the pavement, which then can be combined with an appropriate performance model to estimate pavement durability and performance, taking into account binder oxidative hardening.

Maintenance Treatments to Retard Oxidation

Maintenance treatments applied to the surface of a pavement, typically as a chip seal treatment, may conceivably penetrate into the pores of a pavement to reduce binder oxidation, or to be absorbed by the in situ binder, resulting in a softening of a hardened pavement. Whether such penetration and absorption occurs has not been well documented, if at all, and it remains a very real question as to whether maintenance treatments can play such a role in improving the durability and longevity of pavements.

In the case of hot asphalt cement treatments, some indirect evidence suggests that maintenance binders are able to penetrate into the pavement. In Project 0-1872 cores obtained from Texas SH 21 showed that recovered binder properties became progressively harder and harder over years of sampling, with the exception of cores taken in 2002 after a chip seal and overlay were placed in 2000. Cores were sliced into three 2-inch thick layers and either retrograde stiffening with aging time (i.e., softening), or virtually no stiffening, of the recovered binder from the 1996 cores to the 2002 cores occurred in all three layers, suggesting that sealant penetration may have occurred through the pavement, well beyond its topmost portions. In the more recent Project 0-4688 several pavements were cored that had overlays and probably seal coats or tack coats with the overlay. In these cases too, there appears to be an unusually soft binder in that part of the core underneath the overlay compared to other pavement binders of that age. However, these data are even more problematic because there is no documentation of a seal coat and these results do not constitute controlled data.

The effectiveness of fog seal emulsions in either rejuvenating or slowing the oxidation of the in situ binder was studied rather extensively in the recently completed Project 0-5091. Pavement cores with and without fog seal treatments were cut into nominally quarter inch slices and each slice was analyzed for binder properties and the presence of the fog seal treatment. In virtually all cases there was no evidence found of softening of the binder or even of the emulsion asphalt material. The results suggested that the emulsions may pass through the pavement. Only the top inch of the pavement was studied so it is entirely possible that the emulsion material flowed through this part of the pavement and away from the surface. These emulsions contain the asphalt material as asphalt droplets of the order of 10 µm diameter that may be able to be carried by the emulsifying solvent (typically water) through the pavement pores, which are typically an order of magnitude bigger in diameter, without being absorbed by the in situ binder. At any rate, no evidence of rejuvenation by these emulsions was found and neither was there any evidence that the emulsions retarded binder oxidation in the pavements. The single exception to these conclusions is that EB44 coal tar material was detected in the top 6 mm (1/4 inch) of the pavement and this treatment actually resulted in a harder recovered binder.

There appears to be very inconclusive evidence that hot asphalt maintenance treatments may penetrate the pavement and remain behind with the in situ binder to affect its oxidative hardening. Furthermore, there are rather careful data pointing to an ineffectiveness of fog seal treatments. However, this research team found no case of documentation showing that maintenance treatments may actually soften the in situ pavement binder and therefore rejuvenate the binder from the perspective of fatigue or other cracking. The issue is two-fold: 1) whether the maintenance treatments penetrate into the pavement (and how deep); and 2) whether once the binder penetrates into the pavement it then can reduce the aging of binders. Extracting and recovering the binder may give an indication as to this latter effect. An alternative method is to actually test the mixture properties.

Ultimately, the effectiveness of an asphalt maintenance treatment will depend upon its ability to penetrate into the pavement. It will also depend upon the nature of the maintenance treatment as to composition of the binder (asphaltene free) and viscosity. If the hot asphalt is too high a viscosity, then it will not flow effectively into the pores of the pavement. Transport of the binder through the pavement will also depend upon the temperature of the pavement versus the temperature of the binder and how much the binder cools as it penetrates the pavement. Of course, another factor is the structure of the pavement itself as both the air voids content and the pore size distribution will affect the flow of the maintenance treatment into the pavement.

Pavement Service Life Design

Pavement service life depends upon a large number of variables:

- overall pavement system strength,
- pavement integrity in the face of climate (moisture damage),
- pavement resistance to permanent deformation, and
- embrittlement of the pavement binder due to oxidation.

The mechanistic empirical pavement design guide has been developed in recent years to take all of these factors into account in optimizing the design of a pavement. Unfortunately, from a binder oxidation and hardening perspective, most of what it does is wrong because it is based upon old literature. To be specific, the MEPDG assumes that pavement binders do not oxidize below the top 25 mm (1 inch) of the pavement. It assumes that hardening of the binder stops after a certain period of time and does not take into account the deterioration of mixture fatigue resistance with binder oxidative hardening. The net effect of these difficulties is that in the controlled stress environment that the design guide calculates in most cases, binder oxidative hardening actually improves fatigue resistance for about the first ten years of the pavement and thereafter ceases to have a positive effect because at about that point it assumes no more binder hardening. These calculations were made in TxDOT Project 0-4468 and likely are the result of the design guide calculating that in a controlled stress environment a stiffer pavement (due to binder oxidation) results in less pavement deformation under load and therefore a reduced negative impact on fatigue life. Thus the design guide almost certainly is in serious need of correction in the area of binder oxidation and its impact on pavement durability.

MAINTENANCE TREATMENT SURVEYS

In order to evaluate the effectiveness of maintenance treatments in reducing aging, a better understanding of the design and construction practices associated with these is necessary. Data from current and previous surveys were collected and summarized with respect to Texas seal coats, more commonly called chip seals and officially termed surface treatments by TxDOT. These surveys included information related to material selection processes, design, and construction practices. The review was also conducted in order to discover what practices, if any, are being used to address oxidation and aging in HMA pavements.

User Survey – TxDOT Project 0-1787 (Texas Tech)

While performing a study for the development of the current TxDOT Seal Coat Manual, Texas Tech researchers conducted structured face-to-face interviews with TxDOT employees from each of the 25 districts. Those interviewed included district employees who were familiar with the seal coat process, including contract administrators, designers, inspectors, maintenance workers, and materials personnel (Senadheera et al., 2000. The Texas Tech interviewers examined the current construction practices for seal coats including planning methods and design, materials used, quality control, equipment, and construction methods.

Much of the information gleaned from the interviews for the TxDOT Seal Coat Manual study was similar to the information to be acquired through surveys for this project, 0-6009. Questions in the following specific categories were asked with respect to seal coats:

- general information,
- design,
- contract,
- materials,
- equipment,
- construction,
- quality control,
- performance, and
- continuous improvement.

For the purposes of this report, information was reviewed and summarized from the general information, design, materials, construction, and performance categories.

General Information

From the general information category of questions, Texas Tech researchers discovered that the TxDOT districts with more rural roads had significantly more lane miles with seal coat than those districts in urban areas. Among all districts, 76 percent of the districts had 50 percent or more of their roads seal coated. Only one district was using seal coats strictly as a preventive maintenance measure. Thirteen of the other districts attempted to follow a preventive maintenance schedule. However, lack of maintenance funding prevented them from strictly adhering to the schedule. The remaining twelve districts applied seal coats on an as needed basis.

Design

In the *Statewide Seal Coat Constructability Review* report, the design section covered questions that ranged from project selection to bid or contract letting. For this study, relevant items addressed in the interview include the project selection process and design procedures. Roads selected for seal coats were those that exhibited cracking, flushing, lack of skid resistance, and oxidation. Generally, seal coats are not applied to roads that have significant structural failures or deficiencies. However, in cases where funding for full or partial depth repair is not available, seal coats may be applied to seal the pavement until funding does become available.

Two methods of design were used: the Modified Kearby method and an experience based method. The Modified Kearby method is based on aggregate embedment for a determined binder application rate. The binder application rate is determined from existing conditions on the roadway receiving the treatment. The experience based method depends upon the experience of an individual to determine the application rates of the materials. Most districts determined their application rates based on past experience. Many districts believed that because of the many field adjustments that are made in seal coat applications, relying on a specific design method was not practical. However, at the time that the *Statewide Seal Coat Constructability Review* was published, the Modified Kearby method was gaining approval. This method determines a starting application rate and then adjusts that rate depending on existing field conditions at the time of application. TxDOT personnel stated that this method is a good method for training inexperienced personnel.

Materials

In the materials section of the interviews, selection of material type and grade, availability, and cost were addressed. For the purposes of this report, responses with respect to material type and grade are summarized.

Material selection was based on either maximization of seal coat performance or maximization of lane miles sealed for the amount of funding available. The majority of the districts used two main aggregate gradations. These were Grade 3 and Grade 4. Grade 4 was used most frequently due to its smoother finish, which is believed to reduce windshield damage from loose aggregate and requires less binder. Grade 4 also seems to provide a smoother ride surface than the Grade 3, thus resulting in fewer complaints by the public. The users of the Grade 3 aggregate claim that it is much more forgiving of variation in the binder application rate. The larger aggregate size exhibits less flushing and bleeding problems. Some modified Grade 3 and 4 aggregates were used by some districts. These aggregates were more uniformly graded. However, some believe that the additional cost for minimal benefit does not warrant its use.

Regardless of the aggregate type used, aggregates are generally pre-coated in order to control the dust particles on the aggregate surfaces. Softer asphalts are typically used, such as AC-3 and AC-5, for pre-coating. The pre-coated aggregate method seems to be effective only when asphalt cement is used as the binder for the seal coat.

Selection of binder type varies from district to district. Some districts use one binder while others use up to six different binders for various jobs. Most of the districts used three different binders in their seal coat projects. The binder used can be based on several factors. Some districts select binders based on average daily traffic (ADT), with higher ADT roads getting the higher quality binders. Other districts may select binders based on local prices or allow the contractor to select the most economical binder available to them. The most commonly used asphalt cement binder types include the following:

- AC-10-latex,
- AC-5-latex,
- AC-10,
- AC-5,
- AC-15-5TR, and
- AC-15P.

Of these binders, the AC-15-5TR binder is used by the majority of the districts. This tire rubber modified asphalt seemed to produce satisfactory results. The AC-15P and AC-5 are also frequently used. However, districts that used the AC-5 binder seemed to have significant problems with bleeding. Asphalt cement binders were typically used in the hotter and drier months of the year.

Of the emulsified asphalt binders used, the most common were:

- CRS-2H,
- HFRS-2P,
- HFRS,
- CRS-2, and
- CRS-2P.

Significantly more districts chose CRS-2P over the other emulsified asphalt binders. The emulsified asphalt binders were typically used in cooler months or when there was a higher probability of rain.

Construction

For the construction portion of the interviews, seal coat season, surface preparation, traffic control, material application, rolling, and brooming were addressed. For the purpose of this project, seal coat season and surface preparation are summarized.

The districts all generally agreed that the summer months were the best for applying seal coats. This period of time varied depending on latitude. Those districts located in the south had a longer seal coat season than those in the north. Districts also preferred to finish seal coating in a reasonable time before the first cold spell. This allowed for better adhesion between aggregate and binder. Start dates run from April 1 to June 1 while finish dates were distributed between August 31 and October 31.

Surface preparation typically involves crack sealing and patching. Crack sealing prevents binder from being lost in the cracks, and patching levels the pavement surface.

Performance

In the performance section of the interviews, the districts were asked which distress types were observed and which were the most predominant. The common distresses observed included flushing, shelling, cracking, streaking, and oxidation. Of these, flushing and shelling were the most predominant distresses observed.

While these interviews provided a wealth of information with respect to the past practices associated with seal coats in Texas, very little was mentioned concerning oxidation and aging. In some instances seal coats were used to address oxidation but usually a secondary concern. If seal coat applications are found to significantly reduce aging in HMA pavements, the practices summarized above may be helpful identify some of the mechanisms that contribute to this effect.

User Survey – TxDOT Project 0-6009

As part of this project, a short answer survey was created in order to assess the use of seal coats to reduce aging on Texas roadways. A limited number of TxDOT personnel from the Fort Worth, Brownwood, and Atlanta districts, who have been with the department for several years and are involved with district laboratory and pavement design, were selected for the survey. These generally included district laboratory and pavement engineers as well as district laboratory supervisors. The questions were designed to assess the current practices and uses associated with seal coats, how the pavements are selected for treatment, and whether or not they are specifically used to reduce aging.

Responses indicate that seal coat treatment sections are most often selected based on routine maintenance/pavement management plans. These management plans provide a timeframe through which pavements are sealed on a regularly scheduled basis. Sealing typically is performed on a five-to-seven year schedule, with some districts treating surfaces on a six-to-eight year schedule.

As a particular pavement section approaches this age range, it is submitted for approval and funding. If funding is approved, the section is sealed, typically during the summer months. Existing pavements are prepared by sweeping and crack sealing. In some cases, small localized repairs of the HMA and subbase are made prior to sealing. If the section to be treated is located in an area without curb and gutter, maintenance crews blade vegetation off the edge of the existing HMA.

Once the surface is prepared, asphalt binder is applied at a rate of 0.40 to 0.45 gallons per square yard. The rate of application varies based on the type of binder used and existing surface conditions. The rate is determined by evaluating field conditions, by visual inspections, by calculations using agency recommended equations from the TxDOT Seal Coat and Surface Treatment Manual, and by past experience. Aggregate application rates range from one cubic yard of aggregate per 90 square yards of pavement to one cubic yard of aggregate per 125 square yards of pavement. These application rates also are determined according to aggregate type, calculation using agency recommended equations from the TxDOT Seal Coat and Surface Treatment Manual, inspection, and past experience. Experienced field personnel are a critical part of a successful application.

Seal coats are not used in areas with high turning movements, high traffic volumes or on road sections where significant vehicle acceleration or deceleration occurs. One respondent also indicated that seal coat use is avoided on sections where the structural repairs needed are beyond the scope of a seal coat application. Problems encountered in seal coat applications included flushing and loss of aggregate.

While respondents indicated that seal coats extend the life of the pavement, aging did not appear to be a primary reason for applying the treatment. Seal coats were typically applied to improve skid resistance and to serve as a moisture barrier. It appears that seal coats are most often applied based on a typical timeframe for application.

SUMMARY

Binder oxidation in pavements and its impact on pavement performance has been addressed by numerous laboratory studies of binder oxidation chemistry, reaction kinetics, and hardening and its impact on mixture fatigue. Studies also have included some work on binder oxidation and hardening in pavements and the effectiveness of maintenance treatments. Yet more such studies are needed to better understand the fundamentals of pavement performance as a function of climate and pavement parameters.

CHAPTER 3

EXPERIMENTAL DESIGN

The objective of the experimental design (ED) is to select representative HMA mixtures, corresponding field sections, and laboratory tests and conditions for the project experimental plan. This plan addresses the three objectives and four products of this project, as outlined in the Background Summary.

The three objectives are:

- development and calibration of a laboratory test to assess binder aging during the production process and during the field service of the pavement;
- incorporation of aging for use in a HMA mix design system to produce mixtures that provide adequate resistance to fatigue cracking, including guidelines to optimize resistance of HMA to aging; and
- evaluation of the use of maintenance treatments to reduce the aging of asphalt pavements starting at early ages.

The four products are:

- a new test procedure to characterize binder aging and predict service life for different applications;
- an HMA mix design component that incorporates aging and its effect on resistance to fatigue cracking;
- guidelines for optimizing HMA mixture resistance to aging; and
- guidelines for the best maintenance treatments to reduce the aging of binders.

In order to fulfill these objectives and develop these products, the following three experimental design elements (EDE) have been developed in detail: EDE 1) a selection of field sections from previous and newly constructed projects for calibration and validation of the binder oxidation and hardening model; EDE 2) a subset of newly constructed field sections exposed to different maintenance treatments (including corresponding control sections) for monitoring with respect to effectiveness in reducing aging in the maintenance treatment experiment; and EDE 3) the same larger collection of field sections from EDE 1 and a corresponding subset of laboratory mixed-laboratory compacted (LMLC) specimens for calibration and validation of the mixture aging model contained in the fatigue analysis system and identification and assessment of mixture factors that affect the decline of mixture fatigue resistance due to aging in the aging experiment.

These EDEs are outlined schematically in Figure 3-1. Experimental measurements will be made on binders, laboratory mixtures, and pavement cores. These measurements will be used to better understand binder oxidation processes in pavements and their resulting impact on mixture and pavement fatigue processes. These results will be used to address the three objectives of the project and to develop the four products.

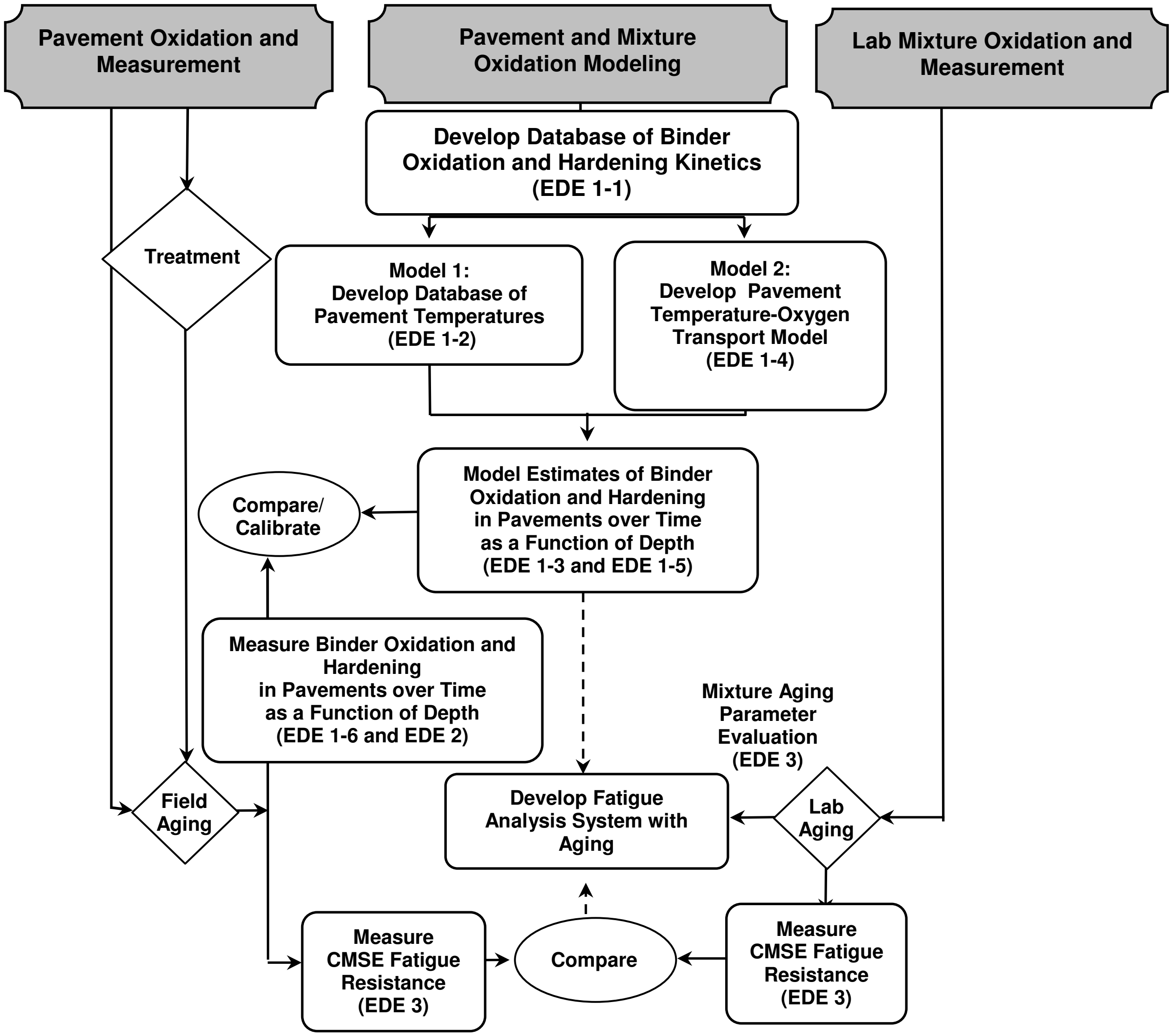

Figure 3-1. Schematic Outline of the Research Plan and Experimental Design Elements.

Figure 3-1 shows three paths of experimental research. Binder oxidative reaction and hardening properties and pavement temperatures will be used in pavement oxidation models and compared to measurements of pavement oxidation (EDE 1). Measurements of pavement oxidation and hardening also will be made on treated pavements (EDE 2). Laboratory mixture measurements will be used to evaluate mixture parameters such as mixture type, air voids, binder content, aggregate type and gradation as to their impact on the decline of fatigue resistance, thereby providing a better fundamental understanding of fatigue resistance in mixtures (EDE 3). Such an understanding is essential to achieving the objectives of developing a laboratory procedure that includes estimating fatigue resistance and predicting service life. Also as part of EDE 3, these mixture measurements will be compared to measurements of fatigue in aged pavements.

The role of model-based estimates of binder oxidation rates in pavements is unique and deserves further comment. The model (initially developed in TxDOT Project 0-4688 and to be further developed in this project) will use fundamental input data: binder oxidation kinetics and hardening susceptibility parameters, pavement temperature cycles (both daily and annual) as a function of time and depth, and oxygen transport in pavements, including diffusion in binder and mastic films. Estimates of binder oxidation and hardening over time, and as a function of pavement depth, in principle, can then be used to estimate pavement performance, specifically changes to fatigue resistance. This work will evaluate and calibrate such an analysis process by conducting parallel measurements of binder oxidative aging and fatigue resistance, obtained from field cores over the five-year term of the project, and comparing them to the model estimates. Laboratory measurements of the effect of binder oxidation on fatigue resistance provide essential information to the modeling process on the importance of various mixture fatigue parameters.

One point bears further emphasis. The combination of 1) developing a transport model of binder oxidation in permeable pavements; and 2) comparing model-calculated oxidation to measured oxidation in pavements is designed to obtain the maximum effect from limited field data. With a sound physical model that is based on fundamental physical laws and laboratory measurements of binder and mixture properties, and then further calibrated with actual field data, much more accurate calibrations of laboratory aging to that in the field can be obtained than from a much larger set of field data used to statistically calibrate field aging to laboratory tests. Basically, a model based in the fundamentals of thermal and oxygen transport is required in order to account for pavement aging that occurs over a range of temperature and with possibly limited oxygen supply. The value of using such a physical model should not be overlooked or underestimated, both from the perspective of obtaining accuracy from a laboratory test and from the perspective of obtaining the most information from the field cores. Such a fundamentals-based approach also will provide a better mix design procedure that includes fatigue resistance of HMA.

In this chapter, the selected field sections and corresponding materials, coring schedule, and specimen fabrication are presented first. Next the three individual EDEs are described in further detail. The chapter concludes with a brief outline of how the data gathered through the EDEs will be used to achieve the three objectives and develop the four products.

FIELD SECTIONS

Nineteen mixtures from eighteen field sections have been identified to span the five different environmental zones in Texas (Tables 3-1, 3-2 and Figure 3-2), and an additional section was identified at MnROAD. These field sections are all dense-graded HMA, and all but six of them are surface mixtures. The Amarillo (AMR) and Atlanta (ATL) sites are now covered with a seal coat and a microseal, respectively. Waco (WAC), Laredo (LRD) 01, and LRD 02 are underlying layers in perpetual pavement sections. Bryan (BRY) is now covered by a course matrix-high binder (CMHB) layer. A range of commonly used TxDOT binders and aggregates are represented (Tables 3-1 and 3-2). Twelve of the field sections are from previous TxDOT projects, and seven of them will be constructed in Texas in the 2008 construction season. Nine new or recently constructed (within the past two years) Texas field sections and the MnROAD test section will be used in both the aging and maintenance treatment experiments as shown in Figure 3-2 (for the Texas sections) and Tables 3-1 and 3-2. A total of twelve field sections have original binder available for development of the laboratory aging test, and three of the new Texas field sections (highlighted in italics in Table 3-1) will be used in the laboratory evaluation of mixture parameters (including binder and AV content) and their effect on decline in mixture fatigue resistance.

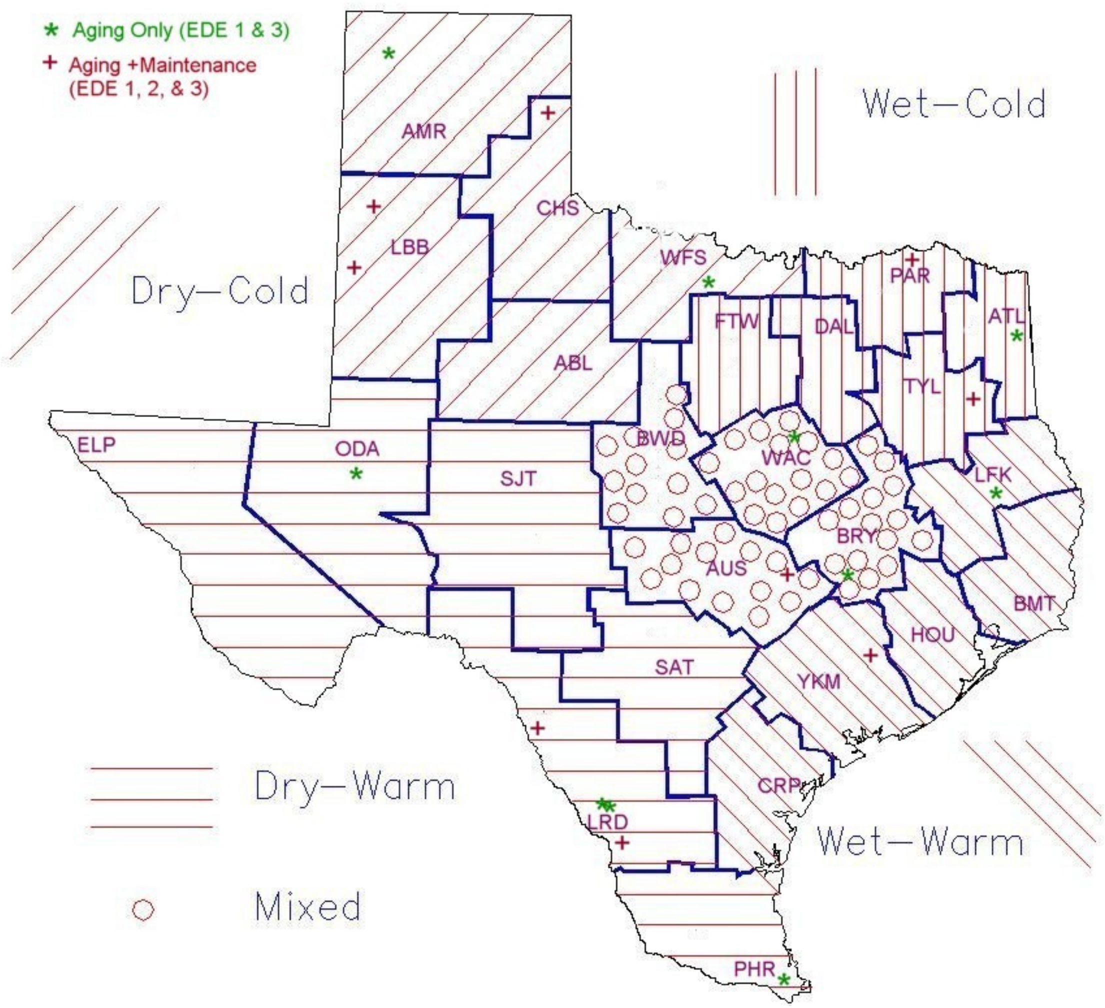

Figure 3-2. Field Section Locations and Texas Environmental Zones.

Table 3-1. Field Sections for the Aging Experiment (EDE 3).

Section ID / District	Location	Environmental Zone	Binder Type (*=original binder)	Aggregate Type	Mix Type (Thickness)	Construction Date
BRY	US 290	WW	PG 64-22	Limestone	Type C (2")	2002
ATL	IH 20	WC	PG 76-22 (SBS)	Sandstone	12.5mm Superpave (2.5")	2001
WAC	IH 35 Layer #5	M	PG 70-22 (SBS)	Igneous/Limestone	19mm Superpave (3.5")	2003
WFS	SH 59	DC	PG 70-22	Limestone	Type D (2")	2007
LRD01	IH 35 Layer #3	DW	*PG 76-22 (SBS)	Traprock/Gravel	25mm SFHMA (6")	2007
LRD02	IH 35 Layer #5	DW	*PG 70-22 (SBS)	Gravel	12.5mm Superpave (2")	2007
LFK	US 69	WW	PG 70-22	Gravel	Type C (2")	2003
LRD03	FM 649	DW	*PG 76-22	Limestone (absorptive)	Type C (2")	2006
LRD04	*US 277*	*DW*	**PG 70-22*	*Limestone*	*Type C (3")*	*2008*
TYL	US 259	WC	*PG 70-22	Sandstone/Limestone	Type C (2")	2007
AUS	SH 21	WW	*PG 70-22	Limestone	Type C (2")	2007
LBB01	US 82	DC	*PG 70-28	Limestone	CMHB-F (3")	2008
LBB02	US 84	DC	*PG 70-28	Gravel/Limestone	CMHB-C (2")	2008
CHS	*US 83*	*DC*	**PG 70-28*	*Granite*	*Type D (2")*	*2008*
YKM	SH 36	WW	*PG 64-22	Limestone (absorptive)	Type D (2")	2006
ODA	FM 1936	DW	PG 70-22 (SBS)	Rhyolite	CMHB-F (3")	2002

Table 3-1. Field Sections for the Aging Experiment (EDE 3). (Continued)

Section ID / District	Location	Environmental Zone	Binder Type (*=original binder)	Aggregate Type	Mix Type (Thickness)	Construction Date
PHR	FM 2994	DW	PG 70-22 (SBS)	River Gravel	Type D (3")	2002
AMR	US 54	DC	PG 70-28	River Gravel	(2")	1998
PAR	*SH 24*	*WC*	**PG 64-22*	*Sandstone*	*Type D (2")*	*2008*
MN	MnRD	NA	*TBD	TBD	TBD	2008

Table 3-2. Field Sections for Maintenance Treatment Experiment (EDE 2).

Section ID / District	Location	Environmental Zone	Seal Coat Binder Type	Seal Coat Aggregate Type
LRD03	FM 649	DW	PASS	Gr. 4 Precoated LRA
LRD04	US 277	DW	AC 15-P	Gr. 4 Precoated LRA
TYL	US 259	WC	AC-20-5TR	TBD
AUS	SH 21	WW	TBD	TBD
LBB01	US 82	DC	AC-15-P or AC 15-5TR	Gr. 4 Precoated limestone
LBB02	US 84	DC	AC-15-P or AC 15-5TR	Gr. 4 Precoated limestone
CHS	US 83	DC	AC-15-5P	TBD
YKM	SH 36	WW	CRS-2P	Pre-coated limestone
PAR	SH 24	WC	AC 20-XP	Gr. 4 Precoated Sandstone
MN	MnRD	NA	TBD	TBD

Five coring dates for new field sections and three coring dates for previous field sections are planned. For the new field sections constructed in the FY08 construction season, cores will be procured at the time of construction or soon after construction and in the next four fall (or fall/winter) seasons after each summer of aging. Additional cores for these new field sections will only be taken at three coring dates for mixture testing (Summer 2008, Fall 2009, and Fall

2011). For previously placed field sections, cores will be procured at these same three coring dates (Summer 2008, Fall 2009, and Fall 2011). For this project, at each coring date cores will be taken both on the shoulder, where only aging will have affected the HMA mixture, and in the wheelpath, where the simultaneous effects of traffic and aging will have affected the HMA mixture properties. Figure 3-3 shows a typical coring layout. Presumably there will be a difference in air voids between specimens obtained from shoulder and wheelpath. Thus to validate the binder oxidation and hardening model, binders will be extracted from cores of field sections every year for new field sections and every other year for previously placed field sections. To calibrate and validate the mixture aging model contained in the fatigue analysis system, mixture tests of cores from field sections will be conducted every other year for both new field sections and previous sections. This coring schedule will provide a significant amount of data to calibrate and validate both the binder oxidation and hardening model and the mixture aging model within the fatigue analysis system. As previously discussed, this project will capitalize on the reduced data required for calibration and validation of theoretical models instead of using statistically-based empirical models with limited application.

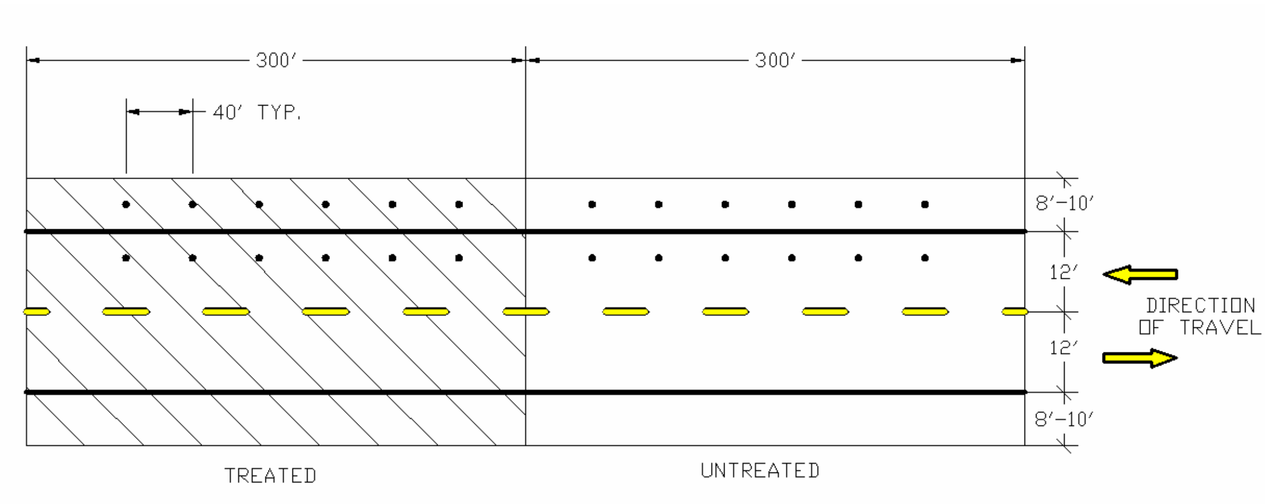

Figure 3-3. Typical Test Section and Coring Layout.

EDE 1. BINDER OXIDATION AND HARDENING

As noted previously, early work supports several observations and conclusions concerning binder aging in pavements and the development of binder aging tests.

- First an aging test, conducted at a single temperature, is not sufficient to rank binder oxidative aging rates in pavements. Based upon the simple, but surprisingly accurate, temperature pavement oxidation model, it was seen for a variety of binders that their rankings of hardening rate at 60 °C in an environmental room (ER) do not necessarily match the rankings that are expected to occur in pavements.
- Second, knowing only binder aging rates in pavements is not sufficient for predicting pavement performance and durability. There are many other factors that are important to pavement performance besides binder oxidation and hardening, including the overall pavement structure (stiffness), loading level and frequency, and loading mode (controlled

strain versus controlled stress, e.g., established largely by asphalt concrete layer stiffness relative to the overall pavement system stiffness).

- Third, there is significant support for the conclusion that if air voids (and interconnected air voids in particular) are high, then binder oxidation rates in pavements are largely determined by pavement temperatures and their variation over time (daily and annual thermal cycles).
- Fourth, if air voids (and especially interconnected air voids) are sufficiently low (probably less than about 2 percent interconnected air voids), then oxidation rates are slowed significantly by oxygen transport in the pavement.

These conclusions support the notion that measuring laboratory oxidation and hardening rates and converting these measurements directly to field hardening rates through a simple calibration is a highly problematic concept. To address these difficulties, several binder aging sub-elements, EDE 1-1 through EDE 1-6, are described below. EDE 1-1 through EDE 1-6, taken together, focus on developing an improved model of binder oxidation and hardening in pavements that would then be used to estimate hardening rates. Such an approach ultimately will be less costly and much more reliable than pavement rate predictions based upon "calibrations" of laboratory measurements for the reasons cited previously. Collectively, these EDEs include but go well beyond those suggested by the project statement.

Then, in spite of the difficulties mentioned above with a simple binder test, and in addition to the planned model-based approach, an alternate method for assessing binder aging rates in the laboratory is described in EDE 1-7 (not shown in Figure 3-1).

EDE 1-1. Database of Binder Oxidation and Hardening Kinetics Parameters

Understanding basic binder oxidation reaction kinetics is key to developing a pavement binder oxidation rate model. Different binders have different activation energies and different initial jump characteristics. As a result, different binders exposed to the same oxidation conditions (temperature and oxygen pressure) will oxidize at different rates. But even more relevant to pavement oxidation, binders that react at different rates at one temperature (60 ^{o}C, for example) may well experience relative rate reversals in service in the pavement due to the range of temperatures that the binders experience over time and the binders' differences in activation energies.

Because the selection of binders that are purchased by TxDOT changes over time, assessing binder properties for use in a pavement oxidation model will be an ongoing effort. However, developing an initial database of binders currently used by TxDOT on a region or district basis, and then adding over time to this database, will allow TxDOT engineers to be able to make reasonable estimates of binder durability in pavements, provided that a good model of oxidation can be developed. Table 3-3 lists 24 binders for study, binders that are those most used by TxDOT, plus ones that are used in the planned field studies (EDE 3). The list also includes a mix of unmodified base binders plus modified grades.

Table 3-3. Binders Selected for TxDOT Project 0-6009.

Manufactures	Binder Types
Alon	PG 64-22 PG 70-22S PG 76-22S
Lion	PG 64-22 PG 70-22S PG 76-22S
Valero-Ardmore	PG 64-22 PG 70-22S PG 76-22S
Valero-CC	PG 64-22 PG 70-22S PG 76-22S
Valero-Houston	PG 64-22 PG 70-22S PG 76-22S
SEM (Koch)	PG 64-22 PG 70-22S PG 76-22S PG 70-28S
Martin	PG 64-22 PG 70-22S
Eagle	PG 64-22 PG 70-22S
Wright	PG 76-22S

Oxidation (carbonyl area) and rheology (low shear rate viscosity and DSR function) of both unaged binders and binders aged at different levels at 0.2 atm oxygen pressure will be tested to measure binder oxidation and hardening kinetics. These data will include both fast-rate and constant-rate period measurements for each binder. Because more temperatures will increase confidence in the measured reaction activation energies, reaction rates will be measured at five temperatures (140, 160, 180, 200 and 210 ^{o}F). At each temperature, oxidation rates will be determined with measurements for at least nine time points, four earlier time points in the fast reaction rate period and at least five time points in the constant-rate period. Approximate times, based on previous binder aging data, are given in the following table.

Aging Temperature	Fast Rate Period Aging Time (days)	Constant Rate Period Aging Time (days)
200 and 210 ^{o}F	1, 2, 4, 6	10, 15, 20, 25, 30
160 and 180 ^{o}F	1, 3, 5, 7	10, 20, 30, 40, 50, 60
140 ^{o}F	1, 5, 10, 15	20, 30, 45, 60, 75, 90

Five pressure oxidation vessels with controllable oxygen pressure and temperature will be used to age binders in thin films. Both modified and unmodified binder oxidation and hardening kinetics in both the fast-rate and constant-rate periods will be determined, and the effect of polymer modification on binder oxidation kinetics will be evaluated.

EDE 1-2. Database of Pavement Temperatures across Texas

Pavement temperatures vary with time (by day, by weather, and by season) and with depth (distance away from the boundary condition established by these temporal variations). Accurate model calculations of binder oxidation will require accurate representations of pavement temperatures. Generally as noted in Chapter 2, these variations are reasonably well represented by a daily sinusoidal function superimposed on an annual seasonal sinusoidal function. Because climate varies across Texas due to cloud cover, moisture, and latitude, these temperature variations will be different in the different climate zones of Texas. This EDE will gather available recorded temperature histories in pavements and versus depth (from the LTPP program, e.g.) throughout Texas and from them establish the temperature model parameters (Equation 2-8) for representative locations in Texas. These parameters include the mean pavement temperature including its seasonal variation, the amplitude of the daily and annual temperature variations, and pavement thermal diffusivity. (As an example, from TxDOT Project 0-4688 the amplitude at Refugio, Texas during the summer, Figure 3-4, was 22 °C and in Minneapolis, Minnesota, the summertime amplitude was 20 °C.)

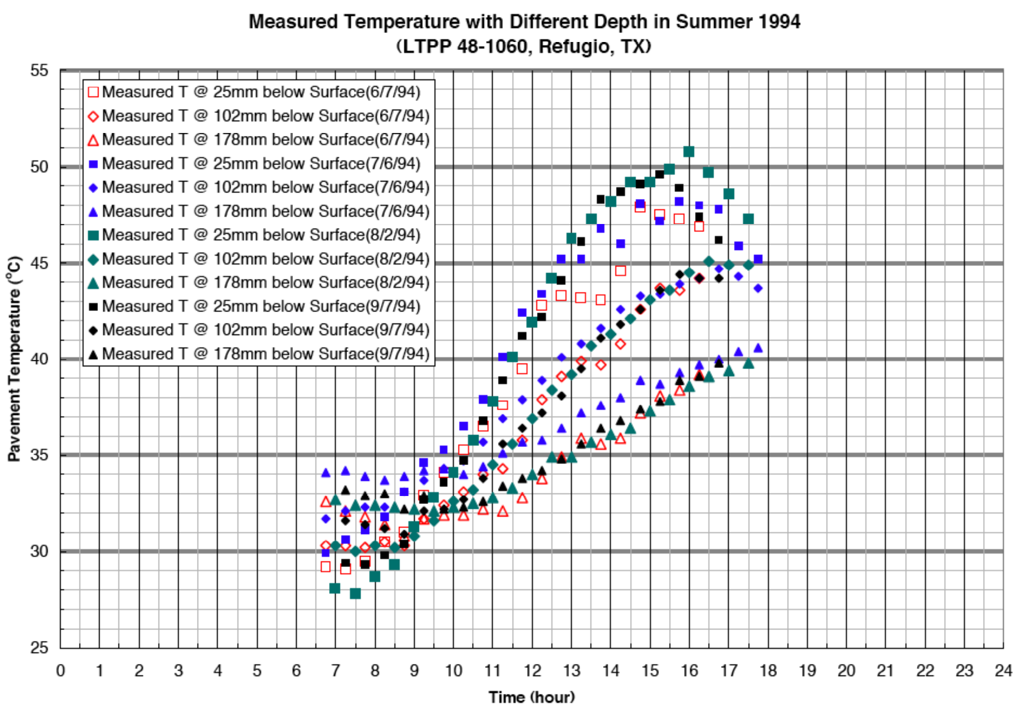

Figure 3-4. Daily Pavement Temperature Variation, July 1994, Refugio, Texas.

As an alternative to pavement temperature data, improved models will be used to calculate temperatures. As noted the EICM model of the MEPDG probably is not satisfactory, so the models of Hermansson et al. (2000, 2004) and Gui et al. (2007), with further improvements made from this research, will be used. The calculated profiles will be compared to the archived LTPP profiles to assess its ability to provide adequate temperature histories as a function of depth.

EDE 1-3. Pavement Oxidation and Hardening Rates (Thermal Transport Model)

This EDE sub-element will use the results of EDE 1-1 and EDE 1-2 and the heat conduction model outlined in the background section of this proposal to estimate typical binder hardening rates in a variety of climates across Texas and for a variety of binders. These model-based estimates will then serve as a look-up catalog for pavement designers to estimate pavement oxidative hardening over time in specific regions and climates of Texas. Again, these estimates will assume that oxygen transport to the binder is plentiful so that only temperature and binder properties determine the binder hardening rates in the pavement. (Extensive pavement and laboratory mixture data from TxDOT Projects 0-1872, 0-4468, and 0-4688 provide no indication that aggregates affect either the fundamental oxidation chemistry or the reaction kinetics of binders in pavements. Therefore, aggregate will be neglected as a factor in this model.)

EDE 1-4. Improved Model of Pavement Oxidation and Hardening Rates

It is clear from pavement binder oxidation data of TxDOT Projects 0-4688 and 0-5091 that oxygen transport limitations sometimes are important in establishing binder hardening rates in pavements. If the interconnected (or accessible) air voids are sufficiently low, then delivery of oxygen to the binder is hindered. In this EDE sub-element, an improved model of binder oxidation in pavements that includes oxygen transport will be developed.

Model development will begin with the model proposed by Lunsford (1996). He approximated the diffusion from an oxygen source (air in the pores in the pavement) through a flat film of binder. A parameter of the model was the binder film thickness and the greater this thickness, the greater the effect of the diffusion limitation. Lunsford also made very approximate measurements of the diffusivity of oxygen in binders with ad hoc experiments that were designed primarily for measuring oxidation kinetics. The statistical error in the diffusivity measurements was appreciable, however. Lunsford concluded that film thickness can have a major impact on binder oxidation rates. His model will be further explored in this EDE sub-element.

The concept of approximating the binder film in the pavement as a thin film is probably reasonable for high air voids content where there are a large number of pores passing through the pavement so that the distance from any pore to the binder, even to the farthest binder away, is not very great. A more realistic model for a reduced number of air voids might be a cylindrical model that assumes that the oxygen diffuses from the pore in a radial direction into a cylindrical shell of binder. In this case, the relevant parameter would be the thickness of this cylindrical shell relative to the diameter of the pore containing the air. The smaller the air voids, the greater the ratio of this binder shell to the pore diameter and thus the more time required for oxygen to diffuse through the binder.

For either model, improved values for the diffusivity of oxygen in the binders will be needed. These diffusivities will need to be measured as a function of binder stiffness, which means they would have to be measured as a function of binder temperature and state of oxidation.

A further hindrance of oxygen diffusion into the binder would be the presence of mineral fines that are impervious to diffusion. Such fines would impede the diffusion of oxygen into the binder and would require that oxygen molecules take a more tortuous path through the binder, thus lengthening the diffusion path and thereby effectively reducing the oxygen diffusivity. Measurements of the diffusivity of oxygen in mastics will be needed in order to quantify this effect.

So, diffusivities in both neat binders and mastics will be measured following the procedure of Lunsford. Films of defined binder (or mastic) thickness will be placed onto aluminum trays and oxidized in a controlled temperature and oxygen environment. The carbonyl growth rate that occurs at the surface exposed to oxygen will be compared to the rate at the interface of the binder (or mastic) film with the tray. The only way oxygen reaches that interface is by diffusion through the film. Thus the carbonyl growth rate at that interface, relative to the growth rate at the air surface, will allow the diffusivity to be measured by matching the growth rate to a reaction and diffusion transport model.

With values of the diffusivities of oxygen in binders and mastics, measured binder oxidation rates in pavements may then be used to measure effective film thicknesses according to either the flat film diffusion model or the cylindrical diffusion model and thereby calibrating the diffusion model.

EDE 1-5. Pavement Oxidation and Hardening Rates (Thermal and Oxygen Transport Model)

This EDE sub-element will use the results of EDE 1-1 and EDE 1-2 and the thermal and oxygen transport model of EDE 1-4 to estimate typical binder hardening rates in a variety of climates across Texas and for a variety of binders and different levels of air voids (total and interconnected) and mixture/pavement types. These model-based estimates will then serve as a look-up catalog for pavement designers to estimate pavement oxidative hardening over time in specific regions and climates of Texas. Alternatively, a spreadsheet or other computational approach may be used to calculate results for a specific situation, given appropriate model parameters and material and pavement properties.

EDE 1-6. Field Binder Aging Rates for Calibration of the Transport Model

This project offers a unique opportunity to monitor a significant number of pavements over enough time to accurately determine binder hardening rates in pavements and to evaluate the effect of air voids and depth in the pavement on these rates. As described in the EDE sub-elements above, the best approach to including the impact of the large number of variables that affect binder pavement aging is with fundamentals-based models, and that is the approach taken in this experimental plan.

However, fundamental principles are not sufficient, and key to calibration and verification of the pavement aging models discussed in EDE 1-3 and EDE 1-4 will be measurements of binder aging in the field. Cores obtained from field sections (Figure 3-2) during the course of this project will be analyzed for air voids (either by the CoreLok® or the saturated surface dry methods-SSD), interconnected air voids (by X-ray CT) or accessible air voids (by CoreLok and SSD) and then the binder extracted and recovered using methodologies developed by the researchers (Burr et al., 1990; Burr et al., 1991; Cipione et al., 1991; Burr et al., 1993; Burr et al., 1994). The recovered binder will then be analyzed for oxidation by infrared spectroscopy and for physical properties by dynamic shear rheometry (DSR) to provide the key data: binder aging and hardening rates in pavements.

EDE 1-7. Laboratory Binder Aging Test

EDE 1-1 through EDE 1-6 address a fundamental, model-based effort to calculate binder aging rates in pavements. Such a procedure will require a detailed binder reaction kinetics database that will be time consuming to update on a routine basis. As an alternative approach, more rapid binder aging to a level that is representative of long-term pavement service will be assessed. One candidate method is to use the TxDOT stirred air flow test (SAFT) apparatus. This method has recently been evaluated for long-term binder aging in NCHRP Project 9-36. The final recommendations from this project are just now being finalized. These findings and recommendations will be reviewed and the SAFT apparatus evaluated for use for comparing binder aging rates and to screen for binders that oxidize and harden too quickly. Other approaches also will be explored.

EDE 2. MAINTENANCE TREATMENT EFFECTIVENESS IN REDUCING AGING

The essential issue of this EDE is to assess the effectiveness of maintenance treatments in reducing aging. Figure 3-2 and Table 3-2 describe the location and materials in the selected field sections for the maintenance treatment experiment. Based on the results of this experiment, recommendations on the optimal treatment and associated HMA mixture parameters and environmental conditions will be produced in a set of guidelines.

Two questions arise with respect to the effectiveness of maintenance treatments in reducing aging:

1) How well do the treatments penetrate into the pavement? and
2) How well do they retard the in situ binder's aging?

Extraction and recovery of binder and measurement of its properties (DSR, Fourier transform infrared spectroscopy, size exclusion chromatography) may be able to address the first question (and such analyses will be conducted), especially if pavement cores are sawn into a number of slices and the recovered binder analyzed. Also, X-ray computed tomography (CT) may be able to detect penetration of the maintenance treatment binder into the underlying pavement layer. These analyses will be done also.

However, neither extraction and recovery nor X-Ray CT alone can address the effect of the treatment on *mixture* properties. Thus, this EDE will require using mixture physical property tests, in addition to binder tests, to evaluate whether the maintenance treatments affect the rate at which oxidative aging changes the mixture properties. Therefore, a modified version of the fundamental calibrated mechanistic with surface energy (CMSE) mixture fatigue analysis approach will be used as the primary method to measure the mixture properties of treated and corresponding untreated pavement sections. Modifications include the following:

- testing of prismatic specimens cut parallel to the road surface from pavement cores and tested on end (Figure 3-4);
- separation of the different mechanisms of energy dissipation during fatigue cracking, including the effects of apparent stiffness and phase angle changes and plastic deformation;
- measurement of Poisson's ratio during the relaxation modulus (RM) test;
- expansion of the healing assessment during the repeated direct tension (RDT) test; and
- expansion of the aging assessment beyond an aging shift factor.

Work on these modifications continues beyond the scope of the work reported in this research report.

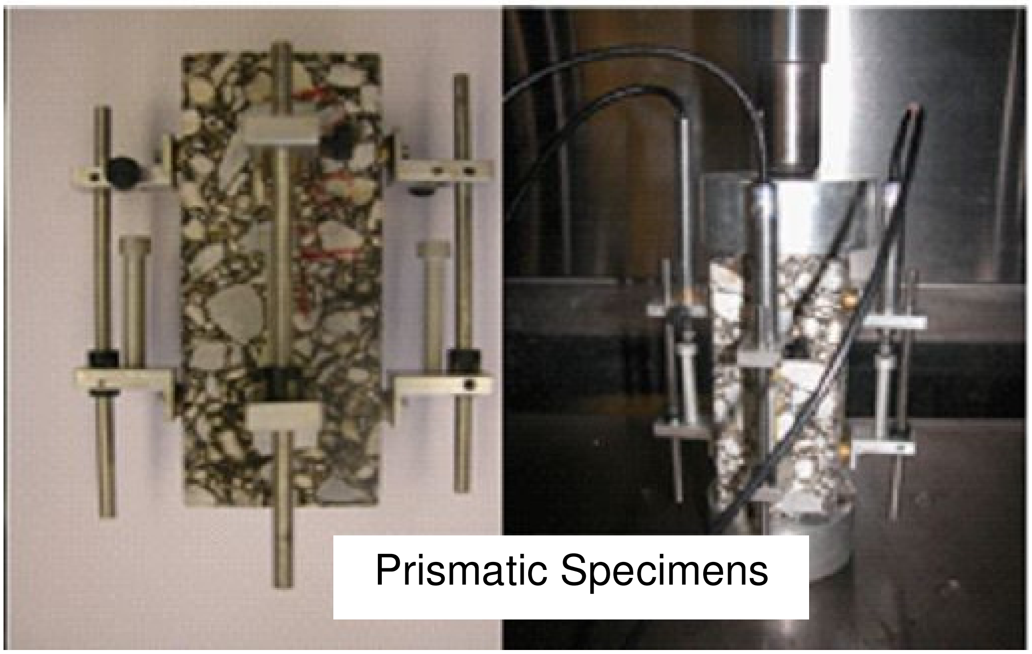

Figure 3-5. Testing of Prismatic Specimens in Direct Tension for CMSE.

EDE 3. DECLINE OF MIXTURE FATIGUE RESISTANCE DUE TO AGING

Figure 3-2 and Table 3-1 describe the location and materials in the selected field sections for the aging experiment that includes mixture testing of field cores taken at construction, after two and four years. Figure 3-5 summarizes the testing of field cores from the selected field sections including extraction, recovery, and testing of the binder for EDE 1.

X-ray CT and image analysis techniques will also be used in the aging experiment to examine the internal microstructure of HMA mixtures, including air void (AV) distribution and interconnectivity and binder content and distribution in terms of film thickness. These factors are some of the HMA mixture parameters to be identified in terms of the role they play in the aging mechanism. CoreLok will be used to determine total air voids as a necessary calibration for the X-ray CT method. Accessible AV and interconnected AV as determined using CoreLok and X-ray CT, respectively, will also be determined as an important parameter related to aging.

The mixture testing will again use a modified version of the fundamental CMSE fatigue analysis approach to further understand aging and its effect on mixture fatigue resistance. Results from this analysis will facilitate quantitative incorporation of aging effects in a practical mix design system that includes the simultaneous effects of traffic, aging, environment, and pavement structure.

An additional experiment using LMLC specimens from a subset of the selected field sections for the aging experiment (Figure 3-2 and Table 3-1) will also be conducted to identify and assess mixture parameters that affect the decline of mixture fatigue resistance due to aging. A modified version of the CMSE fatigue analysis approach will again be used to evaluate the effect of these factors by testing the LMLC specimens. Recommendations on the optimal combinations of the levels of the identified factors or parameters to control aging will be produced in a set of guidelines based on the results of the extensive experiment.

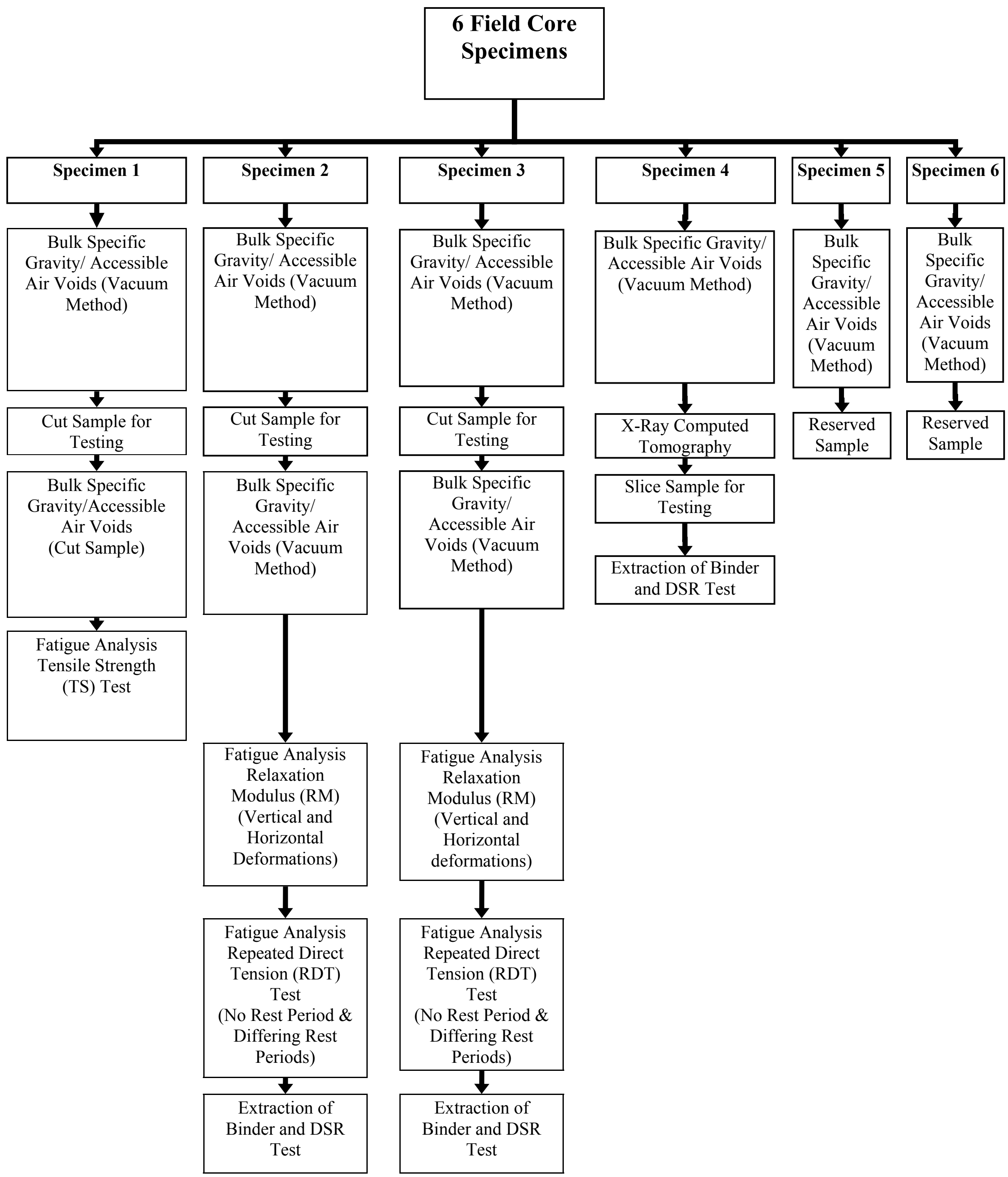

Figure 3-6. Testing Protocol for Pavement Cores.

SUMMARY

The data gathered through the three EDEs described in this chapter will be utilized to achieve the three objectives and develop four products in this project and move closer to being able to use fundamental binder, mixture, and pavement characteristics to predict pavement performance. From an age-related cracking perspective, this would mean being able to predict fatigue cracking and the impact of binder oxidation from a binder oxidation model developed in from the EDE 1-4 data and appropriate pavement and mixture parameters and traffic loading. One essential mixture parameter would be its characteristic fatigue life decline (as defined by CMSE analysis) with binder hardening to be evaluated from data collected in EDE 3. Then the simplest model would be a controlled strain, cumulative damage analysis similar to that performed in TxDOT Project 0-4688. A more complex model would be a controlled stress analysis. The model results of mixture fatigue resistance change over time as the result of binder oxidative hardening will be compared to measurements of field cores for validation.

In addition, two aging shift factors proposed in TxDOT Project 0-4468 will be further explored with the possibility of integrating them into a robust single shift factor to better account for aging effects. In particular, Miner's cumulative damage hypothesis and the effects of cumulative traffic loading will be investigated further and possibly incorporated in the CMSE analysis. Various mix design characteristics including AV structure and distribution will also be evaluated as a function of aging and possibly incorporated in the CMSE analysis models. Additionally, the binder-HMA mixture relationships established in TxDOT Project 0-4468 will be explored as an alternative to predict aging based on binder properties. Based on the materials evaluated in TxDOT Project 0-4468, a HMA mixture visco-elastic function defined as $G'/(\eta'/G')$ correlated linearly with the binder DSR function and this correlation could be a basis for predicting aged HMA mixture properties in this project.

CHAPTER 4

SUMMARY

BACKGROUND

Binder oxidation in pavements and its impact on pavement performance has been addressed by numerous laboratory studies of binder oxidation chemistry, reaction kinetics, and hardening and its impact on mixture fatigue. As binders oxidize, they form more polar compounds that tend to associate with each other and increase the amount of asphaltenes. These asphaltenes behave, rheologically, like solids in asphalts and contribute greatly to increased binder stiffness and viscosity. The reaction kinetics of this process in the laboratory consists of an early-time, fast-rate period that transitions to a slower, constant-rate period (at constant temperature). Binder reaction and hardening rates in pavements depend upon temperature (in an Arrhenius form, i.e., is exponential in inverse absolute temperature) as a function of depth and time in the pavement, plus the availability of oxygen to the binder. For the constant-rate period, reaction kinetics constants are reported in the literature for a number of binders, as are their hardening susceptibilities (amount of hardening in response to a given amount of oxidation, as represented by carbonyl growth). Data for the fast-rate period are much less available, but the general form of this reaction period has been reported.

The impact of binder oxidative hardening on mixture performance also has been reported. The decline of mixture fatigue resistance under controlled-strain conditions is an important phenomenon that varies from mixture to mixture, a result that is not recognized in current mixture design strategies. Unknown, however, are the quantitative contributions of each of the various mixture parameters (air voids, binder content, binder composition, aggregate type, aggregate gradation) to the differences in decline of mixture fatigue life with binder oxidation. Quantitative assessment of these differences is essential. Also, assessing pavement durability as it is influenced by binder oxidation and traffic loading, and in light of laboratory conclusions on the effect of binder aging on mixture fatigue resistance, has not been assessed and will require monitoring pavement fatigue resistance over time.

The extent of binder oxidation in pavements is another critical issue. Binders will oxidize to the extent temperature and oxygen transport to the binder support oxidation. Recent literature reports provide significant data that binders may oxidize in pavements below the top inch, contrary to assumptions coded into the MEPDG. These experimental field results remain to be adequately described by a theoretical model that can be included in an improved design tool. Such a model will require both accurate temperature and oxygen transport characterization. Recent advances in modeling pavement temperature as a function of time and depth, reported in the literature and improved upon in the early stages of this work, have resulted in quite good agreement to experimental measurements to the point that this effort is not the limiting factor in accurate prediction of binder oxidation in pavements. Key to this effort has been to use an unsteady-state heat flux condition at the pavement surface, together with improved databases and methods for calculating the surface fluxes, and an improved boundary condition three meters below the surface. Modeling oxygen transport in pavements is a much more complex and difficult issue and is an ongoing effort of this project. A model has been developed, but key to improving predictive ability is to understand better the porous nature and structure of compacted mixtures.

Maintenance treatments applied to the surface of a pavement, typically as a chip seal treatment, may conceivably penetrate into the pores of a pavement to reduce binder oxidation or to be absorbed by the in situ binder and therefore result in a softening of a hardened pavement. Whether such penetration and absorption occurs has not been well documented, if at all, and it remains a very real question as to whether maintenance treatments can play such a role in improving the durability and longevity of pavements. The issue is two-fold: 1) whether the maintenance treatments penetrate into the pavement (and how deep); and 2) whether once the binder penetrates into the pavement it then can reduce the aging of binders.

Surveys of TxDOT practitioners, conducted in a previous TxDOT project, as well as this one, provided a wealth of information with respect to past practices associated with seal coats in Texas. However, very little information was obtained concerning binder oxidation and aging in pavements or the use of treatments to retard oxidation. In some instances seal coats were used to address oxidation, though this was usually a secondary concern. While other respondents indicated that seal coats extend the life of the pavement, aging did not appear to be a primary reason for applying the treatment. Seal coats were typically applied to improve skid resistance and to serve as a moisture barrier. If seal coat applications are found to significantly reduce aging in HMA pavements, the practices documented from these surveys may help identify some of the mechanisms that contribute to this effect.

EXPERIMENTAL DESIGN

Based on this literature background and practitioner surveys, an experimental design has been developed to meet three objectives:

- to develop and calibrate a laboratory test to assess binder aging during the production process and during the field service of the pavement;
- to incorporate aging for use in a HMA mix design system to produce mixtures that provide adequate resistance to fatigue cracking, including guidelines to optimize resistance of HMA to aging; and
- to evaluate the use of maintenance treatments to reduce the aging of asphalt pavements starting at early ages

and to provide four products:

- a new test procedure to characterize binder aging, and predict service life for different applications;
- an HMA mix design component that incorporates aging and its effect on resistance to fatigue cracking;
- guidelines for optimizing HMA mixture resistance to aging; and
- guidelines for the best maintenance treatments to reduce the aging of binders.

The experimental design includes

- measurements of binder oxidation and hardening at various stages of binder service,
- fundamental studies of binder oxidation and hardening kinetics,
- developing a transport model of binder oxidation in pavements,
- measurements of field oxidation and hardening rates,
- measurements of mixture fatigue decline as a function of binder oxidative hardening in both the field and laboratory, and
- measurements of maintenance treatment effectiveness at retarding binder oxidative hardening.

The experimental design is built around field sites and materials, selected to evaluate binder oxidation in pavements, the effect of oxidation on pavement durability, and the effectiveness of surface treatments to retard oxidation. Nineteen mixtures from eighteen field sections have been identified to span the five different environmental zones in Texas, and an additional section was identified at MnROAD. These field sections are all dense-graded HMA, and all but six of them are surface mixtures. The Amarillo (AMR) and Atlanta (ATL) sites are now covered with a seal coat and a microseal, respectively. Waco (WAC), Laredo (LRD) 01, and LRD 02 are underlying layers in perpetual pavement sections. Bryan (BRY) is now covered by a course matrix-high binder (CMHB) layer. A range of commonly used TxDOT binders and aggregates are represented. Twelve of the field sections are from previous TxDOT projects, and seven of them will be constructed in Texas in the 2008 construction season. Nine new or recently constructed (within the past two years) Texas field sections and the MnROAD test section will be used in both the aging and maintenance treatment experiments as. A total of twelve field sections have original binder available for development of the laboratory aging test. Three of the new Texas field sections will be used in the laboratory evaluation of mixture parameters (including binder and AV content) and their effect on decline in mixture fatigue resistance.

Five coring dates for the new field sections and three coring dates for the previously placed field sections are planned. For the new field sections constructed in the FY08 construction season, cores will be procured at the time of construction or soon thereafter and in the next four fall (or fall/winter) seasons after each summer of aging. Additional cores for these new field sections will only be taken at three coring dates for mixture testing (Summer 2008, Fall 2009, and Fall 2011). For previously placed field sections, cores will be procured at these same three coring dates (Summer 2008, Fall 2009, and Fall 2011). For this project at each coring date, cores will be taken both on the shoulder, where only aging will have affected the HMA mixture, and in the wheelpath where the simultaneous effects of traffic and aging will have affected the HMA mixture properties. Presumably there will be a difference in air voids between specimens obtained from shoulder versus those in the wheelpath.

To validate the binder oxidation and hardening model, binders will be extracted from cores of field sections every year for new field sections and every other year for previously placed field sections. To calibrate and validate the mixture aging model contained in the fatigue analysis system, mixture tests of cores from field sections will be conducted every other year for both new field sections and previous sections. This coring schedule will provide a significant amount of data to calibrate and validate both the binder oxidation and hardening model and the mixture aging model within the fatigue analysis system. An important element of this design is that this project will capitalize on the reduced data required for calibration and validation of theoretical models instead of using statistically-based empirical models with limited application.

The data gathered in conducting this experimental design will move engineers closer to being able to use fundamental binder, mixture, and pavement characteristics to predict pavement durability using a fatigue analysis system with aging. From an age-related cracking perspective, this would mean being able to predict pavement binder oxidation and the impact of this oxidation on fatigue cracking in terms of appropriate pavement and mixture parameters and traffic loading. One essential mixture parameter would be its characteristic fatigue life decline (as defined by CMSE analysis) that occurs due to binder hardening. The simplest model would be a controlled strain, cumulative damage analysis similar to that performed in TxDOT Project 0-4688. A more complex model would be a controlled stress analysis. The model results of mixture fatigue resistance change over time as the result of binder oxidative hardening will be compared to measurements of field cores for validation.

In addition, two aging shift factors proposed in TxDOT Project 0-4468 will be further explored with the possibility of integrating them into a robust single shift factor to better account for aging effects. In particular, Miner's cumulative damage hypothesis and the effects of cumulative traffic loading will be investigated further and possibly incorporated in the CMSE analysis. Various mix design characteristics including air voids structure and pore size distribution will also be evaluated as a function of aging and possibly incorporated in the CMSE analysis models. Additionally, the binder-HMA mixture relationships established in TxDOT Project 0-4468 will be explored as an alternative to predict aging based on binder properties. Based on the materials evaluated in TxDOT Project 0-4468, a HMA mixture viscoelastic function defined as $G'/(\eta'/G')$ correlated linearly with the binder DSR function and this correlation could be a basis for predicting aged HMA mixture properties.

In addition to mixture and pavement studies, basic binder oxidation reaction kinetics key to developing a pavement binder oxidation rate model will be evaluated. Different binders have different activation energies and different initial jump characteristics. As a result, different binders exposed to the same oxidation conditions (temperature and oxygen pressure) will oxidize at different rates. But even more relevant to pavement oxidation, binders that react at different rates at one temperature (60 ^{o}C, for example) may well experience relative rate reversals in service in the pavement, due to the range of temperatures that the binders experience over time, and the binders' differences in activation energies.

Because the selection of binders that are purchased by TxDOT changes over time, assessing binder properties for use in a pavement oxidation model will be an ongoing effort. However, developing an initial database of binders currently used by TxDOT on a region or district basis, and then adding over time to this database, will allow TxDOT engineers to be able to make reasonable estimates of binder durability in pavements, provided that a good model of oxidation can be developed. Twenty-four binders have been selected for study, binders that are those most used by TxDOT, plus ones that are used in the planned field studies. The binders include both unmodified base binders plus modified grades.

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