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DETERMINE BINDER AND HMA/WMA AGING RATES AND THEIR EFFECTS ON MIXTURE/PAVEMENT CRACKING RESISTANCE

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16. Abstract

Asphalt aging is a complex process that derives from permanent compositional changes in the asphalt binder which result from its interaction with the atmosphere under prevailing environmental conditions. Hence, both constructed pavement properties and local environmental conditions determine the evolution of aging with time. The properties of asphalt binder change as it ages, leading to hardening of the asphalt pavement. These changes are believed to be a major contributor to pavement failure by cracking. Understanding the factors that drive binder aging and their impact on pavement performance, within the context of local climatic conditions and mix design methods, is important to assess current state practices and to guide the development of improved specifications for binder and aggregate selection. The broad objective of this research project is to develop an understanding of asphalt binder aging mechanisms. Isolating the most influential variables involved and analyzing the aging process within the context of geospatial conditions relevant to the State of New Mexico i.e., climate, typical materials, and construction practices.

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PREFACE

The broad objective of this research project is to develop an understanding of asphalt binder aging mechanisms. Isolating the most influential variables involved and analyzing the aging process within the context of geospatial conditions relevant to the State of New Mexico i.e., climate, typical materials, and construction practices. This work will serve as the basis for preliminary identification of aging mitigation treatments suitable for implementation within the state.

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ABSTRACT

Asphalt aging is a complex process that derives from permanent compositional changes in the asphalt binder which result from its interaction with the atmosphere under prevailing environmental conditions. Hence, both constructed pavement properties and local environmental conditions determine the evolution of aging with time. The properties of asphalt binder change as it ages, leading to hardening of the asphalt pavement. These changes are believed to be a major contributor to pavement failure by cracking. Understanding the factors that drive binder aging and their impact on pavement performance, within the context of local climatic conditions and mix design methods, is important to assess current state practices and to guide the development of improved specifications for binder and aggregate selection. The broad objective of this research project is to develop an understanding of asphalt binder aging mechanisms. Isolating the most influential variables involved and analyzing the aging process within the context of geospatial conditions relevant to the State of New Mexico i.e., climate, typical materials, and construction practices.

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1. INTRODUCTION

Asphalt pavement is one of the major infrastructure assets of the country. Billions of dollars are spent yearly to maintain asphalt pavements and to control distresses associated to aging. Asphalt aging is a complex process that derives from permanent compositional changes in the asphalt binder which result from its interaction with the atmosphere under prevailing environmental conditions. Hence, both constructed pavement properties and local geospatial conditions determine the evolution of aging with time. In this report, the primary binder aging mechanisms are outlined and their implications on pavement performance are explored.

1.1 BACKGROUND

Upon aging, the composition and properties of asphalt binder change, leading to hardening of the aged asphalt pavement. These changes are believed to be a major contributor to pavement failure by cracking. NMDOT adopted Superpave mix design in 2000. Since the Superpave method promotes the use of gap graded aggregates in both Hot Mix Asphalt (HMA) and Warm Mix Asphalt (WMA), interconnected air voids are commonly left within the material. The presence of void space opened to atmospheric oxygen along with the fluctuations in temperature typical of the state could lead to accelerated aging. Understanding the factors that drive binder aging and their impact on pavement performance, within the context of local climatic conditions and mix design methods, is important to assess current practices and to guide the development of improved specifications for binder selection. Ultimately, understanding the extent and impact of binder aging will allow for the pre-selection of “the best suited” binder for a particular project, leading to better performing and longer lasting pavements.

1.2 CONTEXT

1.2.1 New Mexico Climate

Climatic factors govern the initial selection of asphalt binder (i.e., Superpave), the mechanical performance of a flexible pavement in service, and the change of its performance over time (i.e., aging). Seasonal precipitation and temperature changes have an effect as significant as that of the traffic loads the pavement is design to satisfy (1). Asphalt binder aging causes changes in material properties which alter the performance of the asphalt pavement (see Section 2). The magnitude of the changes after a given period of time depends primarily on the extent and rate of aging. The pavement temperature is one of the primary variables that control aging (see Section 2). Hence, knowledge of record and average temperatures throughout the state is instrumental in identifying areas prone to accelerated aging.

New Mexico, the fifth largest state in the union, spans 121,412 square miles, most of which lies between latitudes 32° and 37° and longitudes 103° and 109° W, see figure 1. The average elevation in the state is 4,700 feet (max 13,161 ft; min 2,870 ft). Most of the state is characterized by a mild, arid or semi-arid continental climate, with the exception of high mountains which exhibit a climate common to the Rocky Mountains (2). The state climate is divided into eight zones based on topographic features: (1) the northwestern plateau, (2) the northern mountains, (3) the northeastern plateau, (4) the southwestern mountains, (5) the central valley, (6) the central highlands, (7) the southeastern plains, and (8) the southern desert (3), see figure 1.

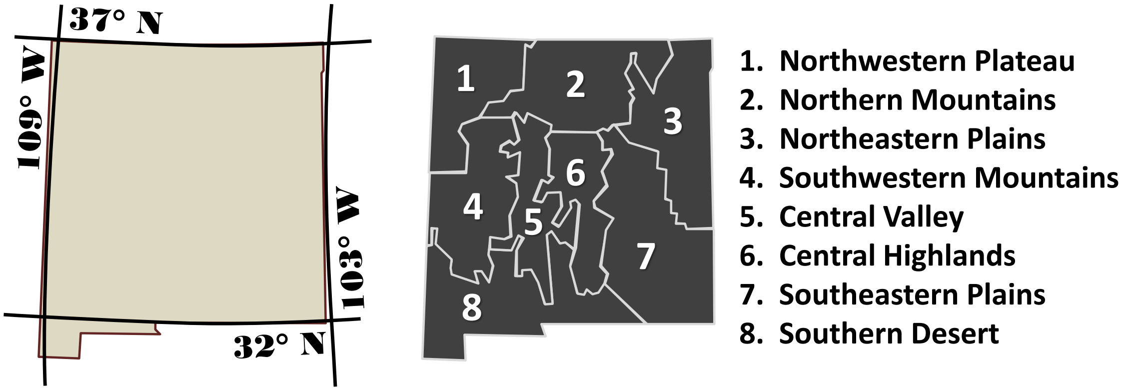


Figure 1. Geographic location and climate units within the state of New Mexico (4).

Mean annual temperatures across the state range from 64 °F (climate unit 7) to 40 °F or lower in the northern mountains (climate unit 2). Within the state, elevation is more important than latitude in determining temperature. While the difference in mean annual temperature between two locations at the same elevation, one in the extreme southwest and one in the extreme northeast, is merely 3 °F, the change between two points 15 miles apart with a difference in elevation of 4,700 feet is 16 °F (2). During the summer months daytime temperatures often exceed 100 °F at elevations below 5,000 ft (climate zone 8). The highest temperature in record is 116 °F (Orogrande 7/14/1934; Artesia 6/29/1918). The coldest month is January with average daily temperatures in the 50's at lower elevations and in the 30's at higher elevations. The record low is -50 °F (Gavilan 2/1/1951). The average range in daily temperature is 25 to 35°F. Figure 2 shows the mean monthly temperature in the different climate zones between May 2011 and March 2013. Zones 3, 5, 8, and 7 exhibit the highest mean monthly temperatures during the summer season whereas zones 1, 2, 4, and 6 exhibit the lowest mean monthly temperatures during the winter season.

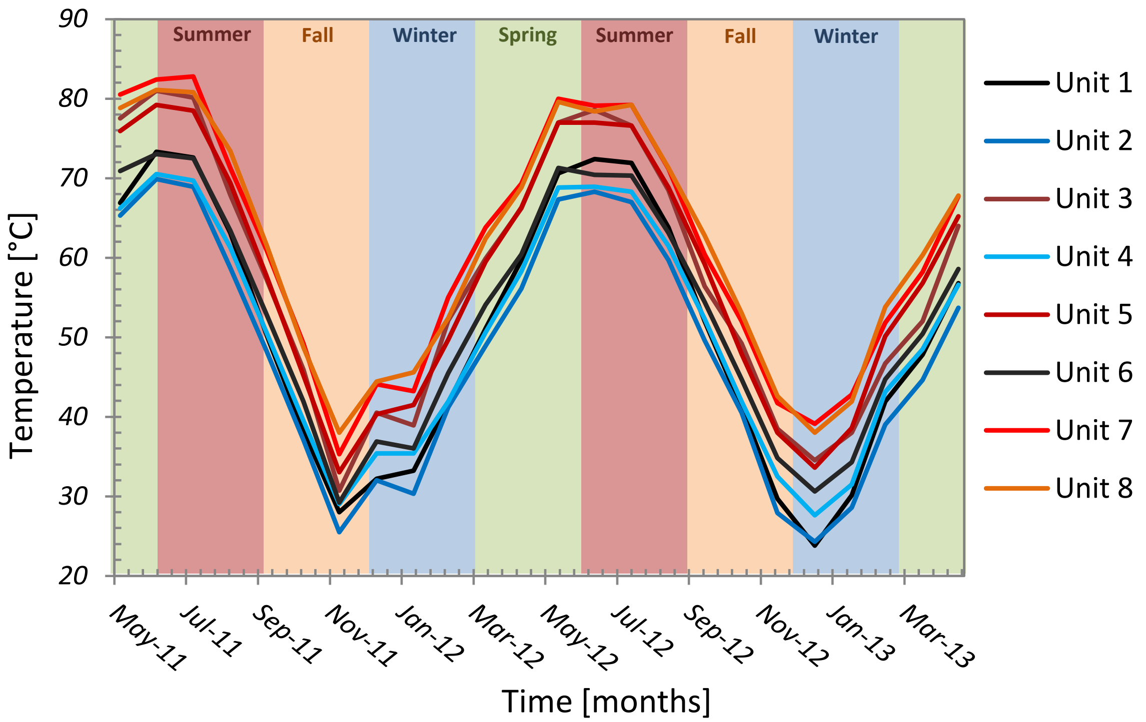


Figure 2. Mean monthly temperatures for the period between May 2011 and March 2013 (3).

Superimposing the district boundaries map and the climate units map, the following can be observed: Districts 5 and 6 overlap by climatic units that exhibit low winter temperatures, and the rest of the Districts include areas of high summer and low winter temperatures, see figure 3.

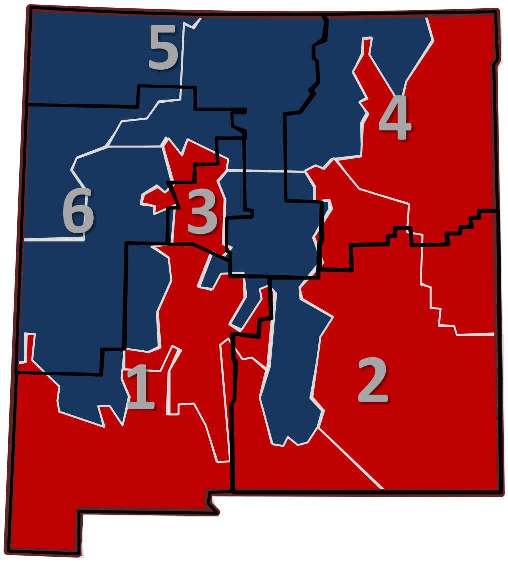


Figure 3. District boundaries superimposed over the state climate units map. Red areas indicate higher summer temperatures while blue areas indicate lower winter temperatures.

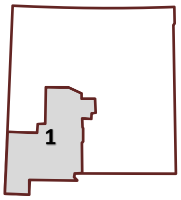
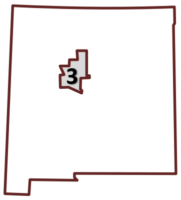
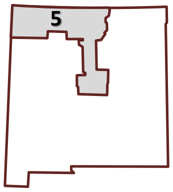
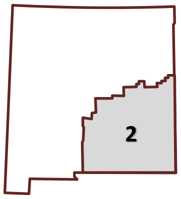
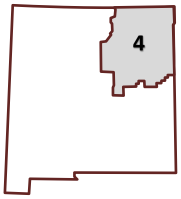
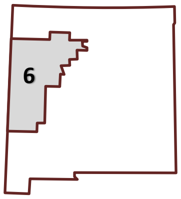
1.2.2 Local Binders

The Superpave binder grading system relies on a battery of rheological tests designed to determine the binder contribution to the performance of the asphalt pavement under three failure modes: rutting, fatigue cracking and thermal cracking. The final binder grading rate takes into consideration its performance in the context of expected climatic conditions. For instance, a PG 64-28 binder is expected to perform satisfactorily in an environment where the maximum pavement temperature does not exceed 64 °C (147.2 °F) and the minimum temperature does not fall below -28 °C (-18.4 °F) (1). Note that while the record high atmospheric temperatures in the state are far below conventional PG grades, asphalts absorb energy from the sun rendering its temperature significantly higher than atmospheric. Table 1 lists the PG grades approved for use in the state of New Mexico. Note that some PG grades while approved are not readily available from the state major suppliers because their use is rare. Table 2 shows the binder grades used in 2013 for projects by district.

Table 1. List of PG binder grades approved for use in the State of New Mexico.

Approved and regularly used	Approved but rarely used
PG 58-28	PG 58-22
PG 64-22	PG 58-34
PG 64-28	PG 64-34
PG 70-22	PG 70-16
PG 70-28	PG 76-16
PG 76-22	PG 82-16
PG 76-28	PG 82-22

Table 2. Binders used in 2013 for projects by district.

District	PG Grade	District	PG Grade	District	PG Grade
	64-22 64-28 70-22		64-22 70-22 76-22		58-28 64-22 64-28
	58-28 64-22 64-28 70-22 70-28		64-28 70-28 76-22		64-22 70-22 76-28

1.2.3 Local Aggregates

The most common aggregates use in asphalt pavements mixtures in the state of New Mexico are: crushed limestone, monzonite, basalt, quartzite, and sand and gravel from pits and river deposits. Aggregates from dacite, gneiss and rhyolite, as well as aggregates of volcanic origin are also used to a lesser extent in certain areas of the state.

1.3 SCOPE AND LAYOUT

The broad objective of this research project is to develop an understanding of asphalt binder aging mechanisms. Isolating the most influential variables involved and analyzing the aging process within the context of geospatial conditions relevant to the State of New Mexico i.e., climate, typical materials, and construction practices. To this purpose, the report has been divided in three sections. Section 2 provides the information necessary to understand aging processes in asphalt binders. Section 3 explores the implications of binder aging on pavement performance (both HMA and WMA). Section 4 provides an assessment of research needs that could derive from this preliminary work.

2. AGING MECHANISMS

2.1 INTRODUCTION

Asphalt binder aging causes an increase in the stiffness and brittleness of flexible pavements; thus, magnifying its susceptibility to cracking failure and ultimately resulting in a reduction in service life. Binder aging results from four distinct mechanisms: (i) oxidation, (ii) volatilization, (iii) steric hardening, and (iv) exudative hardening; the relative significance and extent of which is governed by intrinsic and extrinsic variables (5). Intrinsic variables (i.e., those inherent to the asphalt mixture) include: binder properties, aggregate properties, binder content, and porosity. Extrinsic variables include the environmental conditions the asphalt is exposed to during construction and during its service life.

2.2 ASPHALT BINDER

Asphalt binder is a thermoplastic mixture of various high molecular weight organic compounds. Its chemical composition is complex, and consists primarily of carbon and hydrogen with minor concentrations of sulfur, oxygen and nitrogen, and trace amounts of vanadium, nickel, and manganese (5), see table 3. The organic constituents can be divided into two distinct groups, *asphaltenes* and *maltenes*. Maltenes can in turn be subdivided into saturates, aromatics, and resins, see figure 4. Each of the groups depicted in figure 4 can be subdivided into a very large number of molecule types; however, the binder rheological properties can be generally traced to the fractions of saturates, aromatics, resins, and asphaltenes, SARA-fractions (6, 7). A comparison of SARA fractional compositions between asphalt binder and crude oil is presented in table 4.

Table 3. Elementary composition of asphalt binder (5, 6).

Element	Mass fraction [%]
Carbon	80 – 88
Hydrogen	8 – 12
Oxygen	0 – 2*
Nitrogen	0 – 2
Sulfur	0 – 9

* The fraction of oxygen depends on origin and production methods

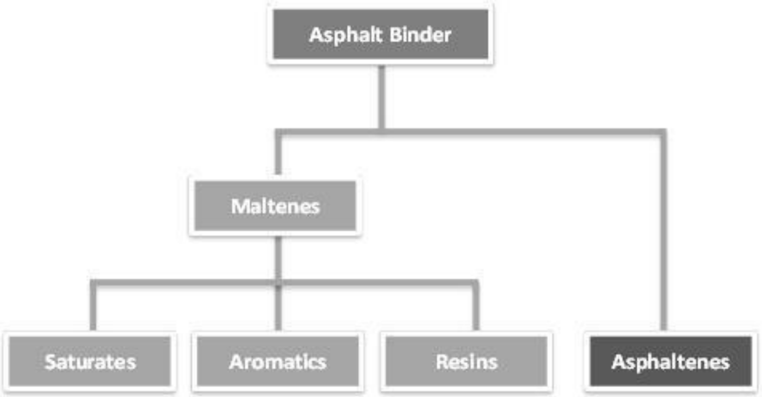


Figure 4. Different types of organic components present in asphalt binder.

Saturates:

Saturates make up between 5 and 20% of the asphalt binder; the group consists of aliphatic hydrocarbons, alkyl-naphthenes, and some alkyl-aromatics. Saturate molecules are non-polar, and have an average molecular weight in the range of 300 to 2,000 g·mol^{-1} (6).

Aromatics:

The aromatic group constitutes 40 to 50% of the asphalt binder. This group comprises the lowest molecular weight naphthenic aromatic compounds (300 to 2,000 g·mol^{-1}). Molecules are dominated by non-polar carbon chains with unsaturated ring systems. Aromatics readily dissolve other high molecular weight hydrocarbons (6).

Resins:

This group constitutes 10 to 25% of the asphalt binder (8). Composed primarily of hydrogen and carbon, resins also contain small amounts of oxygen, nitrogen, and sulfur. With molecular weights between 50 and 50,000 g·mol^{-1}, the typical molecular structure of resins exhibits a polar functional group, an aromatic chore, and an aliphatic chain (9), see figure 2. The polar side of the structure causes resins to interact with electrically charged or polar molecules, while the aliphatic end (being non-polar) yields weak electrical interactions. The unique structure of resins plays a major role in binder properties, i.e., peptizing of asphaltenes (6, 10).

Asphaltenes:

Asphaltenes constitute between 5 and 25% of the asphalt binder. The group comprises highly polar, complex aromatic molecules with very high molecular weights (1,000 to 100,000 g·mol^{-1}). The molecular weight of asphaltenes varies not only because of composition but also because of

Table 4. Differences in SARA composition between asphalt binder, crude oil, and tar sand (6, 8, 11-13) .

	Asphalt binder	Crude oil	Alberta tar sand
Saturates	5 - 20	6 - 22	16 - 23
Aromatics	40 - 50	36 - 55	38 - 42
Resins	10 - 25	18 -37	20 - 29
Asphaltenes	5 - 25	5 -20	15 – 16

the technique used to determine it (14). While all of the maltene components dissolve in n-heptane, asphaltenes are insoluble (this is used as the basis of distinction between asphaltenes and maltenes). The asphaltene content and the ratio of asphaltenes-to-resins govern the rheology of asphalt binders (10).

Graphical depictions of the SARA fractions are presented in figure 5. In the plot, polarity refers to the presence of spatially unbalanced charges in the molecular structure of the material which lead to the development of electrical forces.

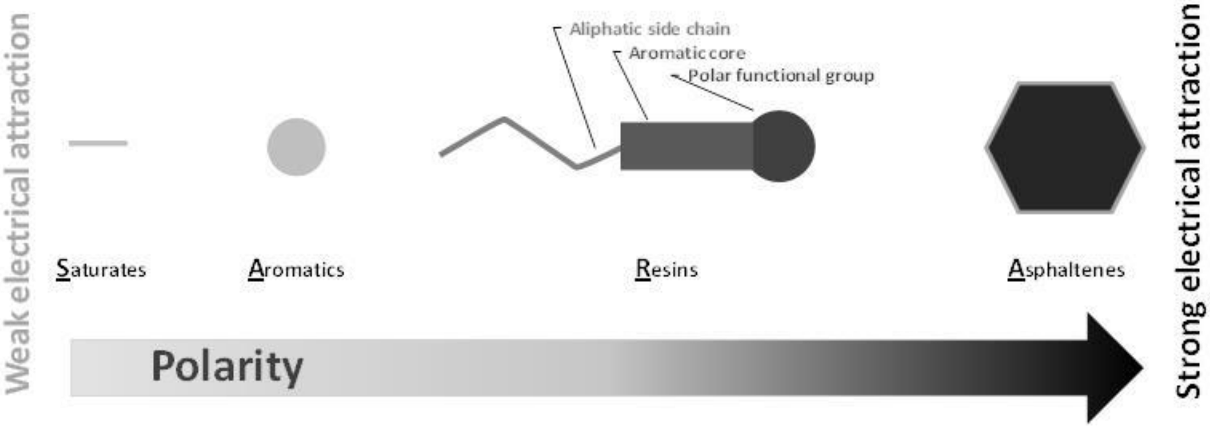


Figure 5. Graphical representation of the SARA fractions. Schematics are shown for visualization only, and do not reflect actual molecular structures.

2.3 BINDER CONSTITUTION, STRUCTURE AND PROPERTIES

Determining the effects of the multiple binder components on the overall performance of the binder can be accomplished by systematic blending of the SARA fractions under controlled conditions. At constant temperature and all other fractions remaining constant (6, 15-18):

i. increasing the aromatic content results in negligible changes in the binder viscosity,
ii. increasing the saturates content reduces the viscosity of the binder,
iii. the addition of resins increases the binder viscosity and reduces the penetration index,
iv. increasing the asphaltenes content results in a substantial rise in the binder viscosity.

At low resins and asphaltenes contents and high resins to asphaltenes ratio, an asphalt binder can be modeled as a colloidal suspension. The matrix is composed of the non-polar fractions (saturates and aromatics) while the suspended phase consists of resin-peptized asphaltenes, see figure 6. The electrical interactions between polar functional groups in the asphaltenes and resins causes resin molecules to align and associate to asphaltene molecules. Since the polarity of the resin decays away from the polar functional group, the associated resin molecules shield the polar asphaltenes, preventing them from interacting with each other. Peptized asphaltenes thus exhibit good mobility and the binder is characterized as a ‘SOL’ type asphalt binder (6). It follows from the model that if the ratio of asphaltenes to resins is maintained while reducing the amount of saturates and aromatics, the decrease in mean free path between peptized-asphaltenes would lead to an increase in the viscosity of the binder. The same phenomenon can be observed by increasing the peptized-asphaltene content while maintaining the remaining fractions constant.

Under certain circumstances, the changes in viscosity caused by variations in the asphaltenes and resins contents can be so pronounced that they cannot be explained solely on the basis of the colloidal suspension model. If the asphaltenes-to-resins ratio is high, or the resins present lack sufficient solvating power, asphaltenes are free to associate (6, 8). Electrical interactions cause asphaltene molecules to rotate, align, and associate with each other leading to the formation of structures that offer substantial resistance to shear, see figure 7. The macroscopic effect is a significant increase in the viscosity of the binder. Such binders are characterized as 'GEL' type.

Most asphalt binders fall somewhere between a SOL and a GEL. The viscosity of a binder depends not only on the relative fraction of asphaltenes but also on the degree to which they are peptized. These effects decrease with increasing temperature; thus, at sufficiently high temperatures the associated asphaltenes in a GEL-type binder are forced apart and the binder will soften.

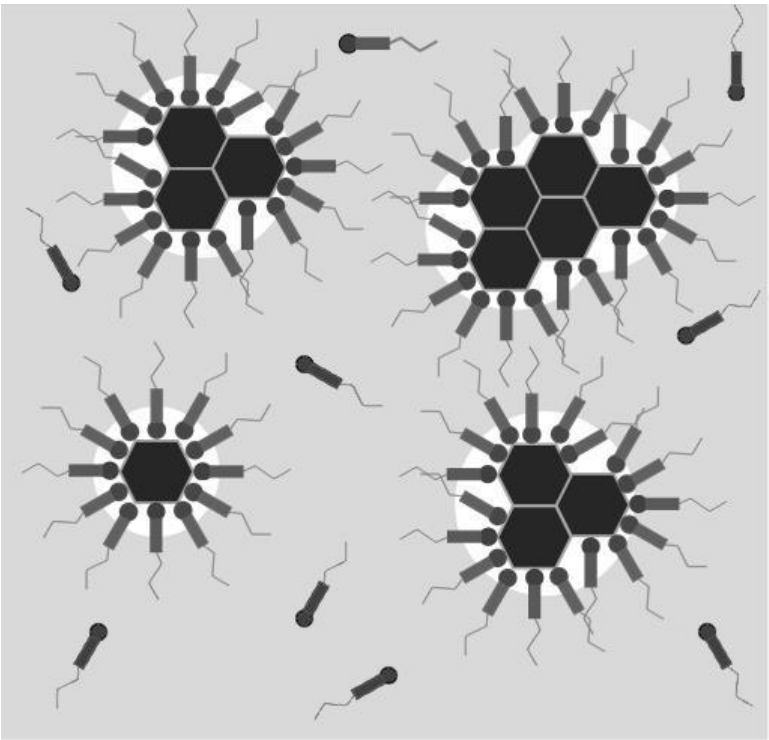


Figure 6. In the colloidal suspension model for asphalt binder the asphaltenes are peptized by resins and both are suspended in a matrix of saturate and aromatic molecules. Binders that exhibit this type of behavior are known as SOL binders.

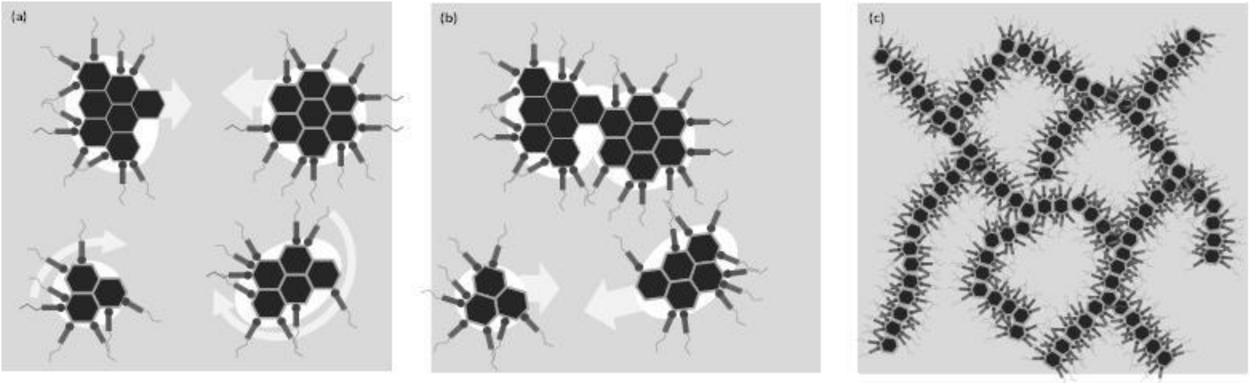


Figure 7. When the ratio of resins to asphaltenes decreases, attraction between partially peptized asphaltene surfaces (a) lead to the formation of structures that resist shear (b,c). Binders that exhibit this type of behavior are known as GEL binders.

2.4 OXIDATION

Oxidation is typically the main cause of binder aging. Upon exposure to oxygen, a binder will progressively oxidize, i.e., oxygen will be incorporated into the molecular structure of binder components. Oxidation is linked to an increase in polar functional groups which cause molecules to associate (under the effect of electrical attractive forces) into micelles of higher molecular weight (6). As a result of these associations the binder viscosity increases; however, not all binders hardened (age) to the same extent. The relative concentrations of SARA components in great part determine the binder susceptibility to oxidation. For example, polar molecules in SOL-type asphalt binders are almost inaccessible to oxygen because of the peptizing effect of resin molecules (8). Therefore, oxidation of the more reactive asphaltenes and resins fractions is hindered. Conversely, in GEL-type asphalt binders the polar molecules form a continuous network with large exposed surface area which makes them easily accessible to oxygen and readily oxidize (8). In addition to the intrinsic properties of the binder, environmental conditions play a major role in the oxidation process: (i) the atmosphere provides the source of oxygen and the driving pressure; (ii) ultraviolet rays from the sun serve as a catalyst for the reactions, accelerating the rate at which oxidation progresses; and (iii) changes in temperature can accelerate (hot) or retard (cold) the process (5-7).

Since the SARA binder components are separated in great part in terms of their polarity, it is important to determine first the extent to which oxidation affects them independently.

Oxidation of Saturates

There are no significant changes in the saturates fraction due to oxidation (19). The low polarity of saturate molecules results in very low reactivity to oxygen.

Oxidation of Aromatics

The Aromatics content is reduced. As a result of oxidation, the polarity of a fraction of aromatic molecules increases, causing them to be now grouped as resins or even asphaltenes (5). The extent of the reduction depends on the reactivity of the various aromatic molecules to oxygen.

Oxidation of Resins

The degree of association of the components in the Resins fraction is very important factor in their oxidation. When the resins are found peptizing asphaltenes their oxidation rate decreases as it becomes difficult for oxygen to reach them; however, at high temperatures peptized structures dissociate, allowing oxidation to proceed (20). When resins oxidize their polarity increases; thus, oxidized resins add on to the asphaltene fraction (21).

Oxidation of Asphaltenes

The asphaltenes content increases as the binder is oxidized. The change in the asphatenes content is caused by the increase in polarization experienced by the aromatics and resins fractions (8).

Changes in polarity of the aromatics and resins fractions, driven by oxidation, result in significant changes in binder composition. The asphaltene fraction increases due to the oxidation of resins, and the oxidized aromatics now contribute to the resins content. However, the ‘new’ asphaltenes and ‘new’ resins that form upon oxidation differ in behavior from the original binder’s asphaltenes and resins. If the distinction is not made, the analysis of aged binders in terms of SARA fractions becomes misleading (8). A series of tests conducted on Chinese binders supports the aforementioned effects of oxidation (21), see figure 8.

Variables that Govern Binder Oxidation

Regardless of the initial binder composition and its resistance to oxidation, the extent and rate of oxidation are controlled by the ambient temperature, the availability of oxygen, the exposed surface area of binder, and the time of exposure.

Temperature

Temperature is a critical factor governing the behavior of a binder. Temperatures at key stages during binder production, storage, transport, placement, and during service dictate the oxidation rate. Since the polar association of asphalt molecules is temperature dependent, at higher temperatures hydrogen bonding and dipole interactions will break, allowing for oxygen to penetrate even the resin peptized asphaltenes (6, 7). Figure 9 presents the effect of temperature on the oxidation of individual SARA fractions.

Exposure to oxygen

Atmospheric oxygen is the primary reactant in the oxidation process. Even though binder is subjected to high temperatures during storage and transport, the surface area exposed to oxygen is small relative to the total volume of binder. Upon mixing with the aggregates the binder coats particles increasing dramatically the exposed surface area and accelerating oxidation (8). During service, the binder is still exposed to oxygen at the asphalt layer surface and within it in the interconnected pore space (6, 7). The higher the void space the faster the binder oxides; therefore, pervious type asphalt layers experience more severe oxidation during their service life.

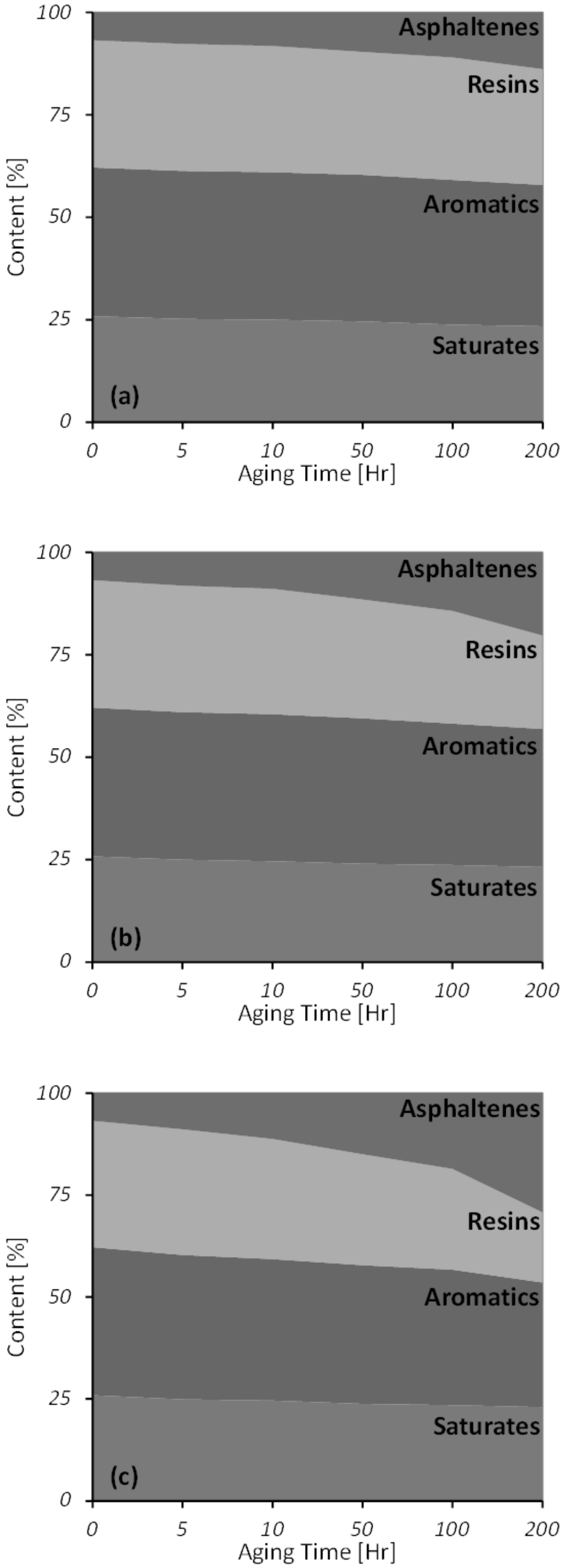


Figure 8. Oxidation effects on binder composition at multiple temperatures: (a) 110 °C, (b) 130 °C, and (c) 150 °C, modified from (21).

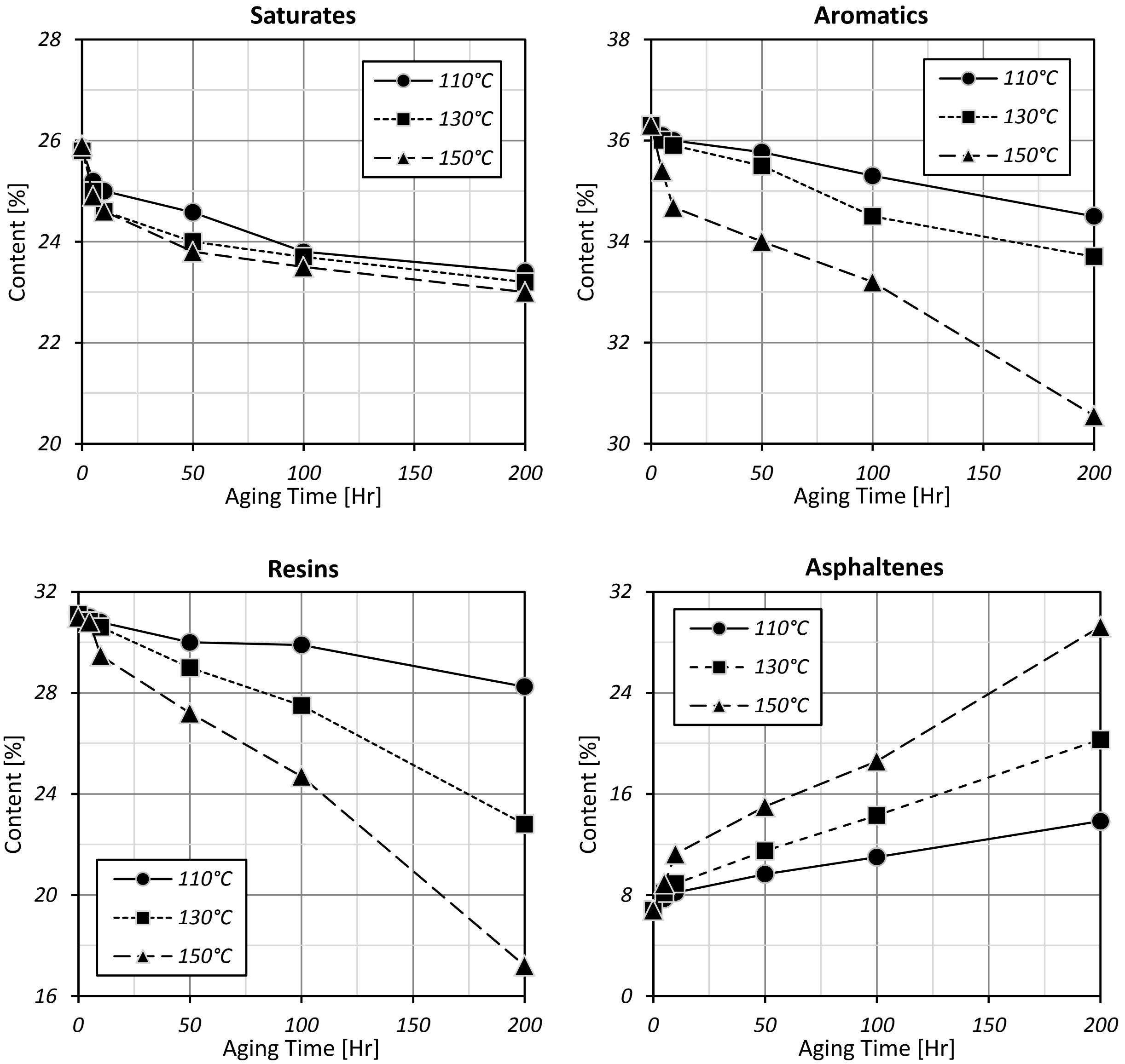


Figure 9. Oxidation of SARA fractions as a function of temperature, modified from (21).

Time of exposure

Short-term aging due to oxidation occurs as soon as the binder is placed in bulk storage tanks. Since the exposed surface area binder is low, the interaction with oxygen is small and oxidation at this stage is typically negligible. Upon mixing with the aggregate, the combination of high temperatures and high specific surface area favor oxidation reactions. Time of exposure under these conditions is critical and can often result in substantial binder oxidation (6). Oxidation will continue during the pavement service life as long as it is exposed to oxygen. The rate of long-term (or in service) oxidation depends on the availability of oxygen, ambient temperature, and ultraviolet radiation (6), this is graphically depicted in figure 10.

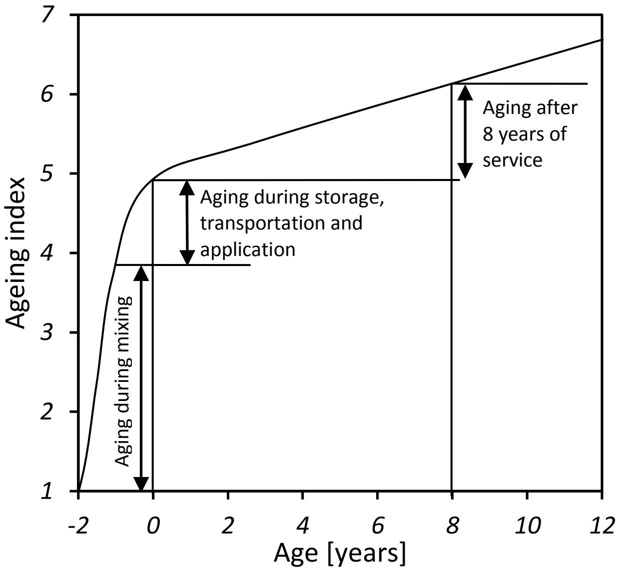


Figure 10. Evolution of asphalt binder aging; modified from (6).

2.5 VOLATILIZATION

In general, volatilization refers to the partition of molecules from the liquid phase into the gas phase. Despite low concentrations of volatile components (i.e., those molecules that readily volatilize under atmospheric conditions) in asphalt binders, changes in temperature particularly during mixing, transportation and placement can lead to significant losses in the fractions of saturates and aromatics. Unlike oxidation, where the more polar binder components are the main target, the saturates fraction can experience substantial volatilization. Studies conducted on 20 different binders showed saturates losses of up to 14.2% in just 80 hours at a temperature of 163 °C (22).

2.6 STERIC HARDENING

Steric or physical hardening occurs over time under service conditions (i.e., ambient temperature) and can be attributed to molecular structure reorientation and slow crystallization of waxes (6, 23). Steric hardening results in an increase in the binder viscosity and minor volume contraction (24, 25). Unlike volatilization and oxidation, steric hardening is not permanent in the sense that the molecular structuring can be disrupted upon heating, and the binder properties revert to their original values. Natural fluctuations in temperature (i.e, day-nigh, summer-winter) often lead to the disruption of steric hardening (5).

2.7 EXUDATIVE HARDENING

Exudative hardening results from the migration of oily components from the binder into the aggregate, and is controlled by both the exudation tendency of the binder and the internal porosity of the aggregate (6). The exudative tendency of a binder is primarily a function of the relative concentrations of low molecular weight paraffinic components and the concentration and type of asphaltenes. GEL-type binders are prone to exudation when used in conjunction with aggregates that exhibit high internal porosity (26). Aging due to exudative hardening is only significant when both the exudative tendency of the binder and the internal porosity of the aggregate are high; otherwise, it is negligible (8). The internal porosity of limestone (a commonly used aggregate in the state of New Mexico) can vary from 5% up to 40% (27, 28) depending primarily in the limestone formation process. Biogenic limestone and aggregates of volcanic origin tend to exhibit higher internal porosity and higher propensity for exudative hardening when used in conjunction with GEL-type binders

2.8 WATER EFFECTS

The presence and interaction of water with asphalt pavement components can result in the deterioration of the strength and durability of the asphalt mixture (29). The available literature identifies the following moisture damage mechanisms: detachment, displacement, emulsification, pore pressure, hydraulic scour, pH instability, and environmental effects (29-32). Most of the aforementioned mechanisms are localized to aggregate-binder interfaces, and impact the adhesion between binder and aggregate. While deleterious to pavement performance, the localized interfacial effects of moisture damage do not necessarily constitute a mechanism of asphalt binder aging. Instead, the stripping effect of the different damage mechanisms may result in an increase in the exposed binder surface area, which can for instance enhance oxidation.

Moisture induced damage is not only limited to the loss of adhesion at the binder-aggregate interfaces. The mechanical effects of pore water pressure build up affect also any interstitial void space capable of storing water. The presence of water and buildup of pore pressure under traffic loading exacerbates the growth of micro cracks and accelerates pavement damage (32). Temperature fluctuations above and below the freezing point can also induce volumetric changes and cracking within the pore pace, even in the absence of traffic induced loads.

Within the binder, the dipolar nature of water causes it to interact electrically with polar binder components. Thus, to some extent, water can be transported into the asphalt by virtue of electrical attraction with polar binder molecules. Water in the binder does not alter its chemical composition (since water is not incorporated into the molecular structure of the binder); however, the presence of water alters the mechanical properties of the binder, typically softening it (33). The effect of water is analogous to that of the dilution of the binder with a low molecular weight solvent, resulting in a reduction in stiffness and a propensity for rutting (33). Aged binders that contain higher concentrations of oxidized molecules tend to exhibit a greater affinity for water. At the same time, aged binders tend to be more viscous (stiffer asphalt pavement) making it difficult to label the effect of the absorbed water in aged asphalt as detrimental or beneficial (33).

2.9. BIOACTIVITY EFFECTS

Multiple types of microorganisms are capable of using asphalt binder as an energy source. As a result of this bioactivity, asphalt concrete can experience changes in fractional composition, decrease in mechanical performance and accelerated aging. The magnitude and rate at which these changes occur depends on the type of microorganism, the binder composition and the conditions of exposure (34). Favorable conditions vary depending on the specific type of microorganism but at a minimum include: a source of carbon for cell mass, a life-sustaining energy source, water, and a favorable environment including temperature, pH, salinity and sufficient space (35). When all favorable conditions are met, biodegradation can be rapid resulting in significant binder loss within weeks of exposure to microorganisms (34); otherwise, biodegradation is hindered. Microorganisms tend to thrive in lower molecular weight paraffinic hydrocarbons; thus, the effect of biodegradation is an increase in binder viscosity (34, 36).

In addition to biodegradation, bioactivity itself can lead to reductions in pavement performance. Micro-tunnels dug by microorganisms become interconnected pore space available for water storage, contributing to moisture induced damage (37). Biological byproducts generated by microbes inhabiting mineral aggregate surfaces can also interfere with binder-aggregate adhesion leading to stripping (36, 38). Despite evidence of microbially induced damage to asphalt pavements it is often regarded as minor by the engineering community (36, 39). This is in part because the presence of microorganisms is associated to high water contents. Since water itself can induce pavement damage, it is difficult to decouple the effect of microorganisms from that of moisture (38).

Climatic conditions in the State of New Mexico (i.e., low relative humidity, low precipitation, and substantial day-night temperature fluctuations) are not ideal for microorganisms to thrive. For this reason, biologically induced pavement damage would be expected to play a minor role in pavement damage across the state. However, there is no available data to support or refute this hypothesis.

3. IMPACT OF AGING ON FLEXIBLE PAVEMENT PERFORMANCE

There are two major pavement distress modes that affect the performance of asphalt pavements: rutting, and cracking. Rutting is the result of excessive permanent deformation in the material, and manifests itself as a depression on the pavement surface along the wheel paths. Rutting can originate from excessive asphalt binder, excessive mineral filler, and/or inappropriate aggregate selection (i.e., grain size distribution, particle shape [40]). Every layer in an asphalt pavement can undergo plastic deformations in response to loads and/or environmental factors; however, the asphalt binder is primarily responsible for the deformation within the asphalt concrete layer. Cracking is evidenced by interconnected cracks visible on the asphalt surface. It can be divided into two main categories depending on the formation mechanism: a) fatigue cracking (or alligator cracking) which is caused by material fatigue under the continuous repetition of vehicle loads (see figure 11); and b) block cracking, which is caused by thermally induced compressive and tensile stresses.

Rutting is associated to softening of the asphalt binder, and cracking is directly related to hardening of the asphalt binder. As previously stated, all the different binder aging mechanisms cause the binder to become more viscous. The increase in viscosity of the binder causes the asphalt concrete to harden. Therefore, aging can positively affect the performance of a soft mixture, allowing it to harden into an adequate pavement (33). The fatigue life of the pavement, on the other hand, could be negatively impacted by binder aging.

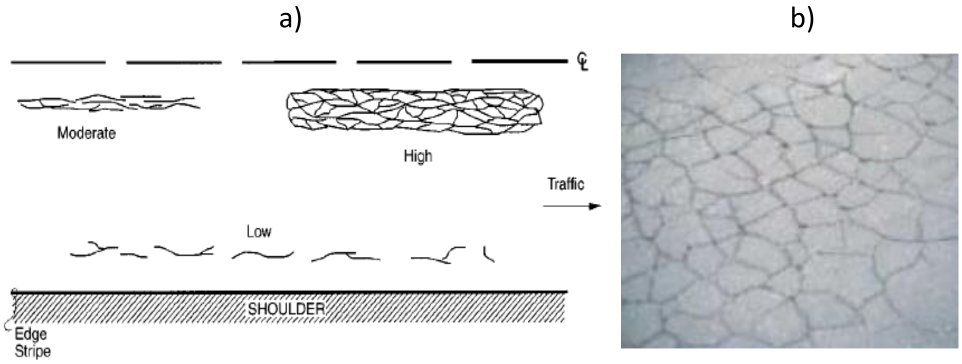


Figure 11. Fatigue cracking: (a) severity of fatigue cracking, and (b) fatigue cracking image (41).

Temperature is a controlling factor in binder aging. Volatilization and oxidation are accelerated by increments in temperature; thus, the thermal field imposed on an asphalt pavement during service is expected to dictate how aging progresses. At the pavement surface, temperature is highest during the day and lowest at night (see figure 12). Hence, oxidation and volatilization would be highest at the surface during the day and at the bottom of the layer at night. However, daytime maximum temperatures at the surface are higher than night time maximums at the bottom of the layer; thus, aging would proceed more rapidly from the surface.

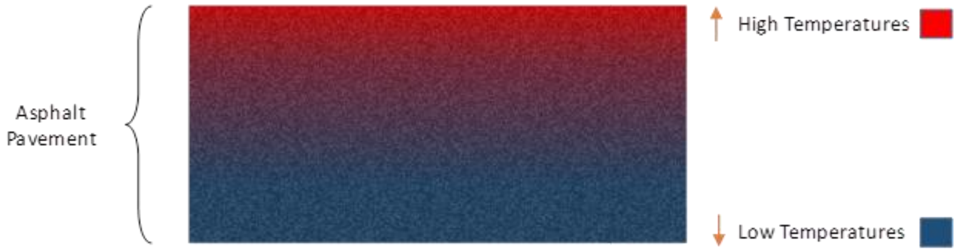


Figure 12. Temperature gradient on asphalt pavement sections during day time.

Oxidative hardening of the asphalt binder is also controlled by the availability of oxygen. The amount of air voids contained within the material is a key variable controlling access to oxygen. An open graded mix with interconnected void space open to the atmosphere would allow oxygen to penetrate and cause oxidation well inside the layer, as supposed to a less porous mixture which could limit oxidation to the surface and the bottom of the pavement. Thermal and/or traffic induced cracking would lead to an increase in the exposed surface area, and the subsequent propagation of the oxidation front into the asphalt layer following the crack, further accelerating aging and pavement deterioration.

Assuming a well compacted asphalt concrete with minimum interconnected pore space, the combined effect of temperature and access to oxygen would lead to aging at the surface and at the bottom of the layer. The aging front would then propagate with time into the asphalt layer. Higher temperatures at the surface and the incidence of ultraviolet radiation would cause the surface front to advance faster than the bottom front, see figure 13. Considering a beam under flexion analogy, as long as the aging surface front is above the flexural neutral axis the aged material will be subjected to compression under traffic loads, figure 14. Since aging leads to hardening the performance of the pavement would be expected to improve. However, thermal stresses induced by differential volume expansion across a non-uniform thermal field could reverse the flexion direction, subjecting the aged surface front to tensile strains.

The effect of the bottom front, considered on its own, is deleterious to pavement performance. The thin layer of hardened material coincides with the location along the asphalt concrete exposed to the greatest tensile stresses under traffic loads (figure 14). Crack initiation and propagation would progress faster than in the unaged pavement, leading to premature failure. The effects of aging fronts on the mechanical response of the asphalt pavement under thermal and traffic induced stresses would depend on the relative magnitudes of the aging fronts' thicknesses and the changes in asphalt stiffness upon aging.

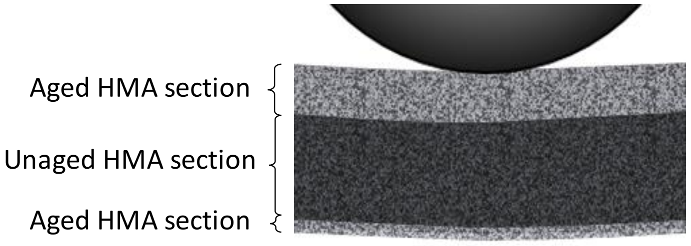


Figure 13. Aged HMA cross section. Aging occurring primarily at the top with oxidation advancing also from bottom.

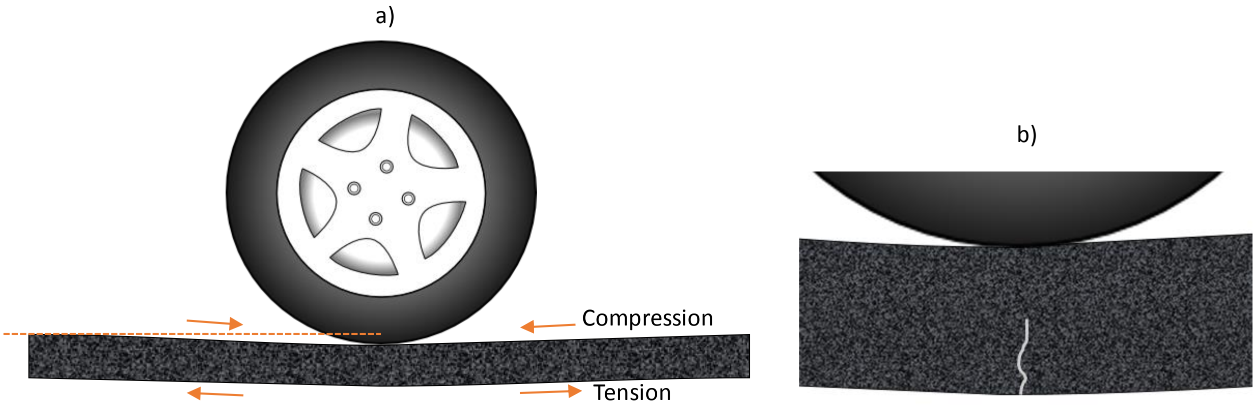


Figure 14. Tension and Compression regions in the pavement as a result of traffic loading.

The existence of aging fronts has been substantiated by a variety of laboratory experiments conducted on field recovered asphalt samples (42). Cores recovered from a site in Arizona (US 93, 50 miles north of Wickenburg) after 4 years in service were subjected to characterization using: (i) Small Sample Photoacustic Fourier-Transform Infrared Spectroscopy, (ii) Small Sample Extraction and Fourier-Transform Infrared Analyses, and (iii) Fourier-Transform Infrared on Extracted slices. The results of all the tests indicated a substantial difference in aging as a function of depth, see figure 15. Heterogeneous aging of asphalt pavements has been observed in multiple other studies (43-45). While the findings support the existence of aging fronts, the absence of research on the fronts' impact on performance hinders an assessment of the true effects of aging on asphalt pavement performance.

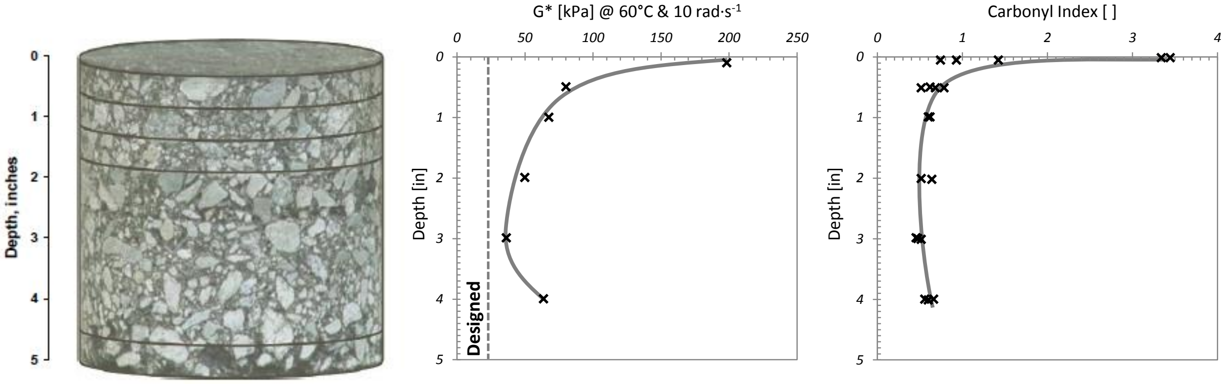


Figure 15. Aging-depth profile. The aging front advances from the surface into the asphalt concrete layer as evidenced by substantial changes in the complex modulus (extracted binder) and carbonyl index (oxidation index that increases with aging); data from (42).

3.1 AGING IN WARM MIX ASPHALTS

Warm mix asphalts (WMA) are typically produced at temperatures 50 °F (10 °C) lower than conventional HMA mixtures (46). Thus, the asphalt production temperature for WMA is between 250 to 260 °F (120 to 130 °C). The temperature reduction is favorable not only in terms of energy savings and safety but also in terms of asphalt binder aging, since both volatilization and oxidation progress at a lower rate when temperature decreases. The majority of the binder volatilization occurs when it comes in contact with the aggregate at temperatures near 280 to 300 °F (140 to 150°C) (5). If the mixing takes place in the presence of oxygen, which is always the case, aging by oxidation is also at its highest (6).

The oxidation rates during the service life of the pavement; however, are not as clearly understood. Figure 16 shows three possible aging scenarios for WMA mixtures. The reduction in transport, mixing, and placement temperature (zone I) results in a significantly less aged asphalt when compared to conventional HMA. After placement (zone II), the binder could age at: (i) the same rate as HMA (curve A), (ii) a slower rate than HMA (curve B), or (iii) a faster rate than HMA (curve C). The binder could be expected to age at the same rate as HMA (curve A) provided the effects of temperature reduction additives were only temporary (during mixing). However, if the effects of additives remained after placement, the binder could age at a different rate. If, for instance, the foaming process resulted in trapped oxygen within the binder, not only would the binder age at a different rate but also exhibit a change in the aging front. Additives could also hinder oxidation which would result in a reduction in aging rates. Thus, WMA binder aging is additive dependent.

WMA additives are generally classified in three categories: (i) water foaming additives, (ii) organic additives, (iii) inorganic additives (47). Aging studies conducted on WMA specimens produced using Evotherm 3G® (MeadWestvaco Corp.), Sasobit® (Seasobit), and Rediset® (Akso Nobel) were compared to conventional HMA specimens with the following results (48):

1. Within 132 days of accelerated aging (rolling thin-film oven – RTFO) in an environmental chamber at 140 °F (60 °C), binders modified with warm mix additives exhibited significantly lower oxidative aging than the HMA specimen used for control.
2. After 132 days, the extent of oxidative aging was not significantly different between the WMA modified binders and the HMA control.

The mixing temperatures of the HMA and WMA in this study were 325 °F (163 °C) and 289 °F (143 °C) respectively, maintained for 4 hours. Therefore, the specimens tested captured the aging difference at the beginning of zone II (figure 16). Based on the results of this study, it appears that the tested additives cause an accelerated (in-service) aging of the binder, following along the trend depicted in curve C (figure 16).

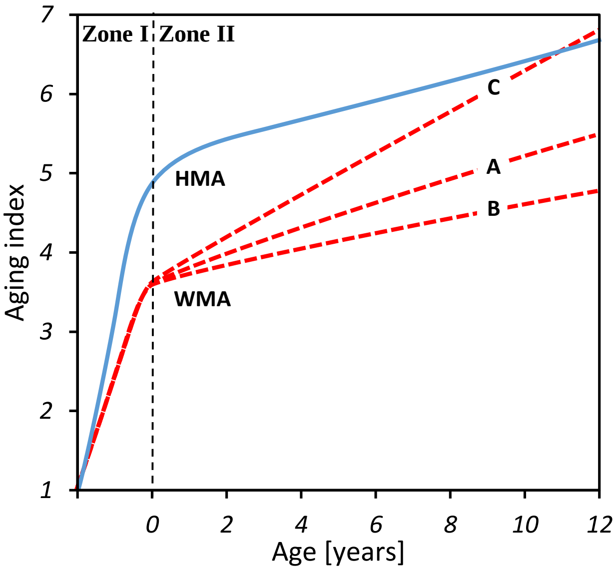


Figure 16. Warm mix asphalt aging scenarios: (A) aging at the same rate as conventional HMA, (B) aging progresses at slower rate than HMA, and (C) aging progresses at a faster rate than HMA.

3.2 AGING IN HOT AND ARID CLIMATES

In hot and arid climates, asphalt binders are required to perform under extremely high temperatures, large day-night temperature fluctuations, and under high incidence of ultra violet radiation from the sun. The prevalent short term pavement failure mechanism under these circumstances is rutting. Thus, binders must be able to accommodate high temperatures while maintaining sufficient stiffness to avoid excessive deformation (8). The large temperature variation between day and night results in the development of thermal stresses within the asphalt, if the binder is unable to accommodate these stresses the asphalt is prone to cracking. The material must then exhibit low stiffness at long loading times, and a high degree of relaxation in order to minimize the effect of thermally induced stresses (8).

The primary aging mechanisms in hot and arid climates are oxidation and volatilization. In both processes the primary drivers are temperature and exposure to the atmosphere; hence, aging at the surface progresses at a faster rate than within the asphalt layer (43). Upon aging, the asphalt pavement stiffens, reducing the likelihood of rutting. However, as the material hardens, the resistance to cracking diminishes. The binder must then exhibit high resistance to aging which can be attained by minimizing the asphalt air void content and using a high binder content (8). Recommendations for Gulf countries in the Middle East (Temperature range: 14°F to 122 °F [-10°C to 50°C]) include the use of the following binder performance grades: PG 76-10, PG 70-10, PG 64-10, and PG 58-10.

4. NEEDS ASSESSMENT

The following needs have been identified based on the review of the literature in the context of the state conditions and needs:

1. The evolution of asphalt pavement performance, as it ages, needs to be quantified in the context of the advancement of oxidative aging fronts.

2. The developed understanding of aging mechanisms needs to be applied to the management of reclaimed asphalt pavement (RAP) in order to develop specifications that ensure that the maximum amount of binder can be efficiently recovered and reused.

4.1 AGING FRONTS

Determining the influence of aging fronts on the performance of asphalt pavements is crucial to identifying optimal pavement management strategies to extend the service life of roads in the state. Key questions that need to be addressed include:

i. To what extent is binder aging beneficial/detrimental to pavement performance?
ii. What is the difference in performance between artificially aged asphalts and asphalts aged under field conditions?
iii. How can available accelerated aging tests be modified to capture the actual aging evolution of asphalts under field conditions (i.e., mimic aging fronts)?
iv. What is the evolution of the age vs. depth profile within the pavement (aging rate)?
v. Can the aging-depth profile be estimated based on measurements of surface aging?

The work required to address the aforementioned questions can be divided into experimental and numerical tasks as follows:

Task 1. Recovery and characterization of pavement cores and slabs.
Task 2. Assessment of material properties as a function of depth.
Task 3. Laboratory testing of field aged pavement beams.
Task 4. Modified accelerated aging laboratory tests.
Task 5. Numerical simulation of aged beams (calibration with task 3 results).
Task 6. Numerical simulation of asphalt pavement (thermal and traffic induced stresses).

4.2 RAP MANAGEMENT

Understanding the variables that drive aging in asphalt pavements and controlling them to favor the preservation and recovery of binder for reuse in new pavements can prove transformational for state pavement management practices. Following a comprehensive RAP management plan can not only maximize the potential for virgin binder replacement, making roads more affordable, but also minimize the likelihood of premature pavement failures arising from the use of mismanaged RAP. Key questions that need to be addressed include:

i. What is the optimal crushing mechanism for asphalt pavements (the one that minimizes the exposed surface area of RAP)?
ii. What is the shelf life of RAP binder under current stockpiling practices?
iii. How can stockpile practices be improved to better preserve RAP binder?
iv. What characterization tests can be implemented for rapid, simple RAP characterization without the need for chemical binder-aggregate separation?

The work required to address the aforementioned questions can be conducted as follows:

Task 1. Reclaimed asphalt pavement crushing study (optimal harvesting).
Task 2. Reclaimed asphalt pavement shelf life (optimal stockpile management).
Task 3. Development of simplified characterization tests.

It is anticipated that each of the proposed tasks will include several subtasks. Draft specifications for harvesting, storage, and testing of RAP could well be expected as research outcomes.

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