October 2007

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Subject Areas: IIB Pavement Design, Management, and Performance and IIIB Materials and Construction

Responsible Senior Program Officer: Edward T. Harrigan

Research Results Digest 324

SIMULATING THE EFFECTS OF HOT MIX ASPHALT AGING FOR PERFORMANCE TESTING AND PAVEMENT STRUCTURAL DESIGN

This digest summarizes key findings from Part 1 of NCHRP Project 9-23, "Environmental Effects in Pavement Mix and Structural Design Systems," conducted by Arizona State University, Tempe, Arizona. The Part 1 final report was authored by W. N. Houston, M. W. Mirza, C. E. Zapata, and S. Raghavendra and is available online as *NCHRP Web-Only Document 113*.

BACKGROUND

Environment plays a significant role in determining the properties of hot mix asphalt (HMA) as a function of time, which in turn affects the performance of HMA pavements. The major environmental factors that affect HMA material properties include the changes of temperature and moisture over time.

Research conducted in Strategic Highway Research Program (SHRP) Project A-005 clearly demonstrated the effect of environmental temperature on the age hardening characteristics of asphalt binders. The project concluded that higher mean annual air temperatures result in relatively higher rates of aging than the cooler climates. The research also showed the effect of other parameters, such as volumetric properties and the location of the HMA layer in the pavement system on asphalt mix aging. Higher air void contents result in greater oxidation and hence more stiffening of the HMA mix. HMA layers located deeper in the pavement are not in direct contact with air; as a result, the oxidation of the asphalt binder in these layers is reduced. Therefore, the stiffening of the HMA mix is inversely proportional to the depth at which it is located in the pavement system.

Hardening of the original asphalt binder due to the plant mixing and laydown (short-term aging) and normal in situ aging (long-term aging) are extremely complex phenomena because of the numerous factors influencing the rate of aging. While the mechanism of aging is complex, its impact on pavement performance is generally understood. Short- and long-term aging result in hardening of the asphalt binder with time and a gradual, concomitant increase in the dynamic modulus (stiffness) of the HMA mix over time.

This hardening of the asphalt binder and HMA mixture can lead to the development of several types of distress, which may ultimately lead to the failure of the pavement system. These distresses include fatigue cracking, low-temperature cracking, and non-load-associated cracking failure due to random, irregular surface cracking.

Two laboratory procedures were developed in SHRP Project A-003 to simulate the hardening potential of asphalt binders and HMA mixes. These procedures

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

are available today as (1) AASHTO Standard Practice R 28, "Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel" (PAV), and (2) AASHTO Standard Practice R 30, "Mixture Conditioning of Hot-Mix Asphalt."[1] These practices have proven of great value in HMA mix design, but, due to constraints on resources and time in SHRP, these practices have certain limitations.

SCOPE OF THE RESEARCH

AASHTO Standard Practice R 28 (hereafter referred to as "AASHTO R 28") requires testing of asphalt binder samples at the following conditions:

- Asphalt binder aged using AASHTO T 240, "Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test)."
- PAV aging time = 20 hours.
- Air pressure = 2.10 MPa.
- Aging temperature = 90°C, 100°C, or 110°C, depending on the climatic conditions being simulated.

For long-term mixture conditioning for mechanical property (i.e., performance) testing, AASHTO Standard Practice R 30 (hereafter referred to as "AASHTO R 30") specifies:

- HMA mixture aged in a forced draft oven.
- Aging time = 5 days.
- Aging temperature = 85°C.

Potential limitations associated with these two practices can be summarized as follows:

- Although the mean annual air temperature (MAAT) in the United States varies over an approximate range of 35°C to 75°C, AASHTO R 28 specifies only three PAV temperatures and AASHTO R 30 specifies only one oven-aging temperature to represent this wide range of MAAT.
- AASHTO R 28 fails to specify clear "cut-off" points between the climatic conditions represented by each possible PAV aging temperature.
- AASHTO R 28 represents the expected aging of the asphalt binder over a period of 5 to 10 years, while AASHTO R 30 represents the expected aging of the HMA mix over a period of 5 to 7 years. These ranges are wider than desirable, and prediction of aging at any other time during the life of the pavement is not possible with the practices as presently written.
- The laboratory conditions are similar for every asphalt binder. However, the aging potential of a binder depends on its physicochemical properties, which ideally should be accounted for in the practices.
- The aging simulated by the practices does not account for the influence of volumetric properties, in particular variation in air void content, which has a significant influence on oxidative aging.

Part 1 of NCHRP Project 9-23, "Environmental Effects in Pavement Mix and Structural Design Systems," was conducted to (1) verify the work done under the SHRP Projects A-002, A-003, and A-005 in developing these two practices for simulating the real-world aging of asphalt binders and HMA mixes and (2) provide guidance on the significance of the limitations of the practices noted above. To accomplish these goals, a program of laboratory testing and parametric analyses summarized below was conducted at the Advanced Pavement Laboratory at Arizona State University on asphalt binders and HMA cores obtained from LTPP and other field sites across the United States. Detailed information of the conduct and results of these experiments is contained in *NCHRP Web-Only Document 113.*

EXPERIMENTS AND ANALYSES

Correction Factor for Binder Recovery

This experiment was carried out to develop a correction factor to account for the changes in the binder viscosity that may occur due to extraction and recovery of asphalt binder from HMA.

Verification of AASHTO R 28

In order to verify the existing AASHTO R 28, the viscosities of asphalt binders aged in the laboratory were determined and compared to the viscosities of asphalt binders extracted from field cores, the age of which were established from construction records. Comparisons between laboratory- and field-aged binders were used to verify the practice.

---

[1] AASHTO R 28 was developed from Provisional Standard PP 1, and AASHTO R 30 was developed from Provisional Standard PP 2.

Improvement of AASHTO R 28 and Model Development

Possible improvements to AASHTO R 28 were developed in this experiment. A key goal was development of an improved predictive model calibrated to asphalt binder type and specific field aging conditions.

Calibration of the Predictive Model with Field Data

The improved prediction model was calibrated with field data. Cores were obtained from MnRoad, WesTrack, and Arizona DOT field experiments. Asphalt binders were extracted from these cores, recovered, and tested with the dynamic shear rheometer to determine their viscosity. The viscosity of the asphalt binders was predicted for the given set of field aging conditions with the improved model. Predicted viscosities were then compared with the measured viscosities, and the model was calibrated to best fit the available field data.

Validation of the Improved Predictive Model

The improved predictive model was validated with an independent set of LTPP data, using a procedure similar to that used in the previous calibration experiment. Cores were taken at eight LTPP sites, with the field aging conditions obtained from the DATAPAVE database. However, no original asphalt binders were available from these sites, and the rolling thin film oven (RTFO) viscosities were generally not available from the database, so the RTFO viscosities needed as input to the predictive model were estimated using A-VTS values obtained from the Mechanistic-Empirical Pavement Design Guide software, where A and VTS are regression constants in the following equation relating asphalt binder viscosity in centipoise and temperature in degrees Rankine:

$$\log\log\eta = A + \mathrm{VTS}\left(\log T_R\right)$$

Parametric Study of the Improved Predictive Model

A sensitivity analysis was conducted of the calibrated and validated predictive model. Outputs were generated with a matrix covering the possible range of input values, and constraints to be applied on the input parameters were determined.

Verification of the AASHTO R 30 Long-Term Conditioning Protocol

The long-term conditioning protocol in Section 7.3 of AASHTO R 30 is intended to simulate the in situ oxidative aging that occurs in HMA mixes during 5–7 years of pavement service. In this experiment, the dynamic modulus of HMA specimens aged in the laboratory was determined. These modulus values were compared with those of field cores, whose ages were known from construction records. The protocol was verified through comparison of the laboratory-aged specimens with the field-aged cores.

Analysis and Correlation of Laboratory-Aged and Field-Aged Data

This analysis was conducted in the hope of making the AASHTO R 30 long-term mixture-conditioning protocol more reflective of the volumetric properties of the HMA and the specific environmental conditions to which it is exposed.

FINDINGS AND RECOMMENDATIONS FOR AASHTO STANDARD PRACTICE R 28

Findings

Correction Factor for Binder Recovery

There was no practical, significant difference between the viscosities of original and recovered binders. Thus, the particular binder recovery procedure employed in the project had no significant effect on binder viscosity.

No correction factor to the recovered binder viscosity was necessary.

Verification of AASHTO R 28

The performance grade of the asphalt binder (in terms of stiffness), MAAT, and the mix air void content should be considered when deciding the PAV aging temperature required to produce a PAV-aged binder with the same viscosity as a field-aged binder.

AASHTO R 28 should be expanded to include the effects of field aging conditions and the detailed volumetric properties.

AASHTO R 28 can also be improved to better simulate the aging that occurs over a specific time period.

Calibration of the Improved T_{PAV} Predictive Model with Field Data

An improved model (Equation 1) for prediction of the required PAV aging temperature is more accurate than the values in Tables 1 and 2 of AASHTO M 320 and may be valuable addendum to AASHTO R 28.

$$T_{PAV} = \left\{ \begin{array}{l} \left(\begin{array}{l} 2.132432 + 0.193560 \\ \times \left(\log\log \eta_{RTFO,60^\circ C} \right)^2 \times MAAT \end{array} \right) \\ \times \ln\left(t_{aging} \right) + 109.9632 - 78.2945 \\ \times \left(\log\log \eta_{RTFO,60^\circ C} \right)^2 \end{array} \right\} \times \left(0.445445 \times VA_{orig}^{0.378370} \right) \qquad (1)$$

Validation of the Improved T_{PAV} Predictive Model with Field Data

Equation 1 provided reasonable PAV aging temperatures when actual field aging conditions were used as input.

Higher MAAT, air void content, and aging time yield higher PAV-aged temperatures, as expected.

Parametric Study of the Improved T_{PAV} Predictive Model

The parametric study of Equation 1 yielded no significant limitations or constraints on the input values.

Recommendations for Future Work

Further refinement of the improved T_{PAV} predictive model (Equation 1) should be accomplished with data from additional field sites.

In this research, binder viscosity was found to remain more or less constant with depth in the pavement; the differences found were not practically significant. This unexpected result should be further examined and tested.

Recommendations for the Implementation of the Improved T_{PAV} Predictive Model

Equation 1 yields a continuum of PAV temperatures that may fall below 90°C or exceed 110°C in specific instances, while the operation of commercial PAVs is typically limited to temperatures between 90°C and 110°C. One means to remedy this situation is to estimate the field aging time t_{aging} for an expected combination of binder viscosity, air void content, and MAAT at one or more of the standard PAV temperatures (90°C, 100°C, and 110°C). This can be done by inverting Equation 1 to Equation 2 to yield t_{aging}:

$$t_{aging} = \exp\left(\frac{ \left(\begin{array}{l} \left(\dfrac{T_{PAV}}{0.445445 \times VA_{orig}^{0.378370}} \right) \\ - 109.9632 + 78.2945 \\ \times \left(\log\log \eta_{RTFO,60^\circ C} \right)^2 \end{array} \right) }{ \left(\begin{array}{l} 2.132432 + 0.193560 \\ \times \left(\log\log \eta_{RTFO,60^\circ C} \right)^2 \times MAAT \end{array} \right) } \right) \qquad (2)$$

Suggested Revisions to AASHTO R 28

In order to demonstrate the possible implementation of Equations 1 and 2 within AASHTO R 28, ten cities in various climatic regions within the United States were chosen. Values of MAAT for these cities were calculated with the Mechanistic-Empirical Pavement Design Guide software, and an original air void content of 8 percent was used in all cases. Typical binder grades were selected based on the maximum and minimum temperatures found for the cities from LTPPBIND V2.1. RTFO viscosities corresponding to the selected asphalt binder performance grades were calculated using A-VTS values in the Mechanistic-Empirical Pavement Design Guide software for Level 3 designs. With these values input to Equation 1, the PAV aging temperatures required to simulate 5, 10, 15, and 20 years of aging were predicted. Equation 2 was then used to estimate the field aging time in months simulated by PAV aging temperatures of 90°C, 100°C, and 110°C. Based on these two sets of estimates presented in Tables 1 through 3, recommended revisions to AASHTO R 28 were developed and are presented in Table 4.

Table 1 Summary of input data used in the prediction

Site	MAAT (F)	VA_{orig} (%)	Binder PG	loglog RTFO Viscosity cP @ 60°C
Barrow, AK	12.2	8	46–46	0.6851
Fargo, ND	42.7	8	58–34	0.7289
Billings, MT	47.7	8	58–34	0.7289
Chicago, IL	52.8	8	58–28	0.7289
Washington, DC	55.2	8	64–22	0.7572
San Francisco, CA	56.8	8	58–10	0.7265
Oklahoma City, OK	60.6	8	64–16	0.7577
Dallas, TX	66.7	8	64–16	0.7577
Las Vegas, NV	68.9	8	70–10	0.7839
Phoenix, AZ	74.4	8	76–16	0.8061

Table 2 Predicted PAV aging temperatures

Site	5 years	10 years	15 years	20 years
Barrow, AK	85	87	88	89
Fargo, ND	93	97	100	102
Billings, MT	95	100	103	105
Chicago, IL	97	102	105	107
Washington, DC	97	102	106	108
San Francisco, CA	99	104	107	110
Oklahoma City, OK	99	105	109	111
Dallas, TX	102	108	112	115
Las Vegas, NV	102	109	113	116
Phoenix, AZ	104	112	116	119

Table 3 Estimated field aging times (months)

Site	PAV 90°C	PAV 100°C	PAV 110°C
Barrow, AK	328	7671	179561
Fargo, ND	37	179	860
Billings, MT	29	123	524
Chicago, IL	23	88	340
Washington, DC	26	90	310
San Francisco, CA	19	69	250
Oklahoma City, OK	21	66	210
Dallas, TX	17	49	144
Las Vegas, NV	19	50	134
Phoenix, AZ	18	43	104

Table 4 Recommended provisional protocol

Site	MAAT (F)	Recommended PAV Aging Temperature (°C)			
		5 years	10 years	15 years	20 years
Barrow, AK	12.2	85	85	90	90
Fargo, ND	42.7	95	95	100	100
Billings, MT	47.7	95	100	105	105
Chicago, IL	52.8	95	100	105	105
Washington, DC	55.2	95	100	105	110
San Francisco, CA	56.8	100	105	105	110
Oklahoma City, OK	60.6	100	105	110	110
Dallas, TX	66.7	100	110	110	115
Las Vegas, NV	68.9	100	110	115	115
Phoenix, AZ	74.4	105	110	115	120

CONCLUSIONS AND RECOMMENDATIONS FOR AASHTO STANDARD PRACTICE R 30

Long-term HMA mix aging in situ is a complex process that is influenced by several factors—most critically, HMA mix properties and external environment—that should be considered when simulating long-term aging in the laboratory. Warmer temperatures are generally associated with increased rates of oxidation, all other factors being equal. Similarly, higher air void contents in the mix will result in a higher oxidation rate, because more mix is in contact with the circulating air. In addition, the change in air voids under traffic can significantly affect mix aging. This change in air void content is directly dependent on mix type and traffic level.

While the mechanism of aging is complex and not fully understood, its impact upon pavement performance is generally straightforward. Short- and long-term aging results in hardening of the asphalt binder with time. This binder hardening leads to a gradual increase of the rigidity and stiffness of the HMA mix with time, expressed as an increase in its dynamic modulus. This change in modulus, in turn, leads directly to a variable set of changing stress, strain, and deflection patterns within the pavement structure as the pavement system "ages." Stiffer HMA mixes have increased susceptibility to cracking and fracture, which leads to the development of other distress types and, ultimately, to failure of the pavement system.

SHRP proposed a laboratory procedure to simulate long-term field aging of HMA mixes. This procedure was adopted by AASHTO in Standard Practice R 30. According to the practice, the procedure ". . . is designed to simulate the aging the compacted mixture will undergo during seven to ten years of service." However, as was the case for AASHTO R 28, the procedure in AASHTO R 30 does not take into account the effects of HMA mix properties and environmental factors on the aging process.

This research carried out a verification of AASHTO R 30 that was similar to that conducted for AASHTO R 28. Field samples were obtained from three sites in the United States: in Arizona, Minnesota (MnRoad), and Nevada (WesTrack). These sites represented a broad range of environmental conditions. In addition, the pavement sections were constructed under strict quality control standards, and each site had multiple sections representing different binder and mix properties.

Key observations and findings of this portion of the project are presented in the next section.

Observation and Findings for AASHTO R 30

The field sites selected were adequate to verify the laboratory procedure in AASHTO R 30 to simulate the long-term age hardening behavior of HMA mix, but did not provide enough data to improve that laboratory procedure or develop a new, more accurate and precise one. The data that were collected from these sites varied and seemed unable to account for all significant variables.

Plant mixes obtained from the three sites were compacted in the laboratory and then aged at 80°C, 85°C, and 90°C for 5 hours. The dynamic modulus of the aged specimens was determined at two temperatures and six loading frequencies. For all mixes tested, increased aging temperature resulted in higher values of dynamic modulus. This result was expected because higher temperatures will result in relatively more aging and thus an increase in mix stiffness. Based upon this observation, warmer climates will result in more aging than the cooler climatic regions, all other factors being equal. This result contradicts the existing procedure in AASHTO R 30 that employs only one standard aging temperature irrespective of the climatic region.

In general, dynamic modulus values of the laboratory-aged specimens were greater than those of field-aged specimens. This result may be because a more dramatic stiffness profile was found for the field specimens than for the laboratory specimens. That is, field aging, and thus mix stiffness, is very pronounced at the surface, but then rapidly falls off, yielding a lower average or effective stiffness for the entire core. For laboratory-aged specimens, the aging profile is relatively uniform through the entire specimen, giving higher stiffnesses for these specimens.

AASHTO R 30 suggests that the long-term laboratory aging procedure corresponds to 7–10 years of aging in the field, irrespective of the environmental and mix properties. All sites selected for this project were 7–10 years old, and the air void contents varied from 4 percent to 12 percent. Based on the data collected, the laboratory stiffness values were higher than the field stiffness values except for the WesTrack sections that had 8 percent and 12 percent air voids. This observation suggests that for air void contents less than 8 percent, laboratory aging is more severe than aging experienced in situ in the field. However, higher air void contents resulted in more severe field aging, which in time resulted in higher stiffness for the field samples compared with laboratory specimens. This latter observation suggests that a simple linear relationship may not exist between the air void contents of the field samples and specimens compacted in the laboratory for the purpose of simulating field aging. Laboratory specimens are compacted approximately to the design air void content.

Recommendations for Further Research

Modifications to AASHTO R 30 are needed to more accurately predict the aging characteristics of HMA mixes. Additional data are needed from controlled field experiments, and the data should be obtained at several different points of time.

Aging prediction should be examined as a function of the thickness of the HMA layer. That is, thicker pavements will result in lower effective dynamic modulus values than thinner pavements, which age more uniformly with depth. For example, a 50-mm-thick HMA layer will age differently than a 150-mm-layer under the same conditions. Thus, the laboratory aging procedure should account for the asphalt layer thickness.

Air void content is a critical factor that should be considered in any improved laboratory practice for simulating the long-term field aging of HMA mixes. In this study, field stiffness values were generally larger than those of laboratory-compacted specimens when the air void contents were greater than 8 percent. The reverse was observed when air void contents were less than 8 percent. The field sites selected for future research should include sections with a wider range of air void content than that used herein.

These digests are issued in order to increase awareness of research results emanating from projects in the Cooperative Research Programs (CRP). Persons wanting to pursue the project subject matter in greater depth should contact the CRP Staff, Transportation Research Board of the National Academies, 500 Fifth Street, NW, Washington, DC 20001.

COPYRIGHT PERMISSION

Authors herein are responsible for the authenticity of their materials and for obtaining written permissions from publishers or persons who own the copyright to any previously published or copyrighted material used herein.

Cooperative Research Programs (CRP) grants permission to reproduce material in this publication for classroom and not-for-profit purposes. Permission is given with the understanding that none of the material will be used to imply TRB, AASHTO, FAA, FHWA, FMCSA, FTA, or Transit Development Corporation endorsement of a particular product, method, or practice. It is expected that those reproducing the material in this document for educational and not-for-profit uses will give appropriate acknowledgment of the source of any reprinted or reproduced material. For other uses of the material, request permission from CRP.

THE NATIONAL ACADEMIES™
Advisers to the Nation on Science, Engineering, and Medicine

The nation turns to the National Academies—National Academy of Sciences, National Academy of Engineering, Institute of Medicine, and National Research Council—for independent, objective advice on issues that affect people's lives worldwide.
www.national-academies.org

TRB
Transportation Research Board
500 Fifth Street, NW
Washington, DC 20001