Airfield Asphalt Pavement Technology Program Project 04-02: PG Binder Grade Selection for Airfield Pavements

REVISED FINAL REPORT

June 23, 2008

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ENGINEERING SERVICES FOR THE ASPHALT INDUSTRY

ACKNOWLEDGMENT OF SPONSORSHIP

This report has been prepared for Auburn University under the Airport Asphalt Pavement Technology Program (AAPTP). Funding is provided by the Federal Aviation Administration (FAA) under Cooperative Agreement Number 04-G-038. Dr. David Brill is the Contracting Officers Technical Representative for the AAPTP program. Dr. Satish Agrawal is Program Manager of the FAA Airport Technology R & D Branch at the William J. Hughes Technical Center. Mr. Monte Symons served as the AAPTP project Director for this project.

The AAPTP and the FAA thank the Project Technical Panel that willingly gave of their expertise and time for the development of this report: Mr. Robert (Murphy) Flynn, Mr. Gerald Huber, Mr. John D'Angelo and Mr. Jim Greene. They were responsible for the oversight and the technical direction.

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ACKNOWLEDGMENTS

Dr. Donald W. Christensen of Advanced Asphalt Technologies, LLC, is Principal Investigator for AAPTP Project 04-02 and is primary author of this report. Dr. Christensen was primarily responsible for assembling, editing and submitting the Final Report. Dr. Christensen was also responsible for the developing the technical concepts involved in the procedures for adjusting PG binder grades for use in airfield pavements. Dr. Hussain Bahia, of the University of Wisconsin is an Investigator for this project, and a contributing author for this report. Dr. Bahia provided most of the information in this report on the PG grading system and those sections dealing with polymer-modified binders. Mr. Rodrigo Delgadillo, a Graduate Student at the University of Wisconsin, assisted Dr. Bahia in his work on Project 04-02. Mr. Roy McQueen of R. D. McQueen and Associates, Ltd., is a Consultant for Project 04-02, and is also a contributing author for the Draft Final Report. Mr. McQueen has provided information and expertise on the design and construction of airfield pavements, on current procedures for selecting asphalt binder grades for airfield pavements, and on other practical considerations related to AAPTP Project 04-02.

ABSTRACT

This Report documents all significant work performed during AAPTP Project 04-02. It includes a detailed description of various analyses and tests performed during the project, and discussion of the rational used in developing the proposed procedure for selecting binder PG grades for airfield pavements. Appendix B of this report is a clear and concise description of the proposed procedure, written as a revision of section 2.3 of Item P-401/P-403 “Plant Mix Bituminous Pavements.” The procedure itself is quite simple and well suited for use by practicing engineers. It involves the use of a single chart and table, along with the computer program LTPPBind version 3.1, which is available free from an FWHA website http://ltpp-products.com/OtherProducts.asp. Evaluation of the procedure performed as part of this project indicates that it provides appropriate binder PG grades for a wide range of airfield paving projects, and is more effective than existing procedures for selecting PG grades for such applications.

CHAPTER 1
INTRODUCTION AND RESEARCH APPROACH

OBJECTIVE

The AAPTP Project 04-02 Request for Proposal provides the following statement of the project objective:

> *The objective of this study is to develop technical guidance on the selection of a PG Binder for civilian and military airfield applications. This guidance must consider but not be limited to the following:*
>
> *Tire pressure and loading*
> *Channelized traffic*
> *Loading repetitions*
> *Pavement temperature, both high and low*
> *Speed*
> *Depth in the HMA pavement*
> *Non-traffic areas (shoulders, blast pads, paved overruns, etc.)*
> *Temperature reliability*
> *Grade bumping*
> *Modified Binders*

RESEARCH APPROACH

The research approach used in completing this project was straightforward. The overall concept used in developing the binder PG grade selection process was to rely on the computer program LTPPBind version 3.1 for the basic grade selection, and then provide adjustments to the grade to account for airfield type, and aircraft speed and stacking. However, LTPPBind was developed for selecting binders for highway pavements, and so cannot be directly applied for selecting binders for airfield pavements. In making adjustments to LTPPBind, the approach used was to determine equivalent highway ESALs, or EHEs (ESALs stands for equivalent single axle loads) for an airfield pavement, which can then be used in LTPPBind as if it were a design traffic level for a highway pavement. EHEs is simply a way for characterizing the overall magnitude of loading on a flexible pavement subject to a given mix of air traffic. It is necessary to make use of the concept of EHEs because current binder selection software has been developed using ESALs to characterize traffic level on a pavement. Using EHEs does not in any way assume similarity between trucks and aircraft, or between highway and airfield pavement; it is merely a convenient way to characterize the severity of loading on an airfield pavement in such a way that an appropriate PG binder grade can be easily selected using currently available methods. In developing the procedure for determining EHEs, many factors were considered, including differences in tire pressure between aircraft and commercial trucks, differences between aircraft wander and highway vehicle wander, differences in wander among aircraft and between taxiways and runways, differences in aircraft speed on different locations of an airfield pavement, and differences between airfield and highway HMA in composition and construction. In many cases, these differences were accounted for by applying empirical models relating various mixture characteristics and/or loading conditions to HMA properties and performance. The final procedure for PG binder grade selection was simplified as much as possible, so that it could easily be used by practicing engineers and technicians. Alternative methods of implementing the proposed method are discussed, such as including exact calculation of EHEs as part of LTPPBind or airfield pavement design software.

A second aspect of this research involved evaluating polymer modified asphalt binders (PMAs) and their potential use in airfield pavements. Although PMAs have become increasingly common in HMA placed on highways, some engineers remain reluctant to specify their use on airfield pavements. A thorough review of current practice and research results was performed to evaluate whether or not PMAs will be effective in HMA placed on airfield pavements, and if so, how best to specify these unique materials. Part of this evaluation involved laboratory testing, to evaluate different potential specification tests under a variety of conditions. The most important of these tests are the multiple stress creep and recovery (MSCR) test, and the elastic recovery test.

ORGANIZATION OF THIS REPORT

Chapter 2 of this report is by far the longest, and contains all of the significant technical information produced during project 04-02. It includes sections on current binder grade selection procedures for highway pavements, a review of PMA usage in the United States and Canada, current procedures for selecting binder grades for airfield pavements, development of an improved procedure for selecting binder PG grades for airfield pavements, and a presentation and discussion of laboratory tests performed as part of this research. Chapter 2 also includes information on aircraft characteristics relevant to this research project, and concludes with an evaluation of the proposed binder grade selection procedure. Chapter 3 is a relatively brief discussion of these results, including the presentation of the final, simplified grade selection procedure. The chapter also includes an overview of the key technical features of the proposed system. Chapter 4 is a one-page concluding statement for the report, including several key important considerations during implementation of the proposed procedure for selecting binder PG grades for airfield pavements. References for the report are listed in Chapter 5. The report includes two appendices. Appendix A is a list of airfield pavement construction projects used to evaluate the proposed binder grade selection procedure. Appendix B is a concise description of the proposed procedure, formatted as a revision of section 2.3 of Items P-401/P-403, "Plant Mix Bituminous Pavements."

CHAPTER 2
FINDINGS AND ANALYSIS

This Chapter of the report presents in detail the technical findings of Phase I of AAPTP Project 04-02. The chapter begins with a review of the current PG grading system for asphalt binders used in highway pavement construction. This includes a discussion on current procedures for testing and specifying polymer-modified asphalts (PMAs). A review of the procedures now used for selecting asphalt binders for airfield pavements is then presented, including a brief discussion of the use of PMAs in airfield pavements. This is followed by several sections dealing with procedures for modifying the PG grade selection process for use in airfield pavements. These sections for the most part deal with rutting and are quite long and technical, but it must be emphasized that this complexity is not because the research team feels that rutting is a common form of distress in airfield pavements. The length and technical content of the sections dealing with permanent deformation are the result of several factors:

- Modification of this aspect of the PG system is much more complicated than for its other components; factors that must be addressed include tire pressure, tire size, aircraft speed, traffic level, aircraft wander and depth within the pavement.
- The magnitude of grade adjustments for rutting are quite large, and failure to address them adequately could result in catastrophic rutting, even though rutting may not currently be a problem in many airfields.
- Models have been recently developed which lend themselves to analyzing the PG grading system and developing reasonable methods for modifying this system for use in airfield pavements; these models are however somewhat complex. Fortunately, the final implementation of these models is done in a very simple procedure that requires no knowledge of these models.

It is important to understand that the proposed grade selection system has not necessarily been designed to provide stiffer binders for airfield than are now used. The system has been designed to select the appropriate PG grade for a given application—stiff enough to adequately resist permanent deformation, but not excessively stiff. In fact, as discussed later in this report, the final system generally will result in softer PG grades for GA and other small facilities compared to the grades provided using existing procedures.

This chapter concludes with two sections dealing with current airfield pavement technology. The first is short section on pavement aircraft characteristics relevant to binder PG grade selection. The second is a review of current practice in the selection of binders for airfield pavements. Although this section is short, it is a critical part of the project. This review consists of the construction of a database on airfield pavements, including information on the binder grades used, the pavement structure, the amount and type of aircraft using the pavement, and observed performance. This database will be used to evaluate the two PG grade selection procedures that have been identified and developed during Phase I of Project 04-02. Although this evaluation will ultimately probably only be qualitative, it will serve as an important check on the reasonableness of the procedure.

THE PG GRADING SYSTEM FOR HIGHWAY PAVEMENTS

Historical Development

For many years asphalt binders for highway pavements were characterized using test methods that were based mostly on experience. Commonly used tests included the penetration and ductility tests, which are largely empirical and not directly related to performance-related engineering properties. Temperatures at which the tests were carried out were standard and did not necessarily represent the full range of temperatures for typical pavements. In many cases, for example, the lowest test temperature used to grade asphalt binders was 25°C, while expected minimum pavement temperatures in many parts of the U.S. are well below -10°C. This is an especially important issue because the physical properties of asphalt binders vary enormously with temperature. Recognizing the shortcomings of the traditional asphalt binder characterization procedures, the Federal Highway Administration started in 1987 a nationwide research program called the Strategic Highway Research Program, usually referred to as SHRP (*1*). As a result of this 5-year research effort, a performance-based specification for asphalt pavements was developed, which was called "Superpave," an acronym signifying Superior Performing Asphalt

Pavements. The resulting specifications consist of two parts: a volumetric mixture design for HMA mixtures and a performance grade (PG) specification for binders (*2*).

The objective of the Superpave binder specification is to address three pavement distress modes: 1) permanent deformation or rutting at high pavement temperatures, 2) traffic-associated fatigue cracking at intermediate pavement temperatures, and 3) low-temperature cracking, due to thermal stresses in the pavement during rapid drops in temperature during the winter months. To address these three distress modes, the PG grading system provides for specifying the properties of binders at the high, intermediate and low pavement temperatures expected at the selected site.

Three testing devices constitute the core of the PG grading system: the dynamic shear rheometer (DSR), the bending beam rheometer (BBR) and the direct tension tester (DTT). The DSR is used to characterize the binder at high and intermediate pavement temperatures. The BBR is used to measure the properties at expected minimum pavement temperatures. The limits that the asphalt binder properties must satisfy do not vary with climate; instead the temperatures at which those properties are measured vary. For example, the minimum pavement temperature is much lower in Minnesota than in Florida. The temperature at which the BBR test is carried out varies accordingly.

The tests that complete the Superpave system are laboratory aging procedures, which include the rolling thin film oven test (RTFOT) and the pressure-aging vessel (PAV). The RTOFT simulates the aging during production and construction, whereas the PAV is designed to simulate the aging during the first few years of service life of the pavement. The viscosity of the asphalt binder at mixing and compaction temperatures is measured using the rotational viscometer (RV).

Current Standards

The current standards for the selection of PG graded asphalt binders are given in *AASHTO M320-05 Performance Graded Asphalt Binder*. In this specification, test results are specified on the unaged binder, the RTFOT residue and the PAV residue. The RTFOT (AASHTO T 240) is carried out for 75 minutes at 165ºC. After RTFOT aging, the binder is placed in the PAV (R 28) for aging at 100ºC for 20 hours.

AASHTO M 320 limits the binder viscosity at 135ºC to 3 Pa·s to ensure proper workability during production. The viscosity at 135°C is measured with the RV (AASHTO T 316). Two rheological properties are controlled with the DSR: the complex modulus $|G^*|$ and the phase angle δ. The specified parameter at high temperatures—sometimes called the "rutting" parameter—is $|G^*|/\sin \delta$. Minimum values for this parameter help ensure that the binder is not too soft at expected maximum pavement temperatures. The minimum values are 1.0 kPa for the original binder and 2.2 kPa for RTFOT residue. In this, the high-temperature portion of the PG grading system the temperature at which $|G^*|$ and δ are measured is defined as the yearly 7 day average maximum air temperature at the location where the pavement is to be constructed; the testing frequency is 10 rad/s.

In AASHTO M 320, the binder properties at low temperature are determined using either the BBR (AASHTO T 313) or the DTT (AASHTO T 314). The BBR is used to measure the creep stiffness $S(t)$ and the rate of change of stiffness ($m = \mathrm{d} \log S(t)/\mathrm{d} \log t$) at a loading time of 60 seconds. The maximum allowable value for $S(t)$ is 300 MPa, while the minimum allowable value for m is 0.30. The DTT can be used in place of the stiffness requirement. This test is used to measure the failure strain when $S(t)$ is between 300 MPa and 600 MPa. A minimum value of 1% is specified. The minimum m-value of 0.30 must still be met when the DTT is used in place of creep stiffness binder grading at low temperature. Both the BBR and DTT tests are carried out at a temperature 10°C higher than the expected minimum pavement temperature. Normally, PAV residue is used when performing all low-temperature specification tests.

The DSR is used to control binder properties at intermediate temperatures, using the quantity $|G^*| \sin \delta$, which is measured at a frequency of 10 rad/s and at a temperature 4°C above the average of high- and low-temperature grading points. A maximum allowable value of 5,000 kPa is specified for $|G^*| \sin \delta$.

The end result of the PG grading system is a binder with properties controlled at high, low and intermediate temperatures, related to the climate for which the binder is to be used. For example, a PG70-28 binder is suitable to be used in an area where the expected maximum pavement temperature is 70ºC or lower, and the expected minimum pavement temperature is –28ºC or higher. This binder would meet the following requirements as outlined in AASHTO M 320:

- Viscosity at 135°C ≤ 3 Pa-s
- $|G^*|/\sin\,\delta \geq$ 1.0 kPa at 10 rad/s and 70°C, unaged binder
- $|G^*|/\sin\,\delta \geq$ 2.2 kPa at 10 rad/s and 70°C, RTFOT residue
- $S(t) \leq$ 300 MPa at 60 s and -18°C, PAV residue or
  failure strain ≥ 1.0 % at 18°C, PAV residue
- $m(t) \geq$ 0.30 at 60 s and -18°C, PAV residue

Table 1 shows an example of a PG grade specification as given in AASHTO M 320-05. It is important to understand that many state highway agencies have altered this specification slightly in developing their own specification, so that there are differences in PG binder specifications from state to state. The Asphalt Institute has developed a very useful table of binder specifications for various state highway agencies, which can be found on their website at http://www.asphaltinstitute.org.

The Concept of Continuous Grading

When grading an asphalt binder, test reports often include results in terms of *continuous grading*. In this sense, continuous grading means the temperature at which the binder just meets the selected grading requirement. For instance, low-temperature grading using the BBR requires that the creep stiffness as measured by the BBR not exceed 300 MPa, and that the m-value should be at least 0.30. If the creep stiffness at -11.2 °C is 300 MPa, and the m-value is 0.30 at -12.7 °C, the continuous low-temperature grading for this binder would be the based on the higher of these two temperatures: -11.7 °C. This continuous grading is then normally rounded to the next higher standard grade, or PG XX-16.

Consider high-temperature grading for the same binder. High temperature grading is based upon having a minimum |G*|/sin δ value of 1.00 kPa for the unaged binder, and 2.20 kPa for the RTFOT residue. If the same binder discussed above has a |G*|/sin δ value of 1.00 kPa at 62.5°C in the unaged condition, and 2.20 kPa at 65.1 °C as RTFOT residue, the high-temperature continuous grade would be the lower of these two temperatures, or 62.5°C. In final grading, this would be rounded to the next lower standard grade, or PG 58-XX. For this binder, assuming all other pertinent requirements are met, the final PG grade would be PG 58-16, although the performance as indicated by continuous grading would approach that of a PG 64-22 binder.

Engineers can also speak of the continuous grade requirement, which is a very similar concept, but instead of referring to the performance of a selected binder, this term refers to the grade required in a given climate. For instance, LTPPBind version 3.1 gives the continuous high-temperature grade requirement for Philadelphia, PA, as 59.1 °C at 98 % reliability, which would be rounded upward. The continuous low-temperature grade at this reliability level is -16.7 °C. Therefore, the actual grade required for Philadelphia is 64-22 at 98 % reliability. This helps illustrate the usefulness of continuous grading. In this example, the high-temperature grade is just slightly higher than 58 °C, while the low-temperature grade is just slightly lower than -16 °C. The binder discussed in the previous example was graded as a PG 58-16, even though its performance was significantly better than this as indicated by continuous grading. In this case, this PG 58-16 binder would easily meet the requirements for a lightly trafficked pavement in Philadelphia, even though the required grade is PG 64-22. Although this difference would not be an important one in this example, since PG 64-22 binders are widely available, rounding of grade requirements and binder PG grades can become an issue when high-performance grades are involved. Examining continuous grade requirements and continuous PG grades for available binders can sometimes help determine whether or not a premium, high-performance binder is truly necessary.

Continuous binder grade requirements are also important when adjusting binder grades for traffic level and speed. These adjustments are discussed in detail below. It is important to note that these and any other applicable adjustments to a grade requirement should be made to the continuous PG grade requirement; the final continuous grade requirement is then rounded to the appropriate standard grade. For example, in the Philadelphia area, for a slow traffic at a level of 3 to 10 million ESALs, LTPPbind version 3.1 gives the required high-temperature grade adjustment as +9.5 °C. Added to the continuous base requirement of 59.1 °C, this gives a final continuous high-temperature grade of 68.6 °C. The final required grade in this case would be PG

70-22. If the adjustment were mistakenly applied to the rounded high-temperature grade required (64 °C), the final continuous high temperature grade would be 64 + 9.5 = 73.5 °C, and the final grade requirement would be significantly higher than needed: PG 76-22.

Traffic Speed and Volume

Extreme traffic conditions like high traffic volume and slow speeds are likely to generate early distresses in the HMA pavement, especially rutting. Asphalt is a viscoelastic material, which means that the physical response depends on both temperature and time of loading. HMA exhibits behavior that is both viscoelastic and plastic—the response of HMA pavements is not only time and temperature dependent, but also depends on the magnitude of the applied load. This means that large, slow moving loads will cause much more permanent deformation than light, fast moving loads. Very slow moving and heavy traffic can cause especially severe rutting unless the HMA is properly designed. When high traffic volume or slow traffic is expected, the PG grade of the selected binder needs to be adjusted by increasing the high temperature portion of the PG grade. This is often referred to as grade "bumping." AASHTO M 320-05 includes a fairly simply scheme for grade adjustments, that includes adjustments of 0, 1 or 2 grades. These adjustments are based on engineering experience and judgment, and no analysis supporting their use is given in AASHTO M 320 or any other reports or research papers. As a result, there are at least three other sets of recommended high-temperature PG grade adjustments. Grade adjustments as recommended in AASHTO M 320-05 and in three other documents or computer programs are summarized in Table 2. This includes grade adjustments as given in LTPPBind Versions 2.1 and 3.1, and grade adjustments recommended in the NCHRP Project 9-33 Interim Report (*3, 4, 5*). The computer program LTPPBind was developed as an aid in PG grade selection, and is discussed in the section below. There appears to be a wide range in the recommended grade adjustments. As discussed later in this report, it was decided to base grade adjustments for traffic speed and volume on models used in developing LTPPBind version 3.1. This provides consistency with current practice in flexible pavement design for highways, since the models used in this software are essentially the same as used in the AASHTO Flexible Pavement Design Guide (*5*).

LTPP Bind Software

LTPPBind, Version 2.1 was developed in 1999 by Pavement Systems, LLC for the FHWA. The program was developed as an aid to pavement engineers in selecting PG grades for binders used in developing HMA mix designs using the Superpave system (*3*). Some minor modifications to the Superpave system were included in version 2.1 of LTPPBind. LTPPBind 2.1 includes a very large database of climatic data for thousands of locations across the U.S. and Canada. This climatic data is then used in algorithms developed during SHRP to calculate both high- and low-temperature PG grades. The software includes provisions for calculating PG grades at different pavement depths, for estimating the reliability of different PG grades for a given application, and for making appropriate grade adjustments for traffic level and speed. These adjustments were based on engineering experience and judgment, rather than on an analytical approach.

Recently, a newer version of LTPPBind has been developed (Version 3.1), which uses a more theoretically sound, damage-based procedure to estimate high temperature PG-grades (*4*, *5*). Version 3.1 also uses more accurate methods for estimating pavement temperatures from climate data. The damage calculations in LTPPBind 3.1 are based upon the rutting model including the AASHTO Flexible Pavement Design Guide (*5*). LTPPBind 3.1 appears to provide similar high temperature grades in the 52 to 58°C range, but deviates at higher and lower grades. The discrepancy is particular large in hot desert climates, where extended periods of hot weather result in significantly higher PG grades using the damage-based approach (*5*).

Table 1. PG Grade Specification as Given in AASHTO M320-05.

Binder Performance Grade:	PG 46			PG 52							PG 58				
	–34	**–40**	**–46**	**–10**	**–16**	**–22**	**–28**	**–34**	**–40**	**–46**	**–16**	**–22**	**–28**	**–34**	**–40**
Design high pavement temperature, °C:	<46			<52							<58				
Design low pavement temperature, °C:	>–34	>–40	>–46	>–10	>–16	>–22	>–28	>–34	>–40	>–46	>–16	>–22	>–28	>–34	>–40
Test on Original Binder															
Flash Point Temperature (T 48), Min., °C	230														
Viscosity (ASTM D 4402) **Maximum value of 3 Pa-s at test temperature, °C**	135														
Dynamic Shear (TP 5) **G*/sin δ, minimum value 1.00 kPa, at 10 rad/s and Test Temperature, °C**	46			52							58				
Tests on Residue from Rolling Thin Film Oven (T 240)															
Mass Loss, Maximum, %	1.00														
Dynamic Shear (TP 5) **G*/sin δ, minimum value 2.20 kPa, at 10 rad/s and Test Temperature, °C**	46			52							58				
Tests on Residue from Pressure Aging Vessel (PP 1)															
PAV Aging Temperature, °C	90			90							100				
Dynamic Shear (TP 5) **G* sin δ, maximum value 5,000 kPa, at 10 rad/s and Test Temperature, °C**	10	7	4	25	22	19	16	13	10	7	25	22	19	16	13
Physical Hardening	Report														
Creep Stiffness (TP 1) **Stiffness, maximum value 300 MPa** **m-value, minimum value 0.30, at 60 sec ant Test Temperature, °C**	–24	–30	–36	0	–6	–12	–18	–24	–30	–36	–6	–12	–18	–24	–30
Direct Tension (TP 5) **Failure strain, minimum value 1.0%, at 1.0 mm/min and Test Temperature, °C**	–24	–30	–36	0	–6	–12	–18	–24	–30	–36	–6	–12	–18	–24	–30

Table 1. PG Grade Specification as Given in AASHTO M320-05 (continued).

Binder Performance Grade:	PG 64						PG 70					
	–10	**–16**	**–22**	**–28**	**–34**	**–40**	**–10**	**–16**	**–22**	**–28**	**–34**	**–40**
Design high pavement temperature, °C:	<64						<70					
Design low pavement temperature, °C:	>–10	>–16	>–22	>–28	>–34	>–40	>–10	>–16	>–22	>–28	>–34	>–40
Tests on Original Binder												
Flash Point Temperature (T 48), Min., °C	230											
Viscosity (ASTM D 4402) Maximum value of 3 Pa-s at test temperature, °C	135											
Dynamic Shear (TP 5) G*/sin δ, minimum value 1.00 kPa, at 10 rad/s and Test Temperature, °C	64						70					
Tests on Residue from Rolling Thin Film Oven (T 240)												
Mass Loss, Maximum, %	1.00											
Dynamic Shear (TP 5) G*/sin δ, minimum value 2.20 kPa, at 10 rad/s and Test Temperature, °C	64						70					
Tests on Residue from Pressure Aging Vessel (PP 1)												
PAV Aging Temperature, °C	100						100 (110)					
Dynamic Shear (TP 5) G* sin δ, maximum value 5,000 kPa, at 10 rad/s and Test Temperature, °C	31	28	25	22	19	16	34	31	28	25	22	19
Physical Hardening	Report											
Creep Stiffness (TP 1) Stiffness, maximum value 300 MPa m-value, minimum value 0.30, at 60 sec ant Test Temperature, °C	0	–6	–12	–18	–24	–30	0	–6	–12	–18	–24	–30
Direct Tension (TP 5) Failure strain, minimum value 1.0%, at 1.0 mm/min and Test Temperature, °C	0	–6	–12	–18	–24	–30	0	–6	–12	–18	–24	–30

Table 1. PG Grade Specification as Given in AASHTO M320-05 (continued).

Binder Performance Grade:	PG 76					PG 82				
	–10	**–16**	**–22**	**–28**	**–34**	**–10**	**–16**	**–22**	**–28**	**–34**
Design high pavement temperature, °C:	<76					<82				
Design low pavement temperature, °C:	>–10	>–16	>–22	>–28	>–34	>–10	>–16	>–22	>–28	>–34
Tests on Original Binder										
Flash Point Temperature (T 48), Min., °C	230									
Viscosity (ASTM D 4402) **Maximum value of 3 Pa-s at test temperature, °C**	135									
Dynamic Shear (TP 5) **G*/sin δ, minimum value 1.00 kPa, at 10 rad/s and Test Temperature, °C**	76					82				
Tests on Residue from Thin Film Oven (T 240)										
Mass Loss, Maximum, %	1.00									
Dynamic Shear (TP 5) **G*/sin δ, minimum value 2.20 kPa, at 10 rad/s and Test Temperature, °C**	76					82				
Tests on Residue from Pressure Aging Vessel (PP 1)										
PAV Aging Temperature, °C	100 (110)					100 (110)				
Dynamic Shear (TP 5) **G* sin δ, maximum value 5,000 kPa, at 10 rad/s and Test Temperature, °C**	37	34	31	28	25	40	37	34	31	28
Physical Hardening	Report									
Creep Stiffness (TP 1) **Stiffness, maximum value 300 MPa** **m-value, minimum value 0.30, at 60 sec ant Test Temperature, °C**	0	–6	–12	–18	–24	0	–6	–12	–18	–24
Direct Tension (TP 5) **Failure strain, minimum value 1.0%, at 1.0 mm/min and Test Temperature, °C**	0	–6	–12	–18	–24	0	–6	–12	–18	–24

Table 2. Summary of Recommended High Temperature Grade Adjustments.

Traffic Speed	Traffic Volume *MESALs*	*Grade Adjustment, °C*			
		AASHTO M 320-05	**LTPPBind 2.1/ Koch Materials**	**NCHRP 9-33 Resistivity/ Rutting**	**LTPPBind v. 3.1/ Damage Based**
Standard > 70 km/h	< 0.3	0	2	0	0.0
	0.3 to < 3	0	6	4	0.0
	3 to <10	0	8	6	6.5
	10 to <30	0*	10	9	11.3
	≥ 30	1	12	11	13.4
Slow 20 to 70 km/h	< 0.3	0	6	7	0.0**
	0.3 to < 3	6	10	12	2.6**
	3 to <10	6	12	13	8.8**
	10 to <30	6	14	16	13.5**
	≥ 30	6	16	19	15.5**
Standing < 20 km/h	< 0.3	0*	11	15	---
	0.3 to < 3	12	15	20	---
	3 to <10	12	17	22	---
	10 to <30	12	19	25	---
	≥ 30	12	21	27	---

*Consideration should be given to increasing the grade by 6°C.
**Slow traffic in LTPPBind 3.1 appears to be defined as 35 to 70 km/h.

An important question in developing a binder PG grade selection system for use in airfield pavements is which version of LTPPBind to use. LTPPBind 3.1 is more theoretically sound, but is a relatively new piece of software that has not been widely used. On the other hand, during development of Version 3.1 it became clear that there are significant errors in the transfer functions used in Version 2.1. In fact, most highway departments do not use LTPPBind 2.1 to select PG grades, but instead have developed their own guidelines for selecting binder grades; it is likely that the errors in Version 2.1 in part have lead to this dissatisfaction with LTPPBind. Recent work performed during NCHRP Project 9-33 has shown that binder grade selections given in LTPPBind version 3.1 provide reasonable levels of rut resistance for a wide range of climates, mix designs and traffic levels; therefore, this software is recommended for selecting base PG binder grades for airfield pavements, and also for adjusting high-temperature grades according to traffic level. The one major shortcoming in version 3.1 as of the writing of this report is that the range of speeds for which grade adjustments are given is limited, and the precise speeds used in calculating these adjustments are not given. The suggested procedure for selecting PG binder grades and for making appropriate adjustments for traffic level and aircraft speed is discussed later in this report.

PG Grade Slates Within State Highway Departments

The PG grade selection system is based on the temperatures of the area where the pavement is to be constructed, as described in the previous section. Although the potential number of different PG grades in many states is quite large, for practical reasons, the number of grades actually specified by most state agencies is limited. This simplified the grade selection process and makes producing the required PG grades easier for the refiner. Table 3 shows the most common PG grades specified by each state highway agency in the U.S.

Use of Modified Binders For Highway Pavements

A recent survey by Mr. John Casola conducted for the Association of Modified Asphalt Producers (AMAP) and published in 2005 indicated that in 2004 the percentage of modified asphalts to the total used in construction by State Highway agencies was approximately 23 % (*6*). The survey also confirmed the trend of increasing demand for modified asphalts in the highway construction reported earlier by others. The survey also indicated that although a large number of different modifiers can potentially be used in producing asphalt binders, the number of commonly used additives and modifiers is relatively small. Furthermore, Casola found that the Superpave specification is being amended in a number of different ways to better specify the modified asphalts; these special versions of the Superpave PG grading system are often referred to as "Superpave Plus or PG+ (*6*)." The following sections give a brief overview of the types of additives being used in producing different binders and the different versions of the Superpave Plus specification.

Table 3. Common PG Grades Used in Different States (Part I)

State	Common Binder PG Grades																						
	46	52		58			64				67	70					76				82		
	-28	-34	-28	-34	-28	-22	-34	-28	-22	-16	-22	-34	-28	-22	-16	-10	-16	-28	-22	-16	-28	-22	-16
Alabama	--	--	--	--	--	Y	--	--	Y	--	Y	--	--	--	--	--	--	--	Y	--	--	--	--
Alaska	--	--	--	--	Y	--	--	Y	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Arizona	--	--	--	--	--	Y	--	--	Y	Y	--	--	--	--	--	Y	--	--	Y	Y	--	--	--
Arkansas	--	--	--	--	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
Colorado	--	--	--	Y	Y	Y	--	Y	Y	--	--	--	Y	--	--	--	--	Y	--	--	--	--	--
Connecticut	--	--	--	--	Y	--	--	Y	Y	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Delaware	--	--	--	--	Y		--	--	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
Florida	--	--	--	--	--	--	--	--	Y	--	Y	--	--	--	--	--	--	--	Y	--	--	--	--
Georgia	--	--	--	--	--	Y	--	--	Y	--	Y	--	--	--	--	--	--	--	Y	--	--	--	--
Hawaii	--	--	--	--	--	--	--	--	--	Y	--	--	--	--	--	--	--	--	--	--	--	--	--
Idaho	--	--	--	Y	Y	--	Y	Y	Y	--	--	--	Y	--	--	--	--	Y	--	--	--	--	--
Illinois	Y	--	Y	--	Y	Y	--	Y	Y	--	--	--	Y	Y	--	--	--	Y	Y	--	--	--	--
Indiana	--	--	--	--	Y	--	--	Y	Y	--	--	--	Y	Y	--	--	--	--	Y	--	--	--	--
Iowa	--	Y	Y	--	Y	Y	--	Y	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
Kansas	--	--	--	--	--	Y	--	Y	Y	--	--	Y	Y	Y	--	--	--	Y	Y	--	Y	Y	--
Kentucky	--	--	--	--	--	Y	--	--	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
Louisiana	--	--	--	--	--	Y	--	--	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
Maine	--	--	--	Y	--	--	--	Y	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Maryland	--	--	--	--	--	--	--	Y	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
Massachusetts	--	--	--	Y	--	--	--	Y	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Michigan	--	Y	Y	Y	Y	Y	Y	Y	Y	--	--	--	Y	Y	--	--	--	Y	Y	--	--	--	--
Minnesota	--	--	--	Y	Y	--	Y	Y	--	--	--	Y	Y	--	--	--	--	Y	--	--	--	--	--
Mississippi	--	--	--	--	Y	--	--	--	--	--	Y	--	--	--	--	--	--	--	Y	--	--	Y	--
Missouri	--	--	--	--	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
Montana	--	--	Y	--	--	--	Y	Y	Y	--	--	--	Y	--	--	--	--	--	--	--	--	--	--
Nebraska	--	--	--	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--	--

Table 3. Common PG Grades Used in Different States (Part II)

State	Common Binder PG Grades																						
	46	52		58			64				67	70					76				82		
	-28	-34	-28	-34	-28	-22	-34	-28	-22	-16	-22	-34	-28	-22	-16	-10	-16	-28	-22	-16	-28	-22	-16
Nevada	--	--	--	--	--	--	Y	Y	Y	--	--	--	--	--	--	--	--	--	Y	--	--	--	--
New Hampshire	--	--	--	--	--	--	--	Y	Y	--	--	--	--	Y	--	--	--	Y	--	--	--	--	--
New Jersey	--	--	--	--	--	--	--	--	Y	--	--	--	--	--	--	--	--	--	Y	--	--	--	--
New Mexico	--	--	--	--	Y	--	--	Y	Y	--	--	--	Y	--	--	--	--	--	Y	--	--	Y	--
New York	--	--	--	Y	Y	--	--	Y	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
North Carolina	--	--	--	--	--	--	--	--	Y	--	--	--	Y	Y	--	--	--	--	Y	--	--	--	--
North Dakota	--	--	--	Y	Y	--	--	Y	--	--	--	--	Y	--	--	--	--	--	--	--	--	--	--
Ohio	--	--	--	--	Y	--	--	Y	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
Oklahoma	--	--	--	--	--	--	--	--	Y	--	--	--	Y	--	--	--	--	Y	--	--	--	--	--
Oregon	--	--	--	--	--	--	--	Y	Y	--	--	--	Y	Y	--	--	--	--	Y	--	--	--	--
Pennsylvania	--	--	--	--	Y	--	--	--	Y	--	--	--	--	--	--	--	--	--	Y	--	--	--	--
Puerto Rico	--	--	--	--	--	--	--	--	Y	--	--	--	--	Y	Y	--	--	--	--	--	--	--	--
Rhode Island	--	--	--	--	--	--	--	Y	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
South Carolina	--	--	--	--	--	--	--	--	Y	--	--	--	--	--	--	--	--	--	Y	--	--	--	--
South Dakota	--	--	--	Y	--	--	Y	Y	Y	--	--	Y	Y	--	--	--	--	--	--	--	--	--	--
Tennessee	--	--	--	--	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
Texas	--	--	--	Y	Y	Y	Y	Y	Y	Y	--	Y	Y	Y	Y	--	--	Y	Y	Y	Y	Y	Y
Utah	--	--	--	Y	--	--	Y	Y	--	--	--	Y	Y	Y	--	--	--	Y	Y	--	--	--	--
Vermont	--	--	--	Y	Y	--	Y	Y	--	--	--	--	Y	--	--	--	--	--	--	--	--	--	--
Virginia	--	--	--	--	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
Washington	--	--	--	Y	Y	Y	Y	Y	Y	--	--	Y	Y	Y	--	--	--	Y	Y	--	--	--	--
West Virginia	--	--	--	--	Y	--	--	Y	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
Wisconsin	--	--	--	Y	Y	--	Y	Y	Y	--	--	--	Y	--	--	--	--	Y	--	--	--	--	--
Wyoming	--	--	--	Y	Y	--	Y	Y	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--

Types of additives used for asphalt modification—there is currently a large number of modifiers used to make binders for different paving applications. Table 4 lists several published surveys concerning asphalt modifiers and lists the general types of modifiers that each study had identified (*7, 8, 9, 10, 11, 12, 13*). Not all these modifiers however have seen wide acceptability. The literature for the last 10 years has shown that only a handful of these modifiers are commonly used in practice and that polymers are among the most widespread. Table 5 is a summary of asphalt binder modifiers most commonly specified by different state agencies (*14*).

More recently the survey by the AMAP confirmed this trend and listed the percentage of use as follows:

- 67% SBS Modified
- 48% SB Modified
- 39% SBR Latex Modified
- 3% Other Polymer-modified
- 12% Chemical Modified
- 18% Other (generally Ground Tire Rubber; Oils)

The important difference that is also seen in the literature between practice in the mid 1990's and today is the increase in use of chemical modification. This is driven by the low cost of this technology and simplicity of using it. As emphasized elsewhere in this report, the asphalt binder market is driven by the specifications used by different state highway agencies; binders specified for use in airfield pavements must largely follow the highway pavement market and use same types of additives and modifiers.

Table 4. Recent Surveys on Asphalt Modifiers.

Modifier	Reference						
	Terrel and Epps, 1989 (*7*)	Peterson, 1993 (*8*)	Romine et al., 1991 (*9*)	Moratzai and Moulthrop, 1993 (*10*)	McGennis, 1995 (*11*)	Isacsson & Lu, 1995 (*12*)	Banasiak & Geistlinger, 1996 (*13*)
Thermoplastic Polymers	X	X	X	X	X	X	X
Thermoset Polymers	X	X	X	X	X	X	X
Fillers/Reinforcing Agents/Extenders	X	X	X	X	X	X	X
Adhesion Promoters	X		X	X	X	X	X
Catalysts or Chemical Reaction Modifiers	X	X	X	X	X	X	X
Aging Inhibitors	X	X	X	X	X	X	X
Others	X		X	X	X		
Total number of existing brands or types	-	46	-	82 (27ASA)*	48	31	62

*ASA: Antistripping Additives

Specifications for modified asphalts—One of the challenges in using modified asphalts is specifying them to achieve optimum performance at minimum cost. It has become increasingly clear since the conclusion of SHRP that the PG grading system does not fully consider the unique nature of modified asphalts and that the improved performance of these materials is not fully captured by the tests used in the PG grading system. This has resulted in changes and addition to the binder specifications to capture these properties or to specify a specific type of additive that an agency is interested in—the "Superpave Plus" systems referred to earlier in this report. Table 6 is a list of the different types of amendments to the PG grading system used by different agencies. Based on the analysis by AMAP, it appears that most of the agencies responding to the survey (94 %) have used some sort of amendment to the Superpave binder specification. Within the different versions of the Superpave Plus system, agencies specify a variety of tests; of the total tests included in such specification, elastic recovery tests are most commonly used, followed by the DSR:

- 42% of Superpave Plus tests are elastic recovery tests
- 20% are dynamic shear rheometer tests
- 10% are direct tension tests
- 10% are force ductility tests
- 10% are toughness and tenacity tests
- 20% are other procedures (ring and ball softening point; infrared spectroscopy, etc.)

Table 5. Asphalt Modifiers most commonly used by State Highway Agencies in the U.S.

Type	Class	No. of Agencies	Target Distress/Property (No. Of Agencies)				
			PD[1]	FC[2]	LTC[3]	MD[4]	AR[5]
Polymer – Elastomer	Styrene Butadiene Styrene (SBS)	28	18	8	10	3	6
	Styrene Butadiene (SB)	16	13	5	5	0	2
	Styrene Butadiene Rubber Latex (SBR)	17	10	4	4	1	2
	Tire Rubber	3	1		1		
Polymer – Plastomer	Ethyl Vinyl Acetate (EVA)	6	3				1
Anti-Stripping Agents	Fatty Amidoamines	8				4	
	Polyamines	6				4	
	Hydrated Lime	4				3	
	Others	7				3	
Hydrocarbons	Natural Asphalts	6	5				
Fibers	Cellulose	12	3		1		1
	Polypropylene	7	4		1		
	Polyester	6	4		1		1
	Mineral	3	1	1	1		
Processed-Based	Air Blowing	4	2				
Mineral Fillers	Lime	4				1	
Anti- Oxidants	Hydrated Lime	7				4	
Extenders	Sulfur	4					

[1] Permanent Deformation [2] Fatigue Cracking [3] Low-temperature Cracking [4] Moisture Damage [5] Aging existence

Table 6: Superpave Plus Specification Details by State (Part I)

State	Superpave Plus Specifications
Alabama	Polymer type (Elastomer), Quantity (%) and Quality (Measured with Infrared Trace)
Alaska	Softening point. Toughness & Tenacity at 25ºC (Alaska DOT test method)
Arizona	Polymer type (SBS or CRA) Quantity (%) plus the following requirements: • For SBS modified: solubility in TCE, phase angle, elastic recovery at 10ºC and softening point • For CRA modified: rotational viscosity, penetration ant 4ºC, softening point and resilience
Arkansas	Polymer type (Elastomer) and Elongation Recovery at 25ºC
California	NO
Colorado	Ductility, Toughness & Tenacity at 25ºC, Elastic Recovery at 25ºC
Connecticut	NO
Delaware	Rotational viscosity at 165ºC
Florida	Spot Test, Smoke test, Phase Angle, Solubility in TCE, Absolute Viscosity at 60ºC
Georgia	Phase Angle, Separation, Solubility in TCE
Hawaii	NO
Idaho	Elastic Recovery at 25ºC
Illinois	Separation, Force Ratio at 4ºC, Toughness & Tenacity at 25ºC, Elastic Recovery at 25ºC
Indiana	NO
Iowa	NO
Kansas	Separation, Elastic Recovery at 25ºC
Kentucky	Solubility in TCE, Elastic Recovery at 25ºC
Louisiana	Solubility, Separation, Force Ductility Ratio, Force Ductility, Elastic Recovery at 25ºC, Ductility at 25ºC
Maine	NO
Maryland	Critical cracking temperature
Massachusetts	Polymer type (SBR)
Michigan	Polymer type (SBS or SBR, others need approval), Solubility in TCE, separation, Elastic Recovery at 25ºC, plus the following requirements: • For SBS modified: Force Ratio • For SBR modified: Toughness & Tenacity at 25ºC
Minnesota	NO

Table 6: Superpave Plus Specification Details by State (Part II)

State	Superpave Plus Specifications
Mississippi	Polymer type (SBS or SBR, others need approval), Quantity (%), Temperature - Viscosity Curve
Missouri	Separation, Elastic Recovery at 25ºC
Montana	Ductility at 25ºC
Nebraska	Phase Angle, Elastic Recovery at 25ºC
Nevada	Ductility, Sieve, Toughness & Tenacity at 25ºC, Polymer Content
New Hampshire	NO
New Jersey	Elastic Recovery at 25ºC
New Mexico	NO
New York	Elastic Recovery at 25ºC
North Carolina	Polymer type (Elastomer)
North Dakota	To implement in 2005
Ohio	Penetration at 25ºC, Phase Angle, Separation, Homogeneity, Elastic Recovery at 25ºC
Oklahoma	Separation, Solubility in TCE, Spot Test, Elastic Recovery at 25ºC
Oregon	Only for Chip Seal Asphalt
Pennsylvania	Separation, Softening Point, Elastic Recovery at 25ºC
Puerto Rico	
Rhode Island	NO
South Carolina	Polymer type (Elastomer)
South Dakota	Elastic Recovery at 25ºC
Tennessee	Polymer type (Elastomer), Viscosity at 135ºC (Contractor Plant Testing), Softening Point, Elastic Recovery at 10ºC, Screen Test.
Texas	Elastic Recovery at 10ºC
Utah	Phase Angle, Elastic Recovery at 25ºC
Vermont	NO
Virginia	Elastic Recovery at 25ºC
Washington	NO
West Virginia	Elastic Recovery at 25ºC
Wisconsin	To be implemented in 2005
Wyoming	Elastic Recovery at 25ºC

The number of Superpave Plus specifications is large and is not expected to be reduced in the near future due to lack of a good alternative. There are discussions about using the new creep and recovery test developed during NCHRP Project 9-10, but the procedure has not yet been standardized and implementation is not in the near future. It was therefore necessary to develop a new system for use in specifying binders for airfield pavements that could be used in conjunction with the proposed PG grade selection procedure for airfield pavements. This simple system is discussed later in this report.

CURRENT BINDER GRADE SELECTION PROCEDURES FOR AIRFIELD PAVEMENTS

Historical Development

Consistent with the industry, binder selection for airports has gradually evolved from penetration grading to viscosity grading systems. Prior to the adoption of the performance grading (PG) system, most airport pavements constructed before 2000 consisted of AC-10 binder binders in colder regions, AC-20 for the majority of the United States, and AC-30, and in some instances AC-40, for hot climates.

Current Standards and Engineering Briefs

Primary FAA guidance on binder selection is contained in Item P-401 and Item P-403 specifications. The P-401 specification is intended for flexible pavement surface course (i.e., top 4 to 5 inches) and the P-403 specification is primarily intended for bituminous base and leveling courses. Both specifications are contained in FAA Advisory Circular 150/5370-10C, "Standards for Specifying Construction of Airports", dated September 29, 2007. Although the specifications permit the use of PG, penetration and viscosity grades, a "Note to the Engineer" states that PG grades should be specified wherever available. However, virtually all hot mix asphalt pavements constructed today utilize PG binders, including California, which recently adopted the PG system.

FAA guidance on binder selection does include suggested restrictions on the "cold" side of the binder grading and suggests guidance for applying "grade bumps". This guidance is summarized in the following, which is excerpted from a "note to the Engineer":

NOTE: Performance Graded (PG) asphalt binders should be specified wherever available. The same grade PG binder used by the state highway department in the area should be considered as the base grade for the project (e.g. the grade typically specified in that specific location for dense graded mixes on highways with design Equivalent Standard Axle Loads (ESALS) less than 10 million). The exception would be that grades with a low temperature higher than PG XX-22 should not be used (e.g. PG XX-16 or PG XX-10), unless the Engineer has had successful experience with them. Typically, rutting is not a problem on airport runways. However, at airports with a history of stacking on end of runways and taxiway areas, rutting has accrued due to the slow speed of loading on the pavement. If there has been rutting on the project or it is anticipated that stacking may accrue during the design life of the project, then the following grade "bumping" should be applied for the top 125 mm (5 inches) of paving in the end of runway and taxiway areas: for aircraft tire pressure between 100 and 200 psi, increase the high temperature one grade; for aircraft tire pressure greater than 200 psi, increase the high temperature two grades. Each grade adjustment is 6 degrees C. Polymer-modified Asphalt, PMA, has shown to perform very well in these areas. The low temperature grade should remain the same.

Additional grade bumping and grade selection information is given in Table A.

Table A. Binder Grade Selection and Grade Bumping Based on Gross Aircraft Weight.

Aircraft Gross Weight (pounds)	*High Temperature Adjustment to Base Binder Grade*	
	Pavement Type	
	Runway	*Taxiway/Apron*
Less than 12,500	--	--
Less than 60,000	--	*1*
Less than 100,000	--	*1*
Greater than 100,000	*1*	*2*

NOTES:
1. PG grades above a –22 on the low end (e.g. 64–16) are not recommended. Limited experience has shown this to be a poor performer.
2. PG grades below a 64 on the high end (e.g. 58-22) are not recommended. These binders often provide tender tendencies.
3. PG grades above a 76 on the high end (e.g. 82-22) are not recommended. These binders are very stiff and difficult to work and compact.

Therefore, except for exceptional conditions, the FAA suggest the use of only three binder grades in the national standards, PG 64-22, PG 70-22, or PG 76-22, with binder selection consistent with local practice based on the caveats discussed. As discussed below, this can be modified on a regional basis.

Other guidance is provided in FAA Engineering Brief No. 59A, "Item P-401 Plant Mix Bituminous Pavements (Superpave)", dated May 12, 2006; Engineering Brief No. 51, "Polymer-modified Asphalt", dated November 1994; Engineering Brief No. 45, "Polyethylene Modified Asphalt Cement", dated February 1990; and Engineering Brief No.39, "Styrene-Butadiene Rubber Latex Modified Asphalt, dated March 1987. Of these, Engineering Brief No 59 is perhaps more widely applied than the other; however, most hot mix airport pavements are produced using Marshall, rather than Superpave, mixes. In any case, the binder selection guidance contained in Engineering Brief No. 59 is essentially the same as that contained in the P-401 and P-403 specifications.

There are also regional modifications to the national P-401/P-403 standards, which contain guidance applicable to a particular FAA Region. The most comprehensive of these is the Northwest Mountain Region's (ANW) modification concerning binder selection, "Notice 15," which is reproduced below:

> *Note to Engineer -- Performance Graded (PG) asphalt should be locally available and specified. A high reliability (98 percent) on both the high and low temperature categories should be used. Theses cements provide benefits for airfield pavements by minimizing low temperature cracking. It is recommended that the designer consult with the state DOT for the binder used for greater than 10M ESALs highways. Using this grade the high temperature should be bumped up one grade for greater than 60K gross aircraft weight. The upper grade should be bumped by 2 for greater than 100K gross weight aircraft. The following table can be used if no DOT information is available. Notify the FAA District Office if these grades are not consistent with those specified or available in the state.*

State	*PG Binders for Aircraft Gross Loading*	
	60K and Under	*Over 60 K*
Colorado –Western	*58-34*	*64-34*
Colorado – Eastern	*58-34*	*64-28*
Idaho – Northern	*58-34*	*64-34*
Idaho – Southern	*64-34*	*64-34*
Montana – Western	*58-34*	*64-34*
Montana – Eastern	*64-34*	*64-34*

Oregon – Western	*64-22*	*70-22*
Oregon – Eastern	*64-28*	*70-28*
Utah	*64-28*	*70-28*
Washington – Western	*64-22*	*64-22*
Washington – S. Eastern	*64-28*	*70-28*
Washington – N. Eastern	*58-34*	*64-34*
Wyoming – Western	*58-34*	*64-34*
Wyoming – Eastern	*64-34*	*64-34*

Note: For some binders a synthetic additive may have to be added to meet the high temperature specification. When the temperature values added together exceed 90, the asphalt will probably contain a modifier. In this case include the Elastic Recovery Testing requirements from the paragraph shown below:

The binder (RTFO) aged residue shall be tested in accordance with AASHTO T 301 for Elastic Recovery tested at 25 degrees C. The recovery shall be 50% minimum]

Note: The following table for modified asphalt cements to be consistent with State DOT specifications for specified grade. Any changes to these requirements are required to be approved by the FAA Airports District Office.

Property	*Min.*
Toughness, Inch-Pounds	*75*
Tenacity, Inch-Pounds	*50*
(per ASTM D 5801)	

Use of Modified Binders in HMA used in Airfield Pavements

Airfield pavements are subjected to very heavy loads and high tire pressures. For this reason, distresses such as shoving and rutting are likely to appear in early stages of the asphalt pavement life (*15, 16*). Polymer-modified asphalt (PMA) binders are specially suited for resisting permanent deformation and they generally show better adhesion with the aggregates than non-modified asphalts. This makes polymer-modified binders especially well suited for airfield pavements handling large volumes of heavy aircraft. Recognizing this fact, airport engineers in the United States are starting to look at PMA as a better alternative for the design of HMA pavements.

In Europe, the use of PMA is already a common practice in airfield surface pavements (*17*). In Denmark, for example, taxiways pavement surfaces are designed using different kinds of mixtures (dense graded, open graded and SMA) in combination with modified binders, most often using SBS elastomeric modification. In France, it is common that the surface courses of airfield pavements subject to heavy traffic are designed using PMA. PMA is also common in surface rehabilitation projects in French airfields. In Germany, PMA binders are the most popular choice as part of a dense mix or an SMA for runways, taxiways and other airfield paving applications. In Italy, the surface pavement is normally a dense mix and that often employs a PMA (*17*). In the Netherlands there has been research going on for some years about the performance and economic viability of modified binders for airfields (*18, 19*). The results of the studies showed that PMA can not only improve the structural performance of the pavement, but also the functional life span of the pavement.

Unfortunately, little information exists in engineering reports and research papers on the use of PMAs in airfield pavements in the U.S., although they have been used extensively at some facilities, including those of the Port Authority of New York and New Jersey. In part to fill this information gap, a questionnaire was developed as part of Project 04-02 to collect information on airfield pavements. This questionnaire was posted on a website, and letters forwarded to a number of airfield engineers explaining the purpose of this questionnaire and requesting their cooperation. Numerous follow up requests were made at technical meetings and through phone calls to key personnel. Unfortunately, the response was disappointing. The responses to the questionnaire are included in Appendix A of this report, which includes information on other projects not involving the use of PMAs; both types of data are used later in this report in an evaluation of the proposed binder grade selection procedure.

AIRCRAFT CHARACTERISTICS RELEVANT TO BINDER GRADE SELECTION

As discussed later in this report, analysis of binder PG grade requirements for airfield pavements requires information concerning the tire pressure and other aircraft characteristics. Therefore, a database of aircraft characteristics is needed. To meet this need, the characteristics of most commercial and military aircraft have been compiled in six tables for different aircraft types:

- Generic aircraft
- Aircraft manufactured by Boeing
- Aircraft manufactured by Airbus
- Other commercial aircraft

- GA aircraft
- Military aircraft

These tables each list:

- Aircraft type
- Gear type using the old and recently adopted gear type nomenclature
- Typical gross aircraft loads, which can be modified by the user
- Gear loads, i.e., loading on a gear truck or cluster
- Wheel loads
- Tire pressures
- Pass to coverage ratio (PCR) computed at the surface of the pavement

The gear and wheel loads are linked to the aircraft gross loads, so if the gross aircraft load is changed, the gear and wheel loads will be automatically updated. The gross loads, percentage of loading on the main gear, and tire pressures were extracted from FAA's LEDFAA program, which obtained the data from aircraft manufacturers. The PCRs were computed by the LEDFAA program. An example is shown in Table 7, which lists characteristics for aircraft manufactured by Boeing.

MODIFYING THE PG GRADING SYSTEM FOR AIRFIELD PAVEMENTS

As discussed previously, the PG grading system for highway pavements relies on three primary grading criteria: low temperature, high temperature and intermediate temperature requirements. The low-temperature requirements are meant to primarily address low-temperature cracking, while the high temperature requirements address rutting and other forms of permanent deformation. The intermediate temperature grading requirements are meant, at least in part, to address fatigue resistance. In order to effectively modify the PG system for use for airfield pavements, all three aspects should be addressed as appropriate. The general approach proposed for modifying the three components of the PG grading system are discussed below.

Table 7. Boeing Aircraft Characteristics.

Aircraft	Gear Type		Gross Load	Gear Load	Wheel Load	Tire Pressure	Pass-Coverage Ratio
	Old System	*New System*	*lb*	*lb*	*lb*	*psi*	
B-707	DW	D	325,000	154,375	77,188	180	3.46
B-727	DW	D	172,000	81,700	40,850	160	3.16
B-717	DW	D	119,000	56,525	28,263	164	3.61
B-737-100	DW	D	100,000	47,500	23,750	148	3.86
B-737-200	DW	D	128,600	61,085	30,543	182	3.78
B-737-300	DW	D	140,000	66,500	33,250	201	3.80
B-737-400	DW	D	150,500	71,488	35,744	185	3.52
B-737-500	DW	D	134,000	63,650	31,825	194	3.82
B-737-700	DW	D	153,500	72,913	36,456	189	3.65
B-737-800	DW	D	173,000	82,175	41,088	205	3.56
B-737-900	DW	D	174,700	82,983	41,491	205	3.54
B-747-200	DDT	2D/2D2	833,000	197,838	49,459	200	3.56
B-747-400	DDT	2D/2D2	873,000	207,338	51,834	200	3.48
B-747-400ER	DDT	2D/2D2	913,000	216,838	54,209	230	3.65
B-747-SP	DDT	2D/2D2	700,000	166,250	41,563	183	3.68
B-757	DT	2D	250,000	118,750	29,688	180	3.93
B-767-200	DT	2D	335,000	159,125	39,781	190	3.91
B-767-300ER	DT	2D	409,000	194,275	48,569	200	3.63
B-767-400ER	DT	2D	451,000	214,225	53,556	215	3.62
B-777-200	TT	3D	537,000	255,075	42,513	185	4.26
B-777-200ER	TT	3D	634,500	301,388	50,231	215	4.22
B-777-300	TT	3D	662,000	314,450	52,408	215	4.13
B-777-300ER	TT	3D	752,000	357,200	59,533	218	3.91

Low-temperature Grading

As discussed previously, low-temperature grading in the binder PG grading system for highways is based on the climate in any given area—specifically, the lowest expected temperature of the pavement surface. The low-temperature grade is determined by using the BBR to determine the lowest temperature at which the maximum stiffness and minimum m-value values are met. An alternate grading method determines the low-temperature grading based upon results of the direct tension test and empirical calculations to relate these results to observed cracking temperatures in actual pavements. The direct tension procedure was specifically designed to provide more accurate low-temperature grading for polymer-modified binders.

Although neither low-temperature grading method explicitly considers stresses from traffic loading, in reality such stresses must contribute to thermal stresses at low temperature and affect low-temperature performance. In the case of large aircraft with high wheel loads and tire pressures, the distortional stresses near the pavement surface will be significantly higher than is the case in highways under traffic loading—this could cause an increase in expected cracking temperature for a given binder, perhaps requiring an adjustment to the low-temperature grade. However, there is little evidence that runways at large airfields are particularly susceptible to low temperature cracking. It is possible that the relatively open nature of airfield pavements and their large thermal mass help to store heat during the day and prevent extreme low temperatures in the early morning. Heat from jet exhaust and the kneading action of frequency traffic might also help to prevent thermal cracking at large airfields. On the other hand, there is reason to expect that thermal cracking at small airfields can be a problem. It is well known that highway pavements subject to little or no traffic are prone to thermal cracking. Although the reason for this is not clear, it could be that frequent traffic loading helps prevent steric hardening of the pavement; in pavements that receive little or no loading, steric hardening can become significant, causing the pavement to become stiff and brittle and prone to cracking.

Unfortunately, addressing this particular issue in the PG grade selection process is difficult. This is because the PG grades available in a given area tend to be limited by the expected low temperature in that locale. Producers will generally not provide binders with a low-temperature grade exceeding that which is normally required in a given region. Furthermore, it is more difficult to extend the low temperature performance of an asphalt binder than the high-temperature performance. There are however two practical approaches that can be used to help prevent thermal cracking in HMA pavements at small airfields. First, care should be taken in selecting the high-temperature PG grade, to ensure that the binder is no stiffer than needed to resist rutting under the expected traffic. This will help prevent excessive stiffening and may also promote healing when cracking does occur. The specifics of the recommended grade selections are discussed later in this report. The second approach does not involve binder selection, but instead involves mix design. In highway pavements, HMA mixes for low traffic roads are in general designed with more asphalt binder and at lower design compaction levels. This approach should be considered for use in AAPTP project 0-4-03, in which the Superpave method of mix design is being modified for use in airfield pavements. Additional practical guidelines for selecting binder grades and designing HMA mixes to resist non-load associated cracking are being developed as part of AAPTP Project 05-07.

Intermediate Temperature Grading

As discussed above, intermediate temperature PG grades are based on the concept that asphalt binders that are too stiff at intermediate temperatures may be prone to premature fatigue cracking. For this reason, the intermediate temperature criteria in the PG system are sometimes referred to as "fatigue criteria." The specific requirements are a maximum value for $|G^*| \sin \delta$ of 5,000 kPa at 10 rad/s, at a temperature 4°C above the average of the high- and low-temperature grades. This value was based partly on observations of premature cracking on several test roads, and also on experience and typical rheological properties of paving asphalts. The primary assumption of this "fatigue grading" system is that higher traffic levels—either resulting from larger or more numerous axle loads—are addressed in the structural design. For higher traffic levels, the pavement thickness is increased, or the structure is improved (for instance, by stabilizing the subgrade soil).

It is essential to understand that there currently are no provisions within the PG system for adjusting intermediate temperature grades for different traffic levels. Some engineers have been critical of how fatigue resistance is addressed in the PG system, but there is not yet a consensus concerning what changes are needed to improve it. The relationship between binder mechanical properties and pavement fatigue resistance is still very poorly understood. Furthermore, even if there were a basis for modifying the intermediate temperature grading for binders used in airfield pavements, the resulting PG grades would in many cases differ substantially from those being produced for use in highway construction, and would therefore not be produced on a regular basis by refiners. For these reasons, the proposed system for selecting PG grades for airfield pavements will maintain the current system of intermediate temperature grading. However, one important aspect of the proposed PG system is that the specification will clearly state that the temperature at which the value of $|G^*| \sin \delta$ will be evaluated will be based on the base PG grade, and not the grade after adjustments for traffic, speed and depth. This is consistent with the original intent of the PG grading system, although during its initial implementation many agencies did not understand the system and did not interpret the specification in this way. Instead, they determined the temperature for evaluating $|G^*| \sin \delta$ based upon the adjusted high temperature grade, which can substantially increase the intermediate test temperature and allow a much stiffer binder to be used in a given climate. This has in some cases resulted in binders being used that were much stiffer at intermediate temperatures that the developers of the PG system intended. This could be an important contributing factor to the recent increase in top-down cracking in HMA highway pavements. In order to ensure that airfield pavements are not prone to top-down cracking and other forms of surface distress, it is essential that the intermediate temperature grading be correctly interpreted and implemented.

High Temperature Grading

High temperature grading in the PG system is designed to provide a binder with an appropriate degree of resistance to permanent deformation, so that pavements made using a properly graded binder will resist rutting but not be excessively stiff. Adapting this part of the PG system to use for airfield pavements is much more complicated than the low-temperature grading adjustment, and much more important because the impact of higher wheel loads and tire pressures on rutting is probably much more significant than their effects on thermal cracking.

There are several aspects to high-temperature grading in the PG system that must be modified for use of the system for airfield pavements. Probably the most important is the higher stress levels exerted on the pavement surface by many aircraft. The stress at and near the pavement surface will be proportional to the tire inflation pressure—about 90 to 120 lb/in^2 for commercial trucks, but ranging up to 250 lb/in^2 or higher for aircraft. The increased tire pressures for large aircraft will cause a significant increase in rutting compared to a similar number of passes by commercial trucks. Another important difference in rutting in airfields compared to highway pavements is that when aircraft are taking off and landing, they wander over the runway to a much greater extent than do commercial trucks on a highway. Furthermore, the gear configurations on aircraft vary widely and are not directly comparable to the typical number and types of axles on a commercial truck. Therefore, even once a system is devised for determining the rutting damage done by the more heavily loaded aircraft tires, some means of accounting for differences in aircraft wander and gear configuration must be developed.

Because of the complexity of these and related adjustments needed to adapt the PG grading system for use for airfield pavements, addressing it requires a lengthy and complex discussion. This is presented in the following section of this report, and is by far the most important part of this document.

Polymer-modified Asphalts

There are several problems that need to be addressed when addressing PMAs in the selection of binder PG grades for airfield pavements. The first is whether or not PMAs should be used at all; based upon the technology review presented earlier, there appears to be no good reason not to use common PMAs in HMA for airfield pavements, and the improved performance of many PMAs appears to make them particularly well suited for airfield pavements carrying large numbers of heavy aircraft. A second issue is how best to account for the performance of PMAs. Many PMAs exhibit better performance than is indicated by the standard PG grading, which has lead to the proliferation of Superpave Plus specifications. As discussed below (see Equation 13 and the related discussion), research performed during NCHRP Project 9-33 suggests that HMA made with some PMAs can exhibit more than four times the rut resistance of non-modified binders of similar grade. A related problem is, if some PMAs do provide better performance than suggested by the current PG specification, how can such binders be specified for use in airfields? A related issue is what simple test procedure, if any, can be used to ensure that a given PMA does provide the performance level desired for a given airfield pavement application.

The research team has developed an approach to specifying and selecting PMAs for use in airfields that includes three primary features. First, PMAs will be tested using the common elastic recovery (ER) test, meant to be a surrogate for the newly developed multiple stress creep and recovery (MSCR) test. Although promising, there is not yet enough experience with the MSCR test to use it with confidence for specifying binders for use in airfield pavements. The second feature of this approach is that PMAs meeting the ER requirement will be given an additional half-grade (3 °C) in their high temperature PG grading. For example, a PG 76-22

PMA would be acceptable for pavements requiring a high-temperature grading of up to 79.0 °C. The third and final part of this approach is that for taxiways and runway ends experiencing frequent aircraft stacking, it is strongly recommended that the HMA be designed using a PMA. Technical details supporting this approach to the specification and use of PMAs in airfield pavements are discussed later in this report.

EQUIVALENT SINGLE AXLE LOADS FOR HIGHWAYS AND AIRFIELDS

The single most important part of developing an effective PG grading system for airfield pavements is the calculation of equivalent highway ESALs, or EHEs for a given mix of aircraft traffic. The concept of EHEs was introduced under the Research Approach section of Chapter 1 of this report, but is reviewed here for the convenience of the reader. ESALs stands for equivalent single axle loads, and is a means of characterizing the overall amount of traffic on a given pavement. The calculation is based upon how much damage is done to a pavement by a each vehicle type passing over the pavement, and how many vehicles of each type pass over the pavement during its design life. The only software package currently available for selecting PG binder grades—LTPPBind—uses ESALs to characterize the severity of traffic loading. EHEs is simply a way for characterizing the overall magnitude of loading on a flexible pavement subject to a given mix of air traffic, in such a way that LTPPBind can be used to select an appropriate PG binder grade. Using EHEs does not in any way assume similarity between trucks and aircraft, or between highway and airfield pavement. It is merely a convenient tool used in the binder selection process.

The calculation of EHEs revolves around rutting, since tire pressure, wheel loads, and traffic wander. These factors have little or no effect on the low and intermediate temperature grading system currently used in the PG specification system, and so most of the PG binder grade selection process revolves around high-temperature grade selection. In order to develop an effective method for estimating EHEs, it is first necessary to discuss the procedure used to calculate ESALs for highway pavements.

Equivalent Single Axle Loads

In his well-known text *Pavement Analysis and Design*, Huang presents the following equation for calculating ESALs for highways (*20*):

$$ESALs = \left(\sum_{i=1}^{m} p_i F_i\right)(ADT)_0 (T)(A)(G)(D)(L)(365)(Y) \qquad (1)$$

Where

p_i	=	percentage of total repetitions for i^{th} load group
F_i	=	equivalent axle load factor for i^{th} load group
	=	damage caused by one load repetition of i^{th} load group relative to 18 kip axle load
$(ADT)_0$	=	initial average daily traffic
T	=	percentage of trucks in average daily traffic
A	=	average number of axles per truck
G	=	growth factor
D	=	directional distribution factor (usually 0.5)
L	=	lane distribution factor
365	=	days per year
Y	=	design period in years

The construction of Equation 1 is for the most part straightforward, accounting for damage caused by different truck types, the distribution of truck types, bi-directional traffic, distribution of traffic among different lanes, etc. Probably the most critical part of this equation, and the most difficult to determine, is the equivalent axle factor for a given truck type. This factor can either be taken from tables developed on the basis of various test roads, or from a theoretical damage analysis. The discussion below presents a similar equation that can be used to calculate the EHEs necessary for determining the high-temperature PG grade needed for a given airfield pavement.

Determining Equivalent Highway ESALs

Many of the factors in Equation 1 simply do not apply to the case of airfield pavements. For example, the lane and directional distribution factors do not apply to airfield runways since they are not split into arriving and departing lanes, or into fast and slow lanes. Because traffic for airfields is characterized by annual departures, this factor is used in place of average daily traffic. This change also eliminates the factor 365 from the equation for airfield EHEs. Highway traffic is usually assumed to be channelized, meaning that for truck traffic (the only vehicles that do significant damage to the pavement), there is little or no wander, and this does not need to be addressed in the equation for ESALs. However, in airfield pavements, there is significant wander during landing and takeoff. Fortunately, the degree of wander has been characterized for different aircraft through the pass-to-coverage ratio (PCR), which must be included in the calculation of EHEs.

As discussed above, perhaps the most critical factor in Equation 1 is the equivalent axle load factor *F* for each vehicle group. This factor accounts for the amount of damage done by one axle pass of a vehicle in the given group. Furthermore, *F* accounts for both fatigue damage and rutting. Values for *F* for highway vehicles can be determined either by analyzing data from test roads, or by analytical methods. When determining *F* from test roads, measurable indications of pavement distress are correlated to number of axle loads for different vehicle groups, and this data is then translated to determine how many axle loads for a given vehicle do damage equivalent to a single pass of a standard 18,000 lb axle. In analytical methods, mechanistic-empirical models for predicting pavement distress are used to estimate damage under a given axle type, and this information is used to determine the equivalent number of standard axles. This approach has been limited to fatigue damage and subgrade rutting, since these are the only distress modes for which generally accepted analytical techniques exist.

In the case of determining EHEs for the purpose of selecting PG grades for airfields, it is not necessary to consider damage caused by fatigue or subgrade rutting. This is because these modes of distress are already addressed in airfield pavement design, and in any case, the relationships between binder grade and structural pavement response is not well understood and is not addressed in the existing PG grading system. Therefore, the determination of EHE’s depends only upon rutting. Furthermore, because the PCR for a given aircraft effectively accounts for differences in damage caused by tire size, undercarriage design and aircraft wander, these factors for the most part need not be considered separately. However, because of the larger size of many aircraft tires, it should be expected that the reduction in damage with depth in the pavement might be significantly different from that which occurs under truck tires. This changes the extent to which PG grades can be reduced with depth from the pavement surface, and is discussed in detail later in this section—for convenience, it will not be handled through the calculation of EHEs. Because vehicle speed effects rutting, and aircraft speeds vary tremendously among different areas in an airfield, this must also be considered when selecting PG grades for HMA in airfield pavements. However, in the PG grading system, vehicle speed is normally addressed by applying an adjustment to the base high temperature grade. For simplicity and ease of implementation, this approach will be maintained here, so a speed factor is not included in the EHE equation. Another factor that must be considered when developing an equations for EHEs is that the analyses used in the MEDG and LTPPBind v. 3 were based on HMA designed and constructed for highway pavements; the design and construction of HMA for airfield pavements differs significantly in several important respects, and this potentially has an effect on the rut resistance of these materials and the selection of high-temperature binder grades. The three areas in which the two HMA types differ that are expected to cause differences in rut resistance are mix composition (design VMA and mineral filler content), design compaction and field compaction. The final adjustment that is needed relates to the issue of reliability against failure; because of the potential catastrophic results of accidents on airfield pavement, the reliability against failure should probably be somewhat higher compared to that for highway pavements. Incorporating all the appropriate factors in the calculation of EHEs leads to the following equation:

$$EHEs = \sum_{i=1}^{m}\left[(TP_i)\left(\frac{PDR_i}{PCR_i}\right)(N_i)\right](COMP)(LC)(FC)(REL)(Y)\left(1+\frac{R}{100}\right)^{0.5Y} \quad (2)$$

Where

TP_i = tire pressure factor for the ith aircraft group

PCR_i = pass to coverage ratio for the ith aircraft group

PDR_i	=	pass to departure ratio for the i^{th} aircraft group
	=	1 for parallel taxiways
	=	2 for central taxiways
	=	2 for runways with parallel taxiways
	=	3 for runways with central taxiways
N_i	=	annual departures for the i^{th} aircraft group
COMP	=	composition factor, to account for differences in rut resistance between typical airfield and highway HMA caused by differences in design VMA and mineral filler content
LC	=	lab compaction factor, to account for differences in design compaction between typical airfield and highway HMA mixtures
FC	=	field compaction factor, to account for differences in field compaction between typical airfield and highway HMA pavements
REL	=	reliability factor, to address any adjustment needed in reliability level of airfield pavements relative to highway pavements
Y	=	design life, in years (assumed to be 20 unless otherwise noted)
R	=	annual growth rate in traffic, %

Development of Tire Pressure Factor

The stress levels near the surface of a pavement have a very strong effect on rutting—as the stress level increases, the rutting increases. Furthermore, this effect is not necessarily linear, since the response of asphalt concrete under high stress levels at elevated temperatures is highly non-linear. As a first estimate, the stresses near the surface of a pavement are proportional to the applied stress—which is equal to the tire inflation pressure. Because tire pressures for aircraft are often much higher than for commercial trucks, accounting for the effect of increased tire pressure on rutting is a critical aspect of selecting binder PG grades for airfield pavements.

During Phase I of Project 04-02, four different models were identified that relate stress level to rutting in HMA pavements:

1. The model used in the Mechanistic Empirical Design Guide (MEDG) developed during NCHRP Project 1-37 (*21*)
2. The rutting/resistivity model developed during NCHRP Projects 9-25 and 9-31 (*22, 23*)
3. The rutting model developed by Kaloush and Witczak early during NCHRP Project 1-37 (*24*)
4. The model developed in the early 1990's by Leahy and Witczak (*25*)

The first two of these have been calibrated to a range of field data and appear reasonably accurate, and predict a similar relationship between tire pressure and rutting. Kaloush and Witczak's model is based on laboratory data alone, and in fact is a precursor to the MEDG model; therefore, it should not be considered for use in developing the tire pressure factor. Leahy and Witczak's model is also based on laboratory data alone. Furthermore, this model predicts much less sensitivity to stress level than the MEDG and rutting/resistivity models. Therefore, it does not appear to be applicable to field rutting and the determination of the tire pressure factor for airfield pavements. Of the first two models, it was decided to use the first—the MEDG model—to maintain consistency with what will likely be standard practice in highway pavement design in the future, and also for consistency with LTPPBind 3.1, which is based on the MEDG model.

In the latest published version of the MEDG, the following equation is used to model permanent deformation in flexible pavements (*20*):

$$\frac{\varepsilon_p}{\varepsilon_r} = k_1 \times 10^{-3.4488} T^{1.5606} N^{0.479244} \tag{3}$$

Where

k_1 = a factor that depends upon total thickness of HMA layers and depth within the pavement of the point considered

ε_p = accumulated plastic strain at N repetitions in the given HMA layer, in/in

ε_r = resilient strain in the HMA mixture under the given conditions, in/in

T = temperature, °F

N = number of load repetitions

The value of k_1 is calculated using the following equation:

$$k_1 = \left(C_1 + C_2 Z\right)0.328196^Z \tag{4a}$$

$$C_1 = -0.1039h^2 + 2.4868h - 17.342 \tag{4b}$$

$$C_2 = 0.0172h^2 - 1.7331h - 27.428 \tag{4c}$$

Where:

Z = depth from pavement surface of point of interest, in.

h = total thickness of HMA layers, in.

Note that for a given pavement structure, and a selected point within that pavement, k_1 is a constant. Equation 4 can be rearranged to give an equation for plastic strain:

$$\varepsilon_p = \varepsilon_r k_1 \times 10^{-3.4488} T^{1.5606} N^{0.479244} \tag{5}$$

Because linear elastic analysis is used to determine εr, it will be proportional to tire pressure *p*. Therefore, for any given pavement structure at any given temperature, plastic strain will be proportional to tire pressure and load repetitions raised to the exponent 0.479244:

$$\varepsilon_p = pk_2 N^{0.479244} \tag{6}$$

Where k_2 is a factor encompassing k_1, the pavement response, and $T^{1.5606}$. For any given pavement structure, rut depth will be proportional to the accumulated plastic strain. Therefore, Equation 6 can be rewritten:

$$RH = pk_3 N^{0.479244} \tag{7}$$

Where RH is rut depth and k_3 is a function of temperature, pavement structure, and various other factors. For comparing two cases that are identical (including the same rut depth) except for tire pressure, Equation 7 leads to the following equation:

$$p_1 N_1^{0.479244} = p_2 N_2^{0.479244} \tag{8}$$

Which in turn leads directly to

$$N_2 = \left(\frac{p_1}{p_2}\right)^{2.09} N_1 \tag{9}$$

Where the exponent 2.09 is the inverse of 0.479244. In this case, N_2 would be the equivalent highway ESALs—that is, load repetitions at p_2 required to cause the same damage as N_1 repetitions at some higher tire pressure p_1. If the average truck tire pressure is assumed to be 120 lb/in^2, and the exponent is rounded to 2.0 Equation 9 then leads directly to the equation for tire pressure factor:

$$TP = \left(\frac{p}{120}\right)^{2.0} \tag{10}$$

Since resilient strain in this case is determined using linear elastic analysis, it will be proportional to the applied stress (tire pressure p), all else being equal. Therefore, the MEDG predicts that the number of loads required to reach a given level of plastic strain will be approximately proportional to the square of the tire pressure. The denominator in Equation 10 corresponds to a typical heavy truck tire inflation pressure of 120 lb/in^2.

Verification of the Relationship between Rutting and Applied Stress

Because the relationship between tire pressure, surface stress and rutting is so essential to high-temperature grade selection for airfield pavements, it was felt an independent confirmation of the relationship in Equation 4 was needed. For this purpose, a large data set of results from a repeated load test was analyzed to determine the relationship between rut resistance and applied stress. The test was performed using the newly developed simple performance tests (SPT) developed during NCHRP Projects 9-19 and 9-29 (*26, 27*). In the SPT repeated load test, a pulse load is applied to an HMA cylinder once every second, until failure occurs, failure being defined as the point at which the creep rate begins to increase with continued loading. This is called the flow point, and the number of cycles to the flow point is called the flow number (*26, 27*). The data set was published recently in NCHRP Report 547 (*28*), and includes 31 sections from eight projects:

- Nevada I-80 (3 sections)
- MN/Road (4 sections)
- WesTrack (7 sections)
- FHWA ALF (7 sections)
- Arizona Salt River (5 sections)
- Arizona Bidahouchi (2 sections)
- Arizona US 60
- Arizona Two Guns (lab mix and plant mix)

Various statistical techniques were used to relate the flow number to complex modulus, air void content and applied stress level. The most effective model is given by the following regression equation:

$$\log N_f = -7.3044 + \log \beta_i + 2.478 \log|E^*| - 0.089(VTM)\log\sigma - 0.187\log|E^*|\log\sigma + \varepsilon \quad (11)$$

Where:

N_f	=	flow number
β_i	=	indicator variable, adjusting regression constant for i^{th} projects/sections
$\|E^*\|$	=	complex modulus (lb/in^2) at 10 Hz and same temperature as flow number test
VTM	=	air voids in flow number test specimen, volume %
σ	=	deviator stress for flow number stress, lb/in^2
ε	=	error term

The r^2 value for this model was 78 %, adjusted for degrees of freedom. Equation 11 can also be expressed in the alternate form:

$$N_f = 4.96 \times 10^{-8} \beta_i \left|E^*\right|^{2.478} \sigma^{-0.089VTM - 0.187\left|E^*\right|} \tag{12}$$

Figure 1 shows the measured flow number values and those predicted using Equation 1. Figures 2 and 3 show the values of the indicator variables (βi) for the various projects/sections; note that the reference project/section (one of the Nevada I-80 sections) has a constant value of -7.2044, and the indicator variables only show the difference from this reference value. These figures include two-standard deviation confidence limits for the estimated values. Figure 4 shows the effect of complex modulus and air void content on stress sensitivity, as indicated by the stress exponent in Equation 12. In Figures 2 and 3, about half of the sections show significant differences in the value for the regression constant. ALF sections 7 and 8 show the largest deviations; this is most likely because these sections were made using modified binders. The increase in the regression constant for these sections indicates a significant increase in rut resistance compared to sections made using non-modified binders.

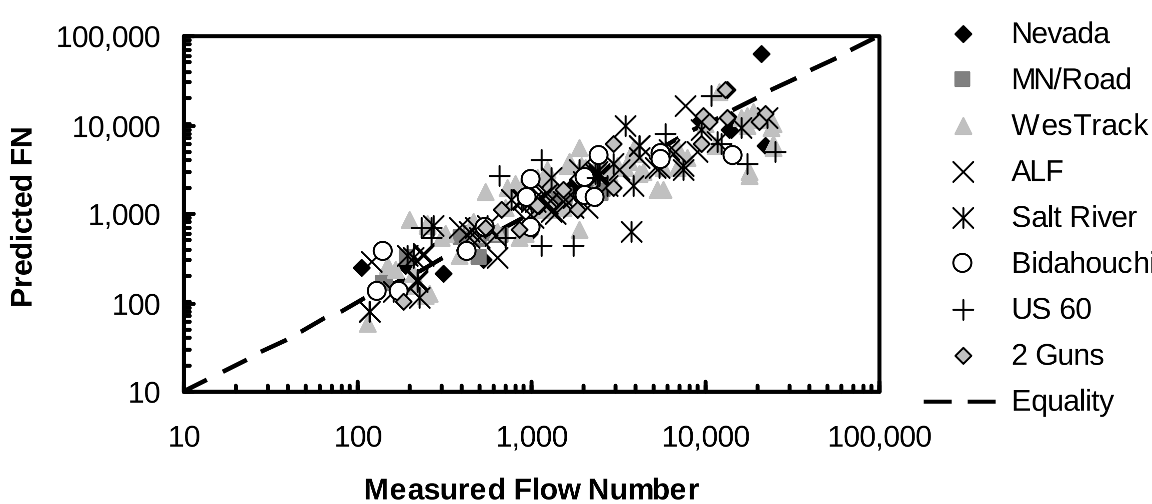

Figure 1. Predicted and Measured Flow Numbers.

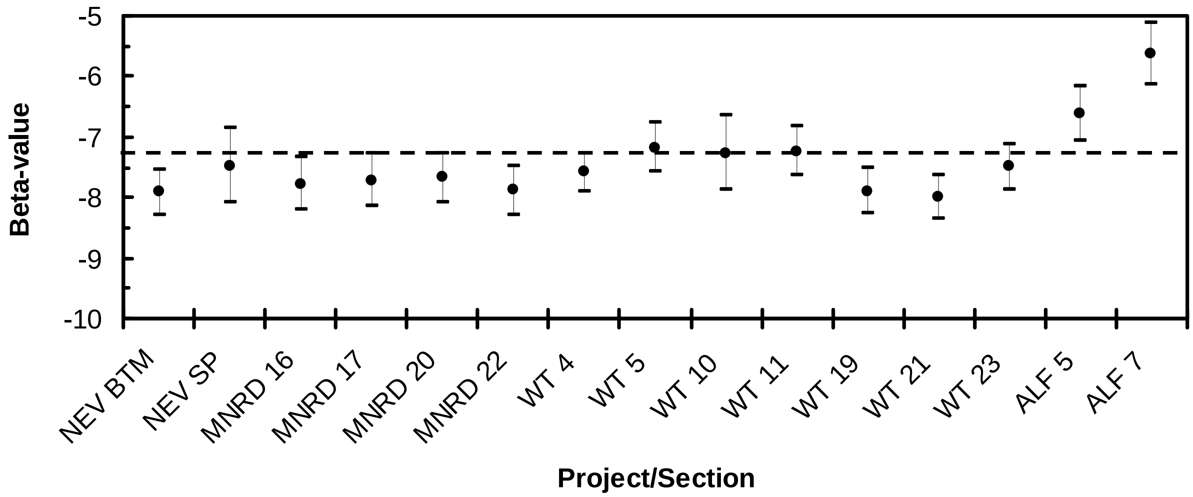

Figure 2. Differences in Regression Constant for Project/Sections 2 through 15. *Project 1 is the reference value; bands represent 2s confidence limits.*

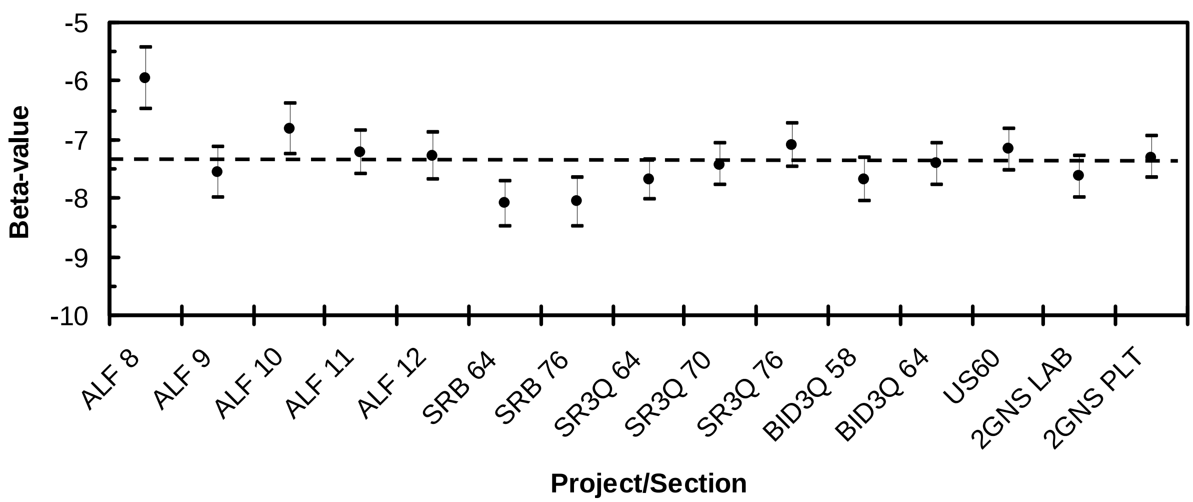

Figure 3. Differences in Regression Constant for Project/Sections 16 through 31. *Project 1 is the reference value; bands represent 2s confidence limits.*

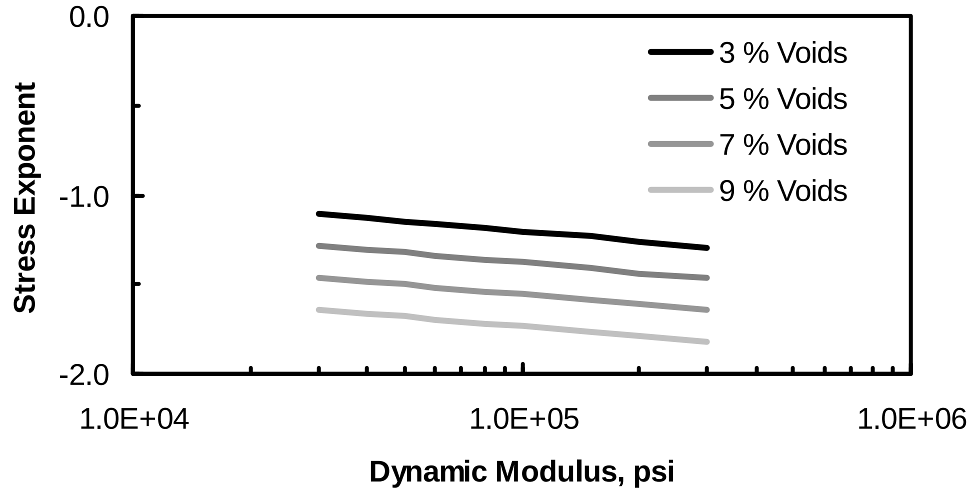

Figure 4. Effect of Dynamic Modulus and Air Void Content on Stress Sensitivity of HMA Mixtures in the Database as Indicated by the Stress Exponent in Equation 12.

The major issue in this analysis is ultimately what value should be used for the stress exponent when calculating the tire pressure factor. As discussed above, the MEDG incorporates a model in which the stress exponent is 2.09. The analysis above suggests that the stress exponent varies from between about 1.0 and 2.0, and is a function of both mixture modulus and air void content. A value of about 1.5 would seem typical for large airfields (where relatively stiff binders would be used) properly compacted to in-place air voids of approximately 6.0 %. However, it must be pointed out that the model upon which Figure 4 is based is not perfect—as seen in Figure 1, there is quite a bit of variability in the model. Furthermore, this model is based on laboratory tests, not on field rutting. Therefore, a conservative approach is to continue using a stress exponent value based upon the MEDG; it is suggested that rather than 2.09, the stress exponent be rounded to 2, for convenience and to reflect the imprecise nature of this value.

Development of Mathematical Relationships between Changes in Mixture Properties and Required Adjustments in High Temperature PG Grade

The effect on rut resistance of differences in mixture properties can be estimated using the resistivity-rutting model developed during NCHRP Projects 9-25, 9-31 and 9-33 (*22, 23, 29*). The most recent version of the resistivity/rutting equation gives allowable traffic as a function of mixture composition, compaction and air voids:

$$TR = 9.85 \times 10^{-5} \left(\mathrm{P} N_{eq} K_s \right)^{1.373} V_{QC}^{1.5185} V_{IP}^{-1.4727} M \tag{13}$$

Where:

TR	=	million ESALs to an average rut depth of 7.2 mm (50 % confidence level)
	=	million ESALs to a maximum rut depth of 12 mm (95 % confidence level)
P	=	resistivity, s/nm
	=	$\dfrac{\left(\lvert G^*\rvert / \sin\delta\right) S_a^2 G_a^2}{49 VMA^3}$
$\lvert G^*\rvert/\sin\delta$	=	Estimated *aged* PG grading parameter at high temperatures, determined at 10 rad/s and at the yearly, 7-day average maximum pavement temperature at 20 mm below the pavement surface, as determined using LTPPBind, Version 3.1 (units of Pa/s); aged value can be estimated by multiplying the RTFOT value by 4.0 for long-term projects (10 to 20 year design life), and by 2.5 for short term projects of 1 to 2 years.
S_a	=	specific surface of aggregate in mixture, m^2/kg
	≅	the sum of the percent passing the 75, 150 and 300 micron sieves, divided by 5.0
	≅	2.05 + (0.623 × percent passing the 75 micron sieve)
G_a	=	the bulk specific gravity of the aggregate blend
VMA	=	voids in the mineral aggregate for the mixture, volume %, as determined during QC testing
N_{et}	=	design gyrations, or for Marshall compaction, 50 gyrations for 35 blows, 75 gyrations for 50 blows, and 100 gyrations for 75 blows
K_s	=	speed correction
	=	$(v/70)^{0.8}$, where v is the average traffic speed in km/hr
V_{QC}	=	air void content, volume %, determined during QC testing at design gyrations
V_{IP}	=	air void content, volume %, in-place
M	=	7.13 for mixtures containing typical polymer-modified binders, 1.00 otherwise

The equation for resistivity can be inserted into Equation 13 and the results simplified to give an alternate form for allowable traffic:

$$TR = 4.71\times10^{-7}\left(\left|G^*\right|/\sin\delta\right)^{1.373} S_a^{2.746} G_a^{2.746} VMA^{-4.119} N_{eq}^{1.373} K_s^{1.373} V_{QC}^{1.5185} V_{IP}^{-1.4727} M \qquad (14)$$

Equation 14 must be manipulated into a form that allows the direct calculation of the temperature adjustment needed to offset a specified change in a given property or combination of properties. This first step in this algebraic transformation is to put Equation 14 into the form involving ratios:

$$\frac{TR_2}{TR_1} = \left[\frac{\left(\left|G^*\right|/\sin\delta\right)_2}{\left(\left|G^*\right|/\sin\delta\right)_1}\right]^{1.373} \left(\frac{S_{a2}}{S_{a1}}\right)^{2.746} \left(\frac{G_{a2}}{G_{a1}}\right)^{2.746} \left(\frac{VMA_2}{VMA_1}\right)^{-4.119} \left(\frac{N_{eq2}}{N_{eq1}}\right)^{1.373} \left(\frac{v_{s2}}{v_{s1}}\right)^{1.098} \left(\frac{V_{QC2}}{V_{QC1}}\right)^{1.5185} \left(\frac{V_{IP2}}{V_{IP1}}\right)^{-1.4727} \left(\frac{M_2}{M_1}\right) \qquad (15)$$

In Equation 15, the subscripts 1 and 2 denote properties for two independent situations. Also note that the speed correction factor has been replaced with actual speed, using the relationship given above in the list of variables for Equation 13. Equation 15 can now be used to determine the effect on allowable traffic (based on maximum rutting) of changes in various mixture properties. For example, if the average aircraft speed on a taxiway falls from 30 to 15 mph due to increased stacking, the allowable traffic would be decreased to $(v_{s2}/v_{s1})^{1.098} = (15/30)^{1.098} = 0.47$ or 47 % of the original design traffic level. Or put another way, the EHEs in this case would have to be multiplied by (1/0.47) = 2.1 to account for the increased rutting potential resulting from the slower aircraft speed. Based upon this *inverse* relationship between changes in allowable traffic and EHEs, Equation 15 can be put in a slightly different form:

$$\frac{EHE_2}{EHE_1} = \left[\frac{\left(\left|G^*\right|/\sin\delta\right)_2}{\left(\left|G^*\right|/\sin\delta\right)_1}\right]^{-1.373} \left(\frac{S_{a2}}{S_{a1}}\right)^{-2.746} \left(\frac{G_{a2}}{G_{a1}}\right)^{-2.746} \left(\frac{VMA_2}{VMA_1}\right)^{4.119} \left(\frac{N_{eq2}}{N_{eq1}}\right)^{-1.373} \left(\frac{v_{s2}}{v_{s1}}\right)^{-1.098} \left(\frac{V_{QC2}}{V_{QC1}}\right)^{-1.5185} \left(\frac{V_{IP2}}{V_{IP1}}\right)^{1.4727} \left(\frac{M_2}{M_1}\right)^{-1} \qquad (16)$$

A few comments are needed to ensure the reader understands the relationships given in Equations 15 and especially 16, since they can be somewhat confusing. It should be clear that as the rut resistance of a pavement increases, the allowable traffic for that pavement will increase. It may not be quite so clear that as the rut resistance of a pavement increases, the value for EHEs will *decrease*, all else being equal. This is because the value of EHEs is in fact an indicator of the amount of damage (permanent deformation only) done to a given pavement under a selected combination of loads in a given environment. When comparing two pavement/load combinations, the one with lower EHEs will be subject to less permanent deformation. The concept of EHEs has been developed as an aid in selecting PG binder grades for airfield pavements: As EHEs increase, a stiffer binder grade is needed, since there is greater potential for permanent deformation. As the EHEs for a given pavement/load system increase, the permanent deformation potential increases, and as EHEs decrease the permanent deformation potential decreases.

The sections below discuss how Equation 16 is applied to specific differences in the typical properties of surface course mixtures for highways and airfields, in order to determine any adjustments in high temperature PG grade needed to maintain proper levels of rut resistance.

Effect of Differences in Mixture Composition

As discussed above, differences in mixture composition can potentially have a significant effect on the rut resistance of HMA pavements, and so this issue must be addressed when developing a method for selecting PG binder grades for airfield pavements. There are unfortunately a number of specifications that have been used in developing HMA mix designs for airfield pavement—FAA specifications P-401 and P-403, UFGS-32 12 15 (formerly UFGS-02749), and various versions and local modifications of these two specifications. The UFGS specification was developed for use on military airfields, but is sometimes applied to commercial airfields. Although some engineers have indicated that the UFGS specification is in fact used more frequently for the design of HMA for commercial airfields than the P-401/403 specification, consulting work and research performed at AAT on HMA mixes used on airfield runways suggests that historically the P-401/403 specifications have been widely used in the design of HMA for airfield pavements. The major difference in these specifications relevant to potential pavement rut resistance is that for equivalent aggregate gradations, the minimum VMA requirements in the P-401/403 specification are 1.0 % higher than in the UFGS specifications (which are similar to those given in the Superpave system). Again, experience at AAT with a variety of HMA mixes used for airfield pavements confirms that VMA for these mixtures is typically significantly higher than for equivalent Superpave mixes—equivalent in this case meaning mixtures with similar aggregate gradations placed at similar locations within the pavement structure. All else being equal, higher VMA will tend to decrease rut resistance of an HMA mixture. Therefore, it is conservatively assumed here that wearing course mixtures for airfield pavements will typically have a design VMA value of 16 %, while equivalent Superpave mixtures will have a design VMA 1.0 % lower, or 15 %.

The other important difference in composition between HMA for airfield pavements and HMA design using the Superpave system that will significantly affect rut resistance is in the mineral filler content. Current Superpave specifications for material finer than 75 μm establish an allowable range of from 2 to 10 % by total aggregate weight. For airfield wearing course mixtures, the comparable requirement is for 3 to 6 % finer than 75 μm. Because additional fines are generated during aggregate handling and hot mix production, the typical content of mineral filler for highway wearing course mixtures is probably about 7.5 %, while for airfield pavements it is probably about 6.0 %. Using the relationship between mineral filler content and aggregate specific surface given above as part of Equation 13, these values correspond to specific surface values of 6.72 m^2/kg for highway mixtures and 5.79 m^2/kg for airfield mixtures. From Equation 16, the effect of these differences on EHEs is calculated as

$$COMP = \frac{EHE_{airfield}}{EHE_{highway}} = \left(\frac{16}{15}\right)^{4.119} \left(\frac{5.79}{6.72}\right)^{-2.746} = 1.96 \qquad (17)$$

In other words, the higher VMA and lower mineral filler content of airfield surface course mixtures means that in general the permanent deformation potential is about twice as great as that of highway pavements, that is, they can handle only about half as much traffic as an equivalent highway mixture at a given maximum allowable rut depth.

Effect of Differences in Design Compaction Level

In the FAA's Item P-401, which is the FAA standard for mix design and construction of HMA surface course mixtures for airfield pavements, two levels of compaction are specified: for airfields handling aircraft less than 60,000 lb or having tire pressures less than 100 lb/in^2, 50 blows of a standard Marshall hammer are specified. For airfields handling aircraft of 60,000 lb or more or having tire pressures of 100 lb/in^2 or more, 75 blows are required. In the Superpave system specified compaction levels for highway pavements are given in terms of ESALs, so it is difficult to develop a direct correspondence. However, an aircraft gross vehicle weight of 60,000 lb is quite small, typical of aircraft using GA airfields. The EHEs for such facilities would be quite low, certainly in the lowest category of traffic for Superpave design of less than 0.3 million ESALs. Based on this assumption, design compaction levels for highway and airfield surface course mixtures are shown in Table 8. Research performed during NCHRP Projects 9-25 and 9-31 indicated that in terms of rut resistance, one Marshall blow is approximately equal to one Superpave gyration. Using this assumption, and assuming that the models upon which the MEDG and the LTPPBind program are based involved approximately equal numbers of Superpave and Marshall pavements, an average compaction level can be calculated for each traffic level. This can then be used in Equation 16 to estimate the EHE ratios, also included in Table 8. The effect ranges for 0.77 to 1.25. The simplest and most conservative approach is to assume the worst case, and use a EHE ratio (airfield/highway) of 1.25 to account for differences in design compaction level.

Table 8. Design Compaction Levels and Average Effect on EHEs.

Design Traffic Level *MESALs*	**Marshall Mix Design Compaction** *Blows*	**Superpave Mix Design Compaction** *Gyrations*	**Marshall-Superpave Average** *Bl./Gyr.*	**Airfield Mix Design Compaction** *Blows*	**EHE Ratio: Airfield/ Highway**
< 0.3	50	50	50	50	1.00
0.3 to < 3	50	75	62	75	0.77
3 to < 10	75	100	88	75	1.25
10 to < 30	75	100	88	75	1.25
≥ 30	75	125	100	N/A	N/A

Effect of Field Compaction

To this point, it would appear that HMA surface course mixtures for airfields are typically more susceptible to rutting than those for highway pavements. However, during construction airfield pavements are in general compacted much more thoroughly than highway pavements. It is commonly assumed that highway surface courses are compacted to in-place air void contents of 7.0 %, but anecdotal evidence and recent research suggest this value is often much higher. Therefore, a reasonable—and potentially conservative estimate of average in-place air void content for highway surface courses is probably 8.0 %.

In airfield pavements, field compaction is controlled through density relative to design density. When discussing airfield pavement construction, a field density of 98 % means that the density is 2 % less than the density of specimens compacted in the laboratory. In this example, if the air void content in the laboratory were 3.5 %, the in-place air void content would be $100 - (100 - 3.5) \times 0.98 = 5.4$ %. In Item P-401, the FAA specifies field density through percent within limits (PWL). Using a lower density limit of 96.3 %, the PWL must be 90 % or higher. Assuming a laboratory density of 96.5 %, this would correspond to an in-place air void content of 7.0 %. A reasonable assumption of a comparable upper limit (at a PWL of 10 %) would be 1 to 2 % lower than the laboratory air voids, or 2.0 %. Based upon these limits, the average in-place density for wearing courses under Item P-401 can be estimated at 4.5 %, considerably lower than the 8.0 % estimated for highway construction. The design air void content for highways pavements is normally 4.0 %. For airfield pavements, it ranges from 2.8 to 4.2 %, with an average of 3.5 %. Laboratory air void content during construction of HMA pavements is normally slightly lower than the design air void content, because of the increased mineral filler content that occurs during aggregate handling in plant production. Therefore, it is assumed here that the laboratory air void content for highway and airfield HMA during production is 3.5 % and 3.0 %, respectively. From Equation 16, the effect on EHEs can then be estimated as follows:

$$FC = \frac{EHE_{airfield}}{EHE_{highway}} = \left(\frac{3.0}{3.5}\right)^{-1.5185} \left(\frac{4.5}{8.0}\right)^{1.4727} = 0.542 \qquad (18)$$

Reliability Factor

Reliability in the selection of high-temperature PG grade refers to the reliability against excessive rutting, caused by an unusually high average pavement temperature over the life of the pavement. In LTPPBind v. 3.1, the high-temperature PG grade, adjusted for a given level of reliability, is calculated using the following formula (*4, 5*):

$$PGrel = PGd + Z(PGd)(CVPG)/100 \tag{19}$$

Where:

PGrel	=	high-temperature PG grade at selected reliability level, °C
PGd	=	damage-based high-temperature PG grade, °C, with no adjustment for reliability
Z	=	z-value from the standard normal distribution at selected reliability level
CVPG	=	coefficient of variation for *PGd*, %
	=	$0.000034(LAT-20)^2 RD^2$
LAT	=	latitude of pavement site, degrees
RD	=	selected maximum allowable rut depth, mm
	=	12.5 mm for LTPPBind v. 3.1

In the proposed procedure, the base binder grade is selected using LTPPBind at a 98 % reliability level. A Monte Carlo simulation of current Superpave specifications and LTPPBind high-temperature PG grades showed a typical reliability level against excessive rutting (greater than 10 to 12 mm) from about 90 to 95 % at traffic levels of 3 million ESALs and higher (*29*). However, in practice it is likely that the reliability levels would be higher, because available binder slates in given regions tend to lead to conservative binder selections. Also, local experience will tend to eliminate marginal mix designs and/or binder grade selections. For these reasons, and because of the uncertainty involved in the various assumptions used in the Monte Carlo analysis, it is assumed here that the binder grade selections in LTPPBind v. 3.1 at a 98 % reliability level are reasonably accurate and suitable for use in HMA in airfield pavements. The reliability factor REL is therefore assumed to be equal to 1.00:

$$REL = \frac{EHE_{airfield}}{EHE_{highway}} = 1.00 \tag{20}$$

Final Equation for EHEs

The analysis above provides the following values for various factors in needed in applying Equation 2 to calculate EHEs:

COMP	=	1.96
LC	=	1.25
FC	=	0.542
REL	=	1.00

According to current analyses by the Department of Transportation, the annual rate of growth for U.S. air traffic for the period 2005 through 2020 is estimated to be 3.8 %. Using this estimate for the value of *R* in Equation 2, assuming a design life of 20 years, and substituting the estimated values for the various other factors lead to the following Equation for EHEs:

$$EHEs = \sum_{i=1}^{m}\left[(TP_i)\left(\frac{PDR_i}{PCR_i}\right)(N_i)\right](1.96)(1.25)(.542)(1.00)(20)(1.038)^{0.5(20)} \tag{21}$$

$$EHEs = 53\sum_{i=1}^{m}\left[(TP_i)\left(\frac{PDR_i}{PCR_i}\right)(N_i)\right] \tag{22}$$

Equation 22 can be used to calculate EHEs for any combination of aircraft on a given runway/taxiway configuration. Application of this equation is straightforward, and suitable for implementation in software applications; it could easily be included in software packages for designing flexible pavements for airfields, such as the newly developed FAARFIELD program, which is the basis for the flexible pavement design method included in FAA Draft Advisory Circular 150/5320-6E. At the writing of this report, Circular 150/5320-6E was expected to be adopted in 2008. Until this calculation is included in such software and in cases where exact data on traffic mixes are not available, a simplified approach has been developed. Equation 22 was applied to a set of representative aircraft traffic mixes for eight different runways, as published in a recent study on airfield pavement design by Ricalde et al. (*30*). The data is summarized in Table 9. It was found that the total EHEs for all eight pavements was directly related to the annual departures multiplied by the square root of gross aircraft weight ($\sqrt{GAW}$), where GAW is the weight for the largest aircraft in a traffic mix with a significant number of departures—about 10 % or more of the total for the given runway/taxiway. EHEs calculated using Equation 22 are plotted against EHE × $GAW^{0.5}$ in Figures 5 and 6; Figure 5 is for taxiways in parallel arrangement, while Figure 6 is for runways with taxiways in parallel arrangements. Because of the variability in these relationships, a 90 % upper confidence limit is shown on these figures, and should be the basis for actual estimation of EHEs using the simplified procedure. Plots for central taxiways and for runways with central taxiways need not be prepared, since the relationships are directly related to those shown in Figures 5 and 6 through the PDRs for these different configurations:

- For parallel taxiways, PDR = 1
- For runways with parallel taxiways, PDR = 2
- For central taxiways, PDR = 2
- For runways with central taxiways, PDR = 3

Table 9. Traffic Mix Used in Analysis of EHEs, from Study by Ricalde et al. (*30*).

Airfield	Taxiway/ Runway	Design Aircraft	Gross Weight *lb*	Total Annual Departures
Sarasota-Bradenton	---	B727	209,000	3,613
Dulles	Taxiway W-1	B727	209,500	10,645
Dulles	Runway 1L	B727	210,000	359,984
Memphis	Runway 18R	B727	210,000	72,567
Charlotte	Runway 18R-36L	B737-300	150,000	20,075
Charlotte	---	DC8	350,000	18,525
Philadelphia 1983	---	B727	209,500	63,002
JFK	Runway 13R-31L	A340-500/600	750,000	89,783

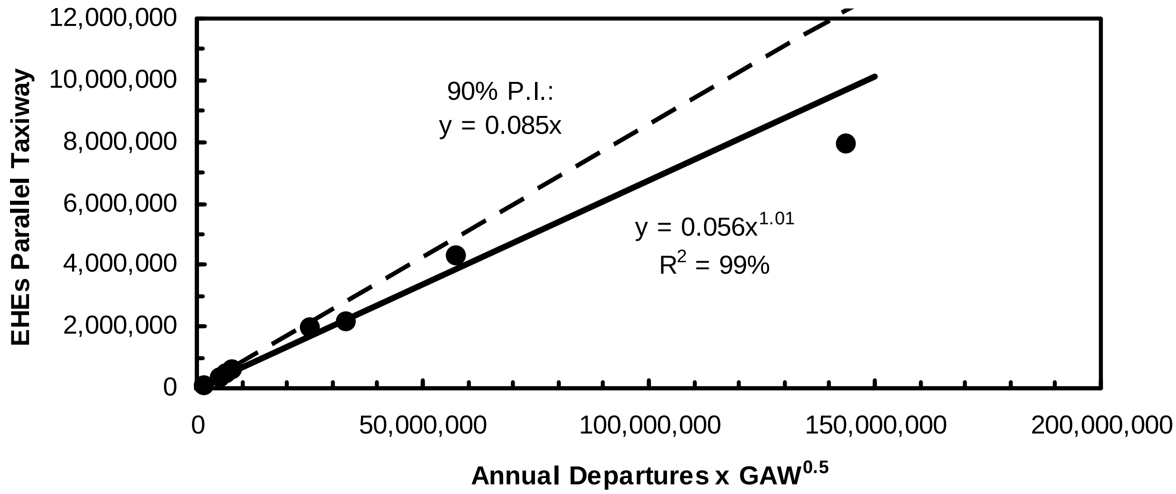

Figure 5. EHEs as a Function of Annual Departures and Gross Aircraft Weight for the Traffic Mixes Listed in Table 8; for parallel taxiways.

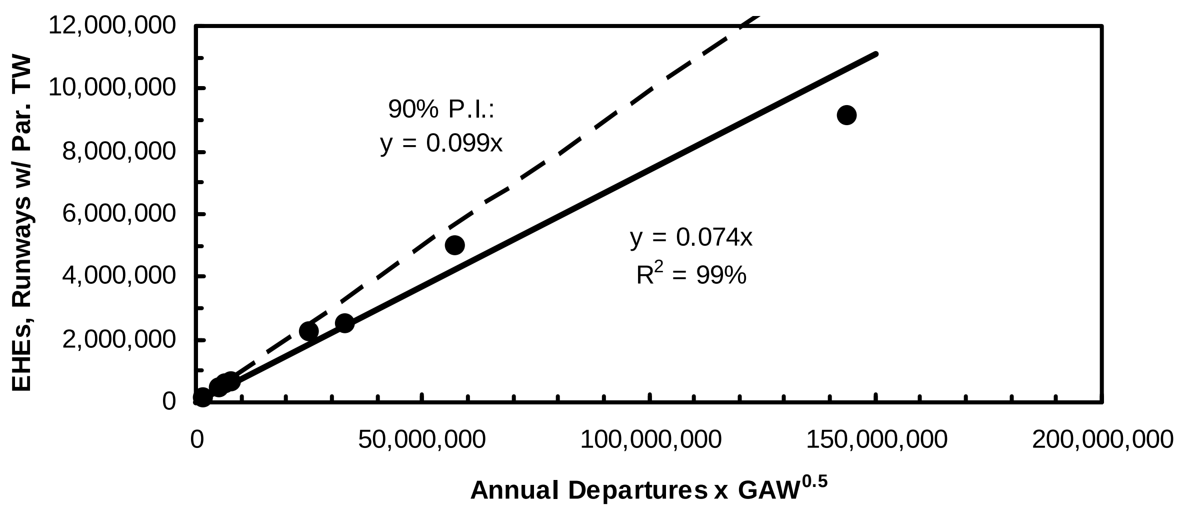

Figure 6. EHEs as a Function of Annual Departures and Gross Aircraft Weight for the Traffic Mixes Listed in Table 8; for runways with parallel taxiways.

Based upon the relationships shown in Figures 5 and 6 and the PDR values for the four different airfield pavement configurations, four equations can be developed for estimating EHEs at an upper 90 % confidence level. For parallel taxiways:

$$EHEs = 0.085 \times annual\ departures \times \sqrt{GAW} \quad (23)$$

For runways with parallel taxiways:

$$EHEs = 0.099 \times annual\ departures \times \sqrt{GAW} \quad (24)$$

For central taxiways:

$$EHEs = 0.171 \times annual\ departures \times \sqrt{GAW} \quad (25)$$

For runways with central taxiways:

$$EHEs = 0.148 \times annual\ departures \times \sqrt{GAW} \quad (26)$$

In the interest of simplicity, and given the approximate nature of this analysis, it is suggested that Equation 24 be used to calculate EHEs for taxiways and runways where the taxiway is in a parallel configuration. Similarly, Equation 25 should be used to calculate EHEs for taxiways and runways where the taxiway is in a central configuration. The relationships between GAW, annual departures and EHEs can be presented graphically, as shown in Figures 7 and 8, for parallel and central taxiway configurations, respectively. Some judgment is needed in selecting the value for GAW to use in Equations 23 through 26 and/or Figures 7 and 8. In cases where the air traffic is relatively evenly distributed among a large number of aircraft types, so that few if any represent 10 % or more of the total departures, the highest GAW should be used. It should be noted that in Equations 23 through 26 and Figures 7 and 8, “runways” refers to the central portion of runways, while “taxiways” refers to both taxiways and the ends of runways, where aircraft are either landing or slowing down to taxiway speeds. Furthermore, the central taxiway configuration is usually used for small airfields—heavy aircraft and a large number of annual departures are unlikely to be encountered for this configuration.

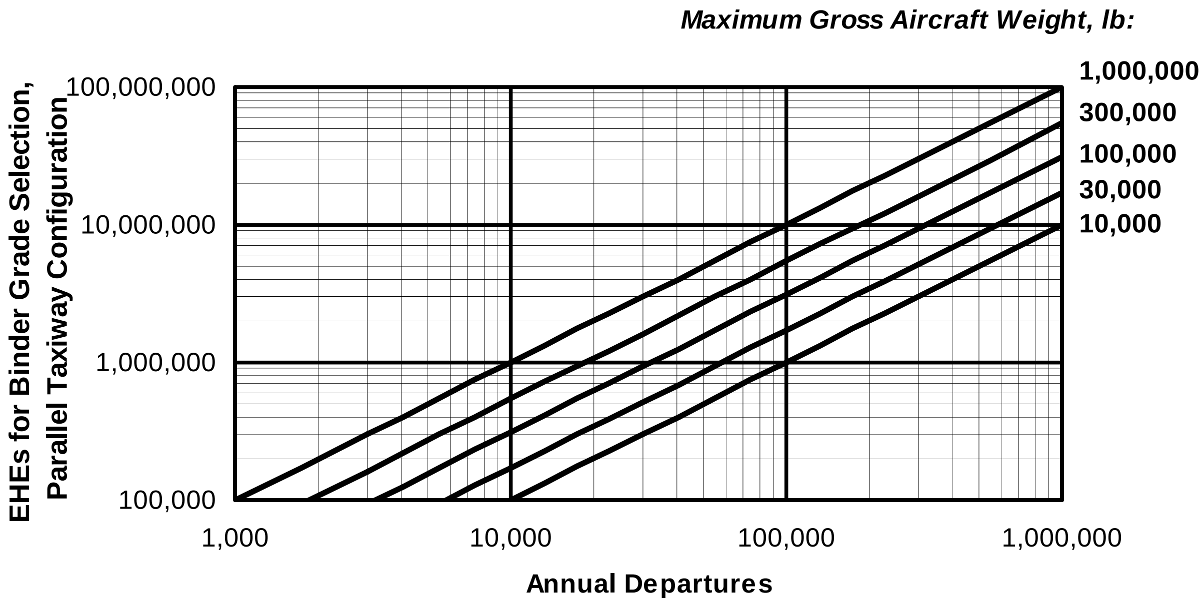

Figure 7. EHEs for High-Temperature Binder Grade Selection as a Function of Annual Departures for Different Values of Gross Aircraft Weight, for Parallel Taxiways and Runways with Parallel Taxiways.

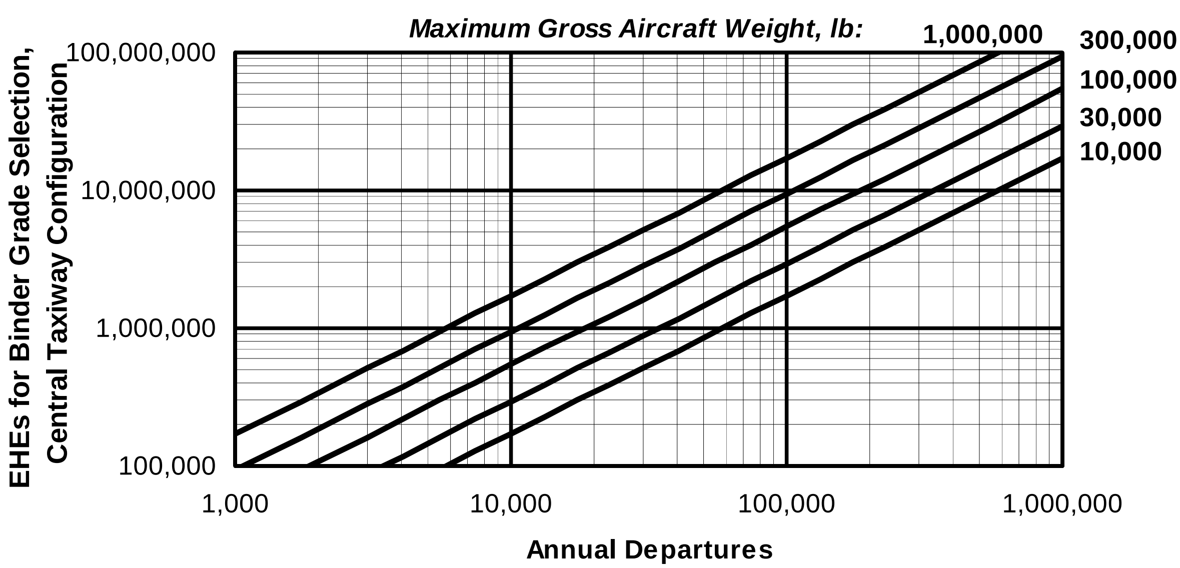

Figure 8. EHEs for High-Temperature Binder Grade Selection as a Function of Annual Departures for Different Values of Gross Aircraft Weight, for Central Taxiways and Runways with Central Taxiways.

The system described above is a powerful tool for selecting high-temperature PG grades for airfield pavements, but this is only one step of the complete procedure; several other refinements are needed to make the grade selection procedure complete. These include adjustments for traffic level and speed; adjustments for GA and other very low traffic airfields; and adjustments to prevent groove closure on runways. These are discussed below.

Grade Adjustments for Traffic Level and Speed

There is no documentation concerning the derivation of grade adjustments for traffic level and speed in the original PG grading system, or in LTPPBind 2.1. It can only be assumed that these adjustments were made on the basis of engineering judgment and experience. Because the distribution of aircraft speeds is probably different than from highway traffic, it cannot be assumed that these adjustments will apply to airfield pavements. A more rational approach is needed to develop these grade adjustments.

The new version of LTPPBind 3.1 includes rational, damage based traffic level and speed adjustments (*4, 5*). The proposed procedure for selecting PG grades for airfield pavements will make direct use of LTPPBind 3.1 for selecting the PG grade for a given location and traffic (EHE) level. Unfortunately, a similar approach cannot be used for grade adjustments due to traffic speed, since LTPPBind 3.1 only provides adjustments for fast and slow traffic, and the precise speeds for which these adjustments apply are not clear. In order to develop corrections for aircraft speed, an analysis was performed on a set of nine different binders from a variety of accelerated pavement tests. Eight of the binders were from projects included in development of the SPT: the FHWA ALF rutting test; MN/Road; and WesTrack (*28*). One binder tested was a PG 64-22 used in NCHRP Projects 9-25 and 9-31 (*22, 23, 29*). These binders were chosen for this analysis because they have been included in well-known studies, and their flow properties have been thoroughly documented. As shown in Figure 9, the relationship between temperature and modulus ($|G^*|/\sin\delta$ in this case) is exponential:

$$\frac{(|G^*|/\sin\delta)_1}{(|G^*|/\sin\delta)_2} = \exp\left[A(T_1 - T_2)\right] \tag{27}$$

The value of constant A in Equation 27 is close to -0.13, as shown in Figure 9, but this value varies slightly among binders. The relationship between modulus and frequency follows a power law relationship:

$$\frac{(|G^*|/\sin\delta)_1}{(|G^*|/\sin\delta)_2} = \left(\frac{\omega_1}{\omega_2}\right)^B \tag{28}$$

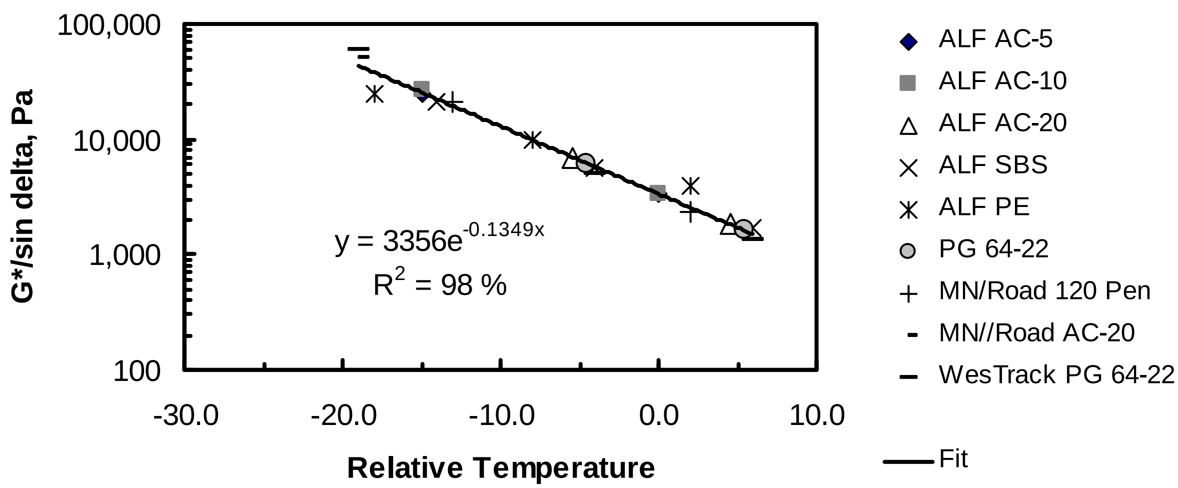

Figure 9. Temperature Dependence of Nine Asphalt Binders Relative to the PG Grading Temperature.

In Equation 28, ω_1 and ω_2 are frequencies (in rad/s) associated with modulus values $(|G^*|/\sin\delta)_1$ and $(|G^*|/\sin\delta)_2$, respectively. Equations 27 and 28 can be combined to give an equation for the temperature difference associated with a given change in frequency:

$$T_1 - T_2 = \frac{B}{A}\ln\left(\frac{\omega_1}{\omega_2}\right) \tag{29}$$

Because the effective loading frequency in a pavement subject to traffic is directly proportional to the traffic speed, Equation 29 can be restated in terms of traffic speed:

$$T_1 - T_2 = \frac{B}{A}\ln\left(\frac{v_1}{v_2}\right) \tag{30}$$

Where v_1 and v_2 are the aircraft speeds associated with temperatures T_1 and T_2, respectively. The values of the constant B/A was determined for the nine binders included in Figure 9. The results ranged between about 6.0 and 7.0, with an average of 6.552, as shown in Figure 10. Therefore, the typical relationship between temperature and speed for asphalt binders and asphalt mixtures can be described using the following equation:

$$T_1 - T_2 = 6.552 \ln\left(\frac{v_1}{v_2}\right) \tag{31}$$

Equation 31 can be used to calculate grade adjustments needed for different aircraft speeds; Table 10 lists adjustments calculated for different locations and conditions on airfield pavements; it should be emphasized that these adjustments, like all other high-temperature grade adjustments, should be applied to the continuous grade given by LTPPBind version 3.1, using the calculated traffic level in terms of EHEs. If there were no other adjustments to the grade, this would then be rounded to the next highest standard grade. However, two more factors must be considered in developing aircraft speed adjustments: (1) binder grades for GA and similar airfields with very low levels of traffic; and (2) grade adjustments needed to prevent groove closure on runways. These are discussed below.

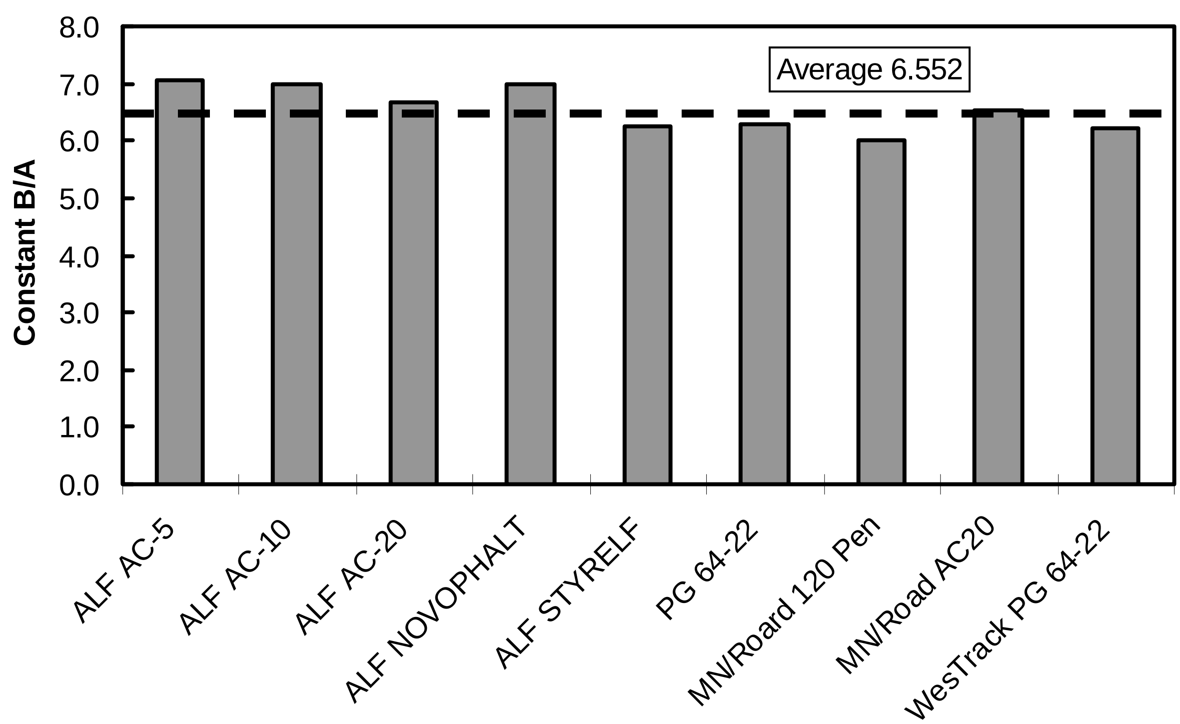

Figure 10. Values of the Constant B/A in Equations 29 and 30 for Nine Asphalt Binders.

Table 10. High-Temperature Binder Grade Adjustments for Aircraft Speed.

Description	Speed *mph*	Grade Adjustment* *°C*
Central portions of runways	≥ 45	0
Taxiways and runway ends without aircraft stacking	15 to < 45	+7
Taxiways and runway ends with occasional aircraft stacking	5 to < 15	+14
Taxiways and runways ends with frequent aircraft stacking	< 5	+20

* *Does not include adjustments for grooved runways and low traffic airfields. Adjustments to be applied to continuous grade and then round upwards to the nearest standard PG grade.*

Grade Adjustments for GA and Other Low Traffic Facilities

Many GA airfields, and other smaller facilities handle very low amounts of traffic consisting of small aircraft (gross weight below 100,000 lb). The pavements on such airfields tend to much more often exhibit durability problems rather than excessive rutting. The high-temperature PG grade selection protocol developed so far includes a 7 °C grade increase for the base traffic level in LTPPBind (< 3 million EHEs). This incorrectly suggests that approximately an entire grade bump is needed for airfield pavements, even for GA and other very low traffic facilities. In fact, for pavements at small airfields subject to loading less than 300,000 EHEs, the high-temperature PG grade requirements could potentially be lowered at least 13 °C. In order to help avoid durability problems on pavements at these facilities, it is recommended that the basic 7 °C grade bump be eliminated for pavements at GA airfields and other facilities for which the estimated EHEs are less than 300,000 EHEs. Although lowering the high-temperature PG grade only 7 °C (rather than 13 °C) is conservative, it should be remembered that quality control may not be as strict on such small facilities, and because of the increased prevalence of central taxiway configurations, such a conservative approach is warranted. This approach should provide for more than adequate rut resistance for HMA pavements at small airfields, while helping avoid the sort of durability problems sometimes seen at such facilities.

Groove Closure on Runways

Virtually all airport runway pavements are grooved, to help prevent hydroplaning in wet weather. In hot weather, the repeated loading by aircraft during takeoff and landing can cause these grooves to close, even though the amount of rutting on the runway may be very small. To help prevent groove closure on runways, it is suggested that the high-temperature PG grade should be increased 7 °C for the central portion of runways. Conveniently, this means that for airfields with low traffic and no stacking of aircraft on the taxiways, the runway and taxiway surface course mixtures will require the same PG grade. This will also tend to reduce the overall level of rutting on the runway, which is desirable because of the potentially catastrophic results of aircraft mishaps caused by hydroplaning or otherwise related to excessive runway rutting.

High-Temperature PG Grade Adjustments Based upon Aircraft Size, Traffic Level, Frequency of Aircraft Stacking and Average Aircraft Speed

Including the adjustments given above for GA and other low-traffic facilities, the high-temperature PG binder grade adjustments for speed are given in Table 11 below. The normal procedure in selecting high-temperature PG grades for HMA airfield pavements is as follows:

1. Calculate EHEs using the annual departures and the GAW among aircraft making up more than 10 % of the total annual departures for the pavement. Note that annual departures are the actual total annual departures for the runway/taxiway, and not the departures in terms of the design aircraft. This calculation can be done using either Equations 24 and 25 or Figure 7 and 8.
2. Determine the continuous base PG grade using LTPPBind, the calculated EHEs, "fast" traffic and a reliability level of 98 %.
3. Determine the pavement classification as given in Table 11, based upon aircraft gross weight, EHEs, and frequency of aircraft stacking on taxiways.
4. Determine the high-temperature PG grade adjustment using Table 11 and the pavement classification determined in step 3.
5. Determine the final PG grade by adding the high-temperature grade adjustment determined in step 4 to the continuous base high-temperature PG grade determined in Step 2.

One more factor must be considered in the selection of PG binder grades for airfields—the use of polymer modified asphalt binders. This topic is discussed in detail in the next section of this report.

Table 11. High-Temperature PG Grade Adjustments for HMA in Airfield Pavements.

Airfield Pavement Classification	Typical Speed *mph* Runway Centers	 Taxiways/ Runway Ends	Grade Adjustment* ℃
Runways and taxiways at airfields handling aircraft with gross weights below 100,000 lb, and with EHEs < 300,000	≥ 45	15 to < 45	0
Taxiways and runways at commercial airfields handling aircraft with gross weights of 100,000 lb or greater, EHEs ≥ 300,000 and little or no aircraft stacking	≥ 45	15 to < 45	+7
Taxiways and runway ends at commercial airfields handling aircraft with gross weights of 100,000 lb or greater, EHEs ≥ 300,000 and occasional aircraft stacking	---	5 to < 15	+14
Taxiways and runway ends at commercial airfields handling aircraft with gross weights of 100,000 lb or greater, EHEs ≥ 300,000 and frequent aircraft stacking	---	< 5	+20

* *Does not include adjustments for polymer modified asphalts. Adjustments to be applied to continuous base grade and then rounded upwards to nearest standard PG grade.*

LABORATORY TESTING OF MODIFIED BINDERS AND HMA MIXTURES

The laboratory testing program includes two primary phases: (1) testing of polymer modified binders, and (2) testing of HMA mixtures. These are described in the following two sections of this report. A short summary of the findings made based upon the laboratory testing follow.

Testing of Polymer Modified Binders

There were three primary objectives of the binder testing program: (1) to evaluate a variety of test procedures that have been proposed for specification testing of PMAs; (2) to evaluate the potential performance of a variety of PMAs compared to conventional binders; and (3) to evaluate the sensitivity of PMAs to increases in stress levels. This last objective is of special concern in airfield pavements because of the high stresses that result from the very high tire pressures used on some aircraft.

The following binder tests were performed as part of AAPTP Project 04-02;

- Testing of 19 binders using the Multiple Stress Creep and Recovery (MSCR) protocol. This testing was performed at two temperatures—25ºC and the PG high grading temperature.
- Stress sweep testing of 7 PG 64-XX binders at the high temperature of the PG grade. To represent the different aircraft speeds, five frequencies were considered: 0.01 Hz, 0.1 Hz, 1 Hz, 10 Hz and 25 Hz.
- Analysis of the relationship between the recovered strain in the MSCR (RS/MSCR) and elastic recovery as determined using the ductilimeter (ER)
- Analysis of the stress sensitivity of MSCR testing
- Determination of the linear viscoelastic limits based on stress sweep testing

Multiple Stress Creep and Recovery MSCR Testing—The MSCR test was recently developed by the FHWA and has been promoted as an alternative to the elastic recovery test (performed using the ductilimeter) in characterizing and specifying polymer modified asphalt binders. The MSCR protocol involves application of a constant stress creep for 1.0 s followed by a zero stress recovery period of 9.0 seconds. The test is run at two stress levels: 100 Pa and 3,200 Pa. Ten cycles are run at each of the two stress levels for a total of 20 cycles. There are no rest periods between changes in stress level. For each stress level, the recovered strain RS/MSCR is calculated by averaging the recovery for the ten cycles. To avoid confusion with the results of the much different elastic recovery test, the term "elastic recovery, multiple stress creep and recovery (ER/MSCR)" will be used in this report to differentiate the results of the MSCR test from those of the empirical elastic recovery test performed using the ductilimeter. Figure 11 is a diagram of the MSCR test.

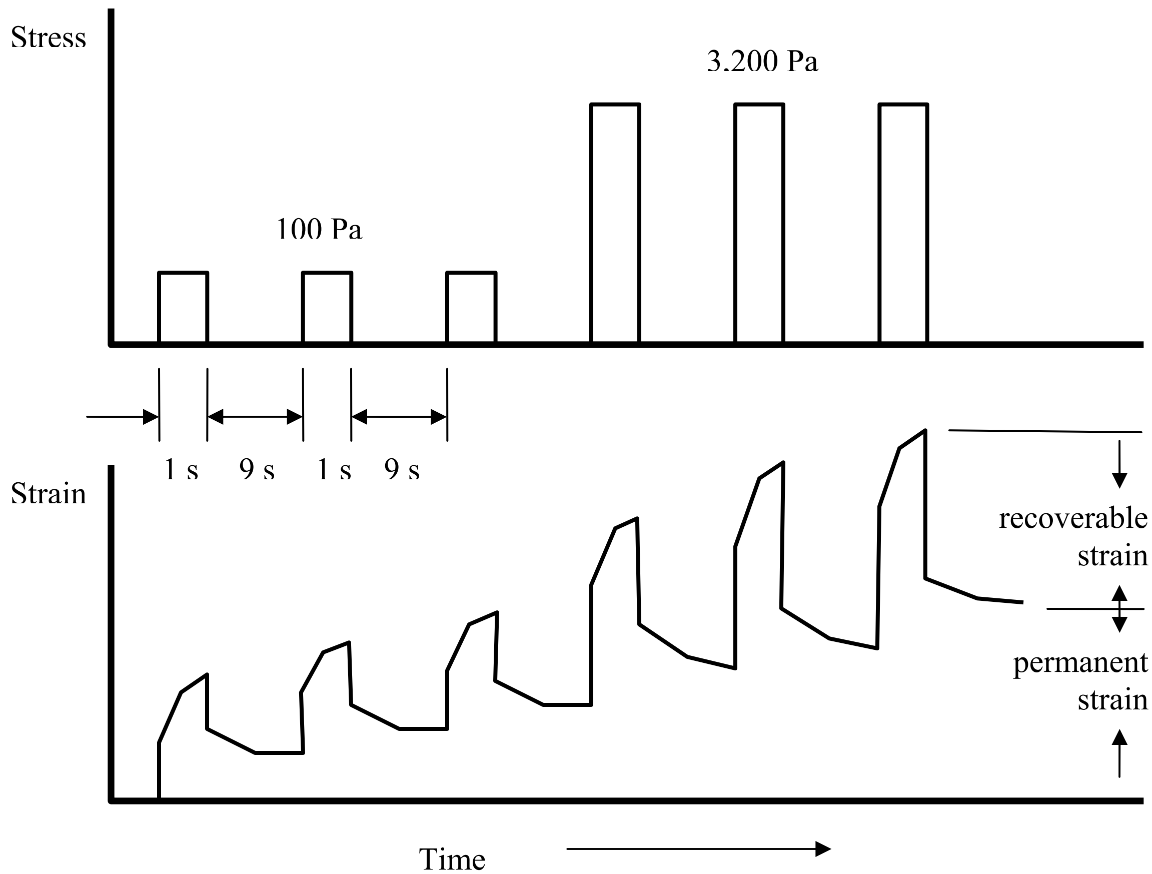

Figure 11. Diagram of Multiple Stress Creep and Recovery Test as Proposed by the FHWA.

The MSCR test was performed on all 19 asphalt binders at two temperatures: 25ºC and the high temperature of the PG grade (PG/HT). The protocol for the MSCR test specifies testing at PG/HT only. However, the additional temperature of 25ºC was included to provide a more direct comparison with the results of ER testing with the ductilimeter, which is performed at 25ºC. For each of the binders and for each of the temperatures, two replicate samples were tested. Table 12 shows the results of the MSCR test for 19 binders. The table also shows the ER measured with the ductilimeter (performed at AAT) for comparison. The repeatability of the ER/MSCR test was very good, with pooled standard deviations of 0.5 % and 1.1 % for testing at 25°C and at the PG/HT, respectively.

Table 12. MSCR Results.

Binder Code	PG Grade	Modifier	Stress *Pa*	Elastic Recovery, %		
				MSCR @ 25 °C	MSCR @ High Grade Temperature	Ductilimeter @ 25 °C
N1	PG 58-28	Neat	100	57	2	2
			3,200	56	0	
N2	PG 64-22	Neat	100	62	3	6
			3,200	62	0	
N3	PG 70-22	Neat	100	71	4	9
			3,200	71	0	
B2	PG 64-28	Elvaloy	100	79	49	60
			3,200	79	33	
B3	PG 76-28	Elvaloy	100	87	74	73
			3,200	87	72	
B5	PG 64-34	Elvaloy	100	85	70	83
			3,200	85	67	
B8	PG 70-34	Elvaloy	100	87	74	81
			3,200	87	72	
C4	PG 64-22	SBS	100	58	0	5
			3,200	58	0	
C5	PG 58-28	SBS	100	52	2	0
			3,200	52	0	
C6	PG 76-28	SBS	100	91	83	83
			3,200	91	84	
C7	PG 70-28	SBS	100	86	95	99
			3,200	86	93	
C8	PG 76-22	SBS	100	82	51	85
			3,200	82	30	
C9	PG 82-22	SBS	100	80	64	83
			3,200	81	41	
D1	PG 64-28	SB	100	69	21	54
			3,200	70	8	
D2	PG 64-34	SB	100	85	79	88
			3,200	85	74	
D5	PG 64-40	SB	100	84	60	93
			3,200	84	36	
D6	PG 70-34	SB	100	90	81	95
			3,200	90	76	
P1	PG 76-16	LDPE	100	69	2	20
			3,200	73	0	
A1	PG 76-16	Air Blown	100	81	2	5
			3,200	84	0	

Stress Sweep Testing

To measure the stress sensitivity of binders, stress sweep testing was performed for 19 binders. Also, since one of the concerns of the project panel was the effect of different aircraft speeds on the different sections of an airfield, stress sweeps were performed at five different frequencies: 0.01Hz, 0.1Hz, 1Hz, 10Hz and 25Hz. The lowest frequency represents the speed in the aprons (less than 0.1mph).

In order to evaluate the stress sensitivity of the binders, the stress levels for which the $|G^*|$ began to decrease with respect to the original value $|G^*|_0$ were determined. Three levels were considered: 90 %, 70 % and 50 % of $|G^*|_0$. The last value (50 % of $|G^*|_0$) could not be obtained for some of the binders because of limits in the capabilities of the DSR. Table 13 shows the summary data obtained from the stress sweep testing for one of the binders (B2); Figure 12 is a plot of these data.

Relationship between MSCR ε_r and Elastic Recovery

The ER/ductilimeter test is commonly used by many state highway agencies to identify polymer modified binders; if the ER/MSCR test is to replace the ER/ductilimeter test, there must be a good correlation between data produced by these two tests. Four ER/MSCR parameters were measured for each binder: ER/MSCR at 25ºC and 100 Pa, ER/MSCR at 25ºC and 3,200 Pa, ER/MSCR at PG/HT and 100 Pa and ER/MSCR at PG/HT and 3,200 Pa. Figures 13, 14, 15 and 16 are plots of these various ER/MSCR test data as a function of ER/ductilimeter. As seen in Figures 13 and 14, the correlation between ER/MSCR and ER/ductilimeter at 25°C at both stress levels is only moderate. Eight of the binders that showed ER/MSCR between 50 % and 80% have ER/ductilimeter values equal or lower than 20 %. Based on these results, determining ER/MSCR at 25ºC is not recommended.

Table 13. Stress Sweep Testing Results for B2, PG64-28 Elvaloy.

Point	Freq.	Sample 1			Sample 2			Average		
	Hz	$\lvert G^*\rvert_0$ *Pa*	Strain *mm/mm*	Stress *Pa*	$\lvert G^*\rvert_0$ *Pa*	Strain *mm/mm*	Stress *Pa*	$\lvert G^*\rvert_0$ *Pa*	Strain *mm/mm*	Stress *Pa*
90 % $\lvert G^*\rvert_0$	0.01	92	13.8	1,140	100	12.0	1,080	96	13.0	1,110
	0.1	319	4.02	1,160	342	3.93	1,210	331	4.00	1,180
	1.0	1,720	1.13	1,740	1,770	1.14	1,810	1,740	1.10	1,780
	10	9,990	0.37	3,330	11,300	0.34	3,490	10,700	0.35	3.410
	25	17,300	0.24	3,770	19,800	0.25	4,380	18,600	0.24	4,080
70 % $\lvert G^*\rvert_0$	0.01	92	29.5	1,910	100	27.0	1,910	96	28.0	1,910
	0.1	319	7.78	1,720	342	8.00	1,910	331	8.00	1,820
	1.0	1,720	2.00	2,370	1,770	2.00	2,430	1,740	2.00	2,400
	10	9,990	0.60	4,130	11,300	0.60	4,510	10,700	0.60	4,320
	25	17,300	0.34	4,960	19,800	0.40	5,520	18,600	0.37	5,240
50 % $\lvert G^*\rvert_0$	0.01	92	59.3	2,720	100	54.0	2,670	96	56.0	2,690
	0.1	319	31.2	4,980	342	32.0	5,480	331	32.0	5,230
	1.0	1,720	3.27	2,780	1,770	3.00	2,940	1,740	3.00	2,860
	10	9,990	0.95	4,670	11,300	0.90	5,200	10,700	0.90	4,940
	25	17,300	0.66	5,450	19,800	0.60	6,080	18,600	0.60	5,770

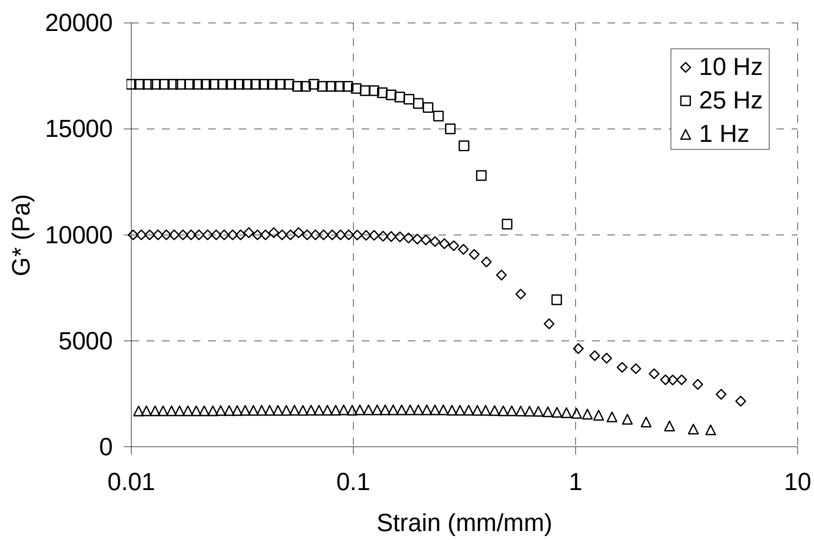

Figure 12. Stress Sweep Results for High Frequencies, B2 PG64-28 Elvaloy.

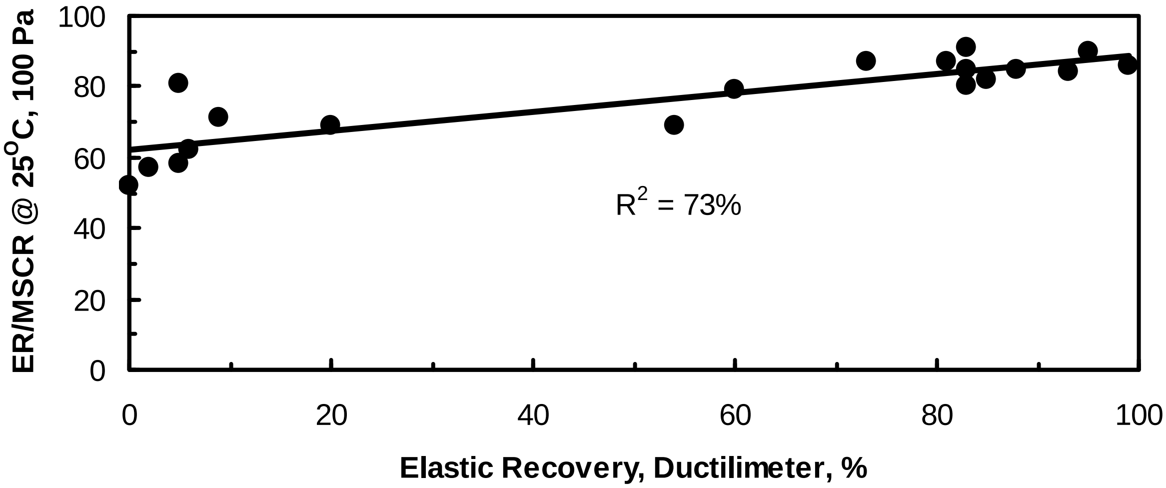

Figure 13. Elastic Recovery/MSCR at 25ºC and 100 Pa as a Function of Elastic Recovery/Ductilimeter, also at 25°C.

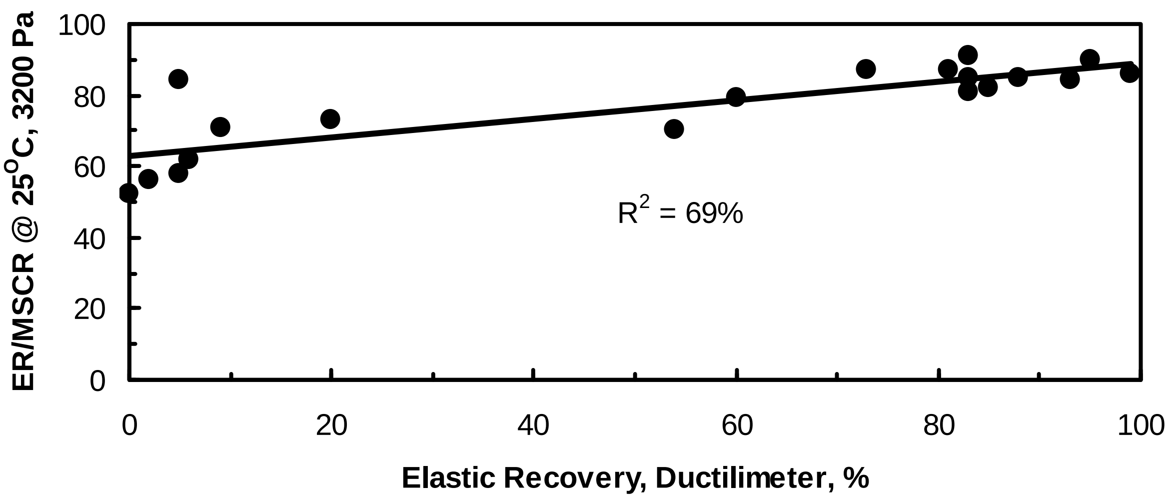

Figure 14. Elastic Recovery/MSCR at 25ºC and 3,200 Pa as a Function of Elastic Recovery/Ductilimeter, also at 25°C.

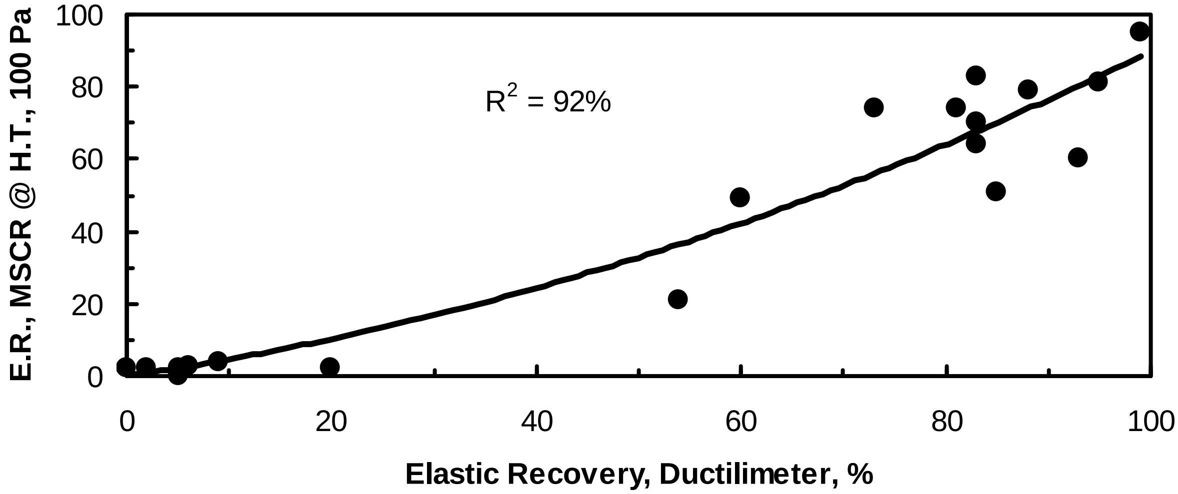

Figure 15. Elastic Recovery/MSCR at High Grading Temperature and 100 Pa as a Function of Elastic Recovery/Ductilimeter at 25°C.

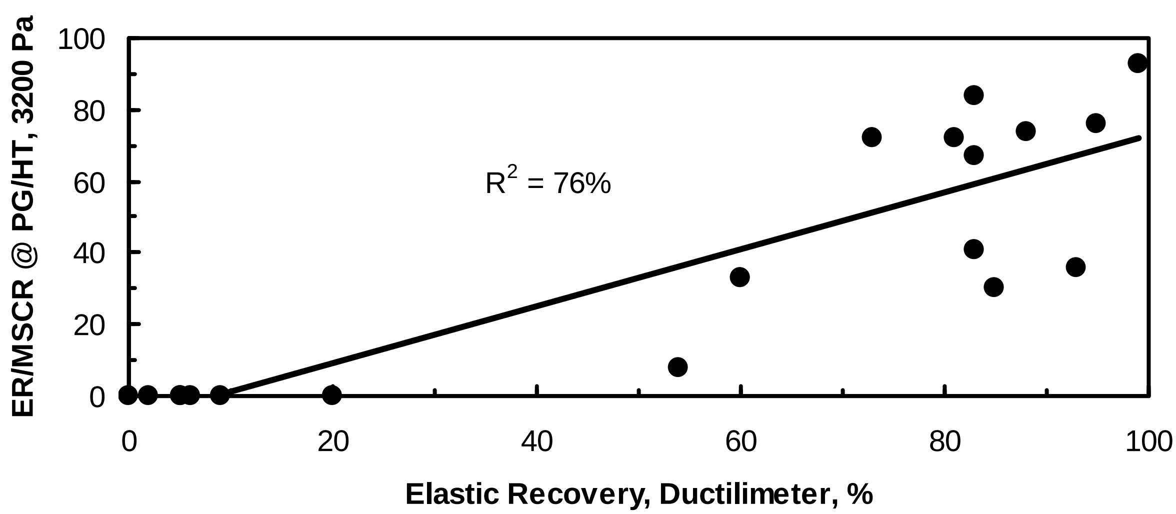

Figure 16. Elastic Recovery/MSCR at High Grading Temperature and 3,200 Pa as a Function of Elastic Recovery/Ductilimeter at 25°C.

The correlations of ER/MSCR data at PG/HT with the ER/ductilemeter test results are more reasonable, as seen in Figures 15 and 16. Also, out of eight binders that showed ER below 20 %, 7 had nearly 0 ε_r, for both stress levels. The binders with this trend were either neat binders (N1, N2 and N3) or binders modified with very low percentages of SBS (C4 and C5). The only exception to this trend was C8, which was a PG76-22 binder modified with SBS. C8 has an ER/ductilimeter value of 20 %, and ER/MSCR values of 51 % and 30 %, for 100 Pa and 3,200 Pa stress levels, respectively. At the other extreme, all the binders that showed ER/MSCR values higher than 60 % at PG/HT, also showed ER/ductilimeter values higher than 60 %; note that 60 % is the standard ER/ductilimeter test result required in many states for accepting a modified asphalt binder. For these reasons, it is recommended that the ER/MSCR test should be performed at the PG/HT.

An important issue that must be addressed is which stress level is most appropriate for testing binders intended for use in airfields. Research has shown that even for highway pavements, the stress levels inside the binder can be much higher than 100 Pa (*31*). It should be expected that these stresses will be even higher in airfield pavements. Therefore, it is recommended that ε_r should be measured at 3,200 Pa when binders are evaluated for use in airfield pavements.

Stress Sensitivity of MSCR Testing

Figures 17 and 18 illustrate the stress sensitivity of ε_r in the MSCR test. Figure 17 shows the contrast between ER/MSCR at 25ºC, 100 Pa and as measured at 25ºC, 3,200 Pa. Figure 18 presents the contrast between ER/MSCR at PG/HT, 100 Pa and ER/MSCR at HT, 3,200 Pa. Examining Figure 17, at 25ºC, ER/MSCR remains approximately constant for both stress levels. Figure 18, however, shows that when binders are tested at PG/HT, some differences can be seen in the ER/MSCR values determined at different stress levels. For example, consider binders C8 (PG76-22 SBS), C9 (PG82-22 SBS), D1 (64-28 SB) and D5 (64-40 SB) tested at PG/HT. When the stress was increased from 100 Pa to 3,200 Pa, the value of ER/MSCR decreased at least 30 % from its original value for the mentioned binders. When these same binders were tested at 25ºC, no changes in ER/MSCR were noticed when the stress was increased. This suggests that testing MSCR at PG/HT is a better tool for determining the stress sensitivity of the binders than testing at 25ºC.

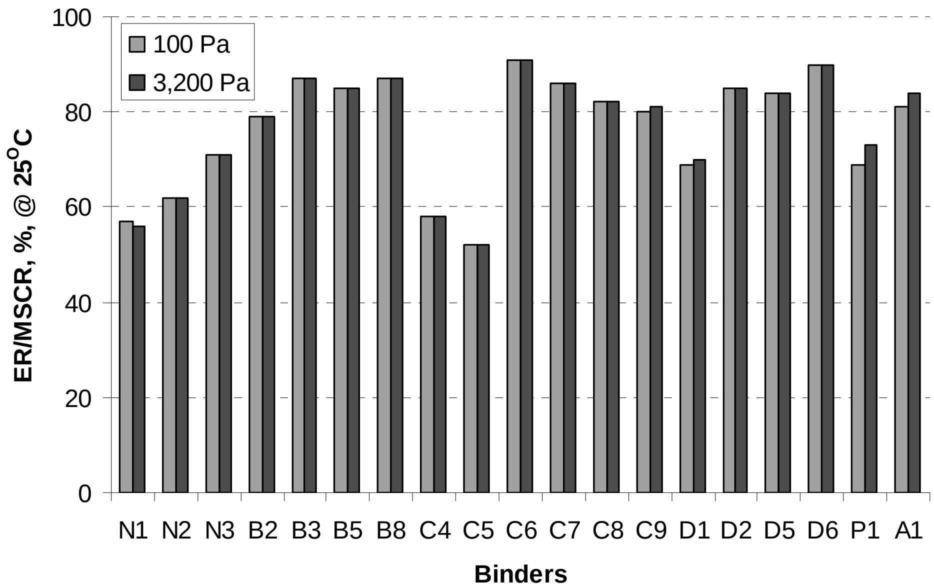

Figure 17. Comparison of ER/MSCR at 25º at 100 Pa and 3,200 Pa.

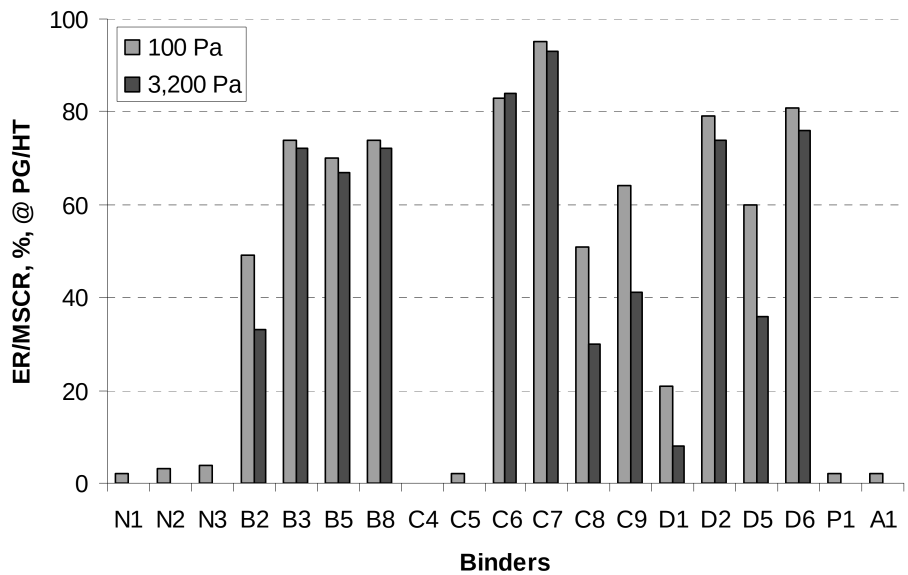

Figure 18. Comparison of ER/MSCR at PG/HT at 100 Pa and 3,200 Pa.

To further evaluate the stress sensitivity of MSCR test, the total accumulated strain after the ten loading cycles was compared for both stress levels for all binders. For the purpose of comparison and to study the non linear effects, the strains were normalized. When a material is linear viscoelastic, the total strain will be proportional to the stress level. So, increasing the stress level by a given factor will make the total strain increase by the same factor. So by dividing the total strains by the stress level used, the non linear effects can be studied. This parameter—the total strain after ten cycles divided by the applied stress in the MCSR test—is similar to a compliance value, and is abbreviated NAS_{10}. Figures 19 and 20 are graphical comparisons of NAS_{10} values for both stress levels and both temperatures. It is observed again that for 25ºC, there are no differences in the NAS_{10} for both stress levels. For the PG/HT however, the NAS_{10} values increased significantly for 12 of the 19 binders, suggesting that the response under a 3,200 Pa load is non linear for many binders. The rest of the binders showed minimal variations in NAS_{10}. This confirms that testing the binders at PG/HT gives more information about stress sensitivity than testing the binders at 25ºC, and is therefore more appropriate for evaluating and/or specifying rut resistance.

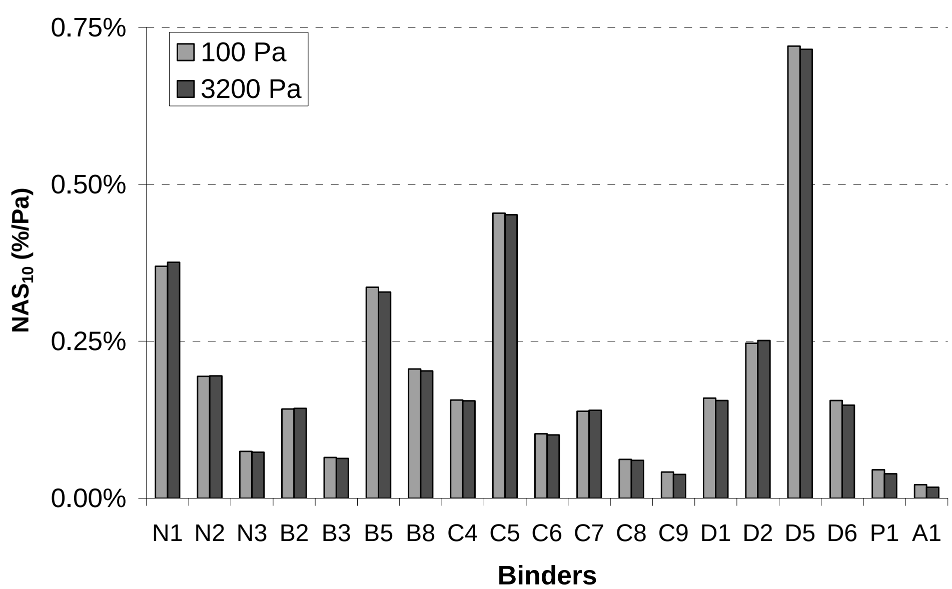

Figure 19. Comparison of NAS_{10} at 25º at 100 Pa and 3,200 Pa

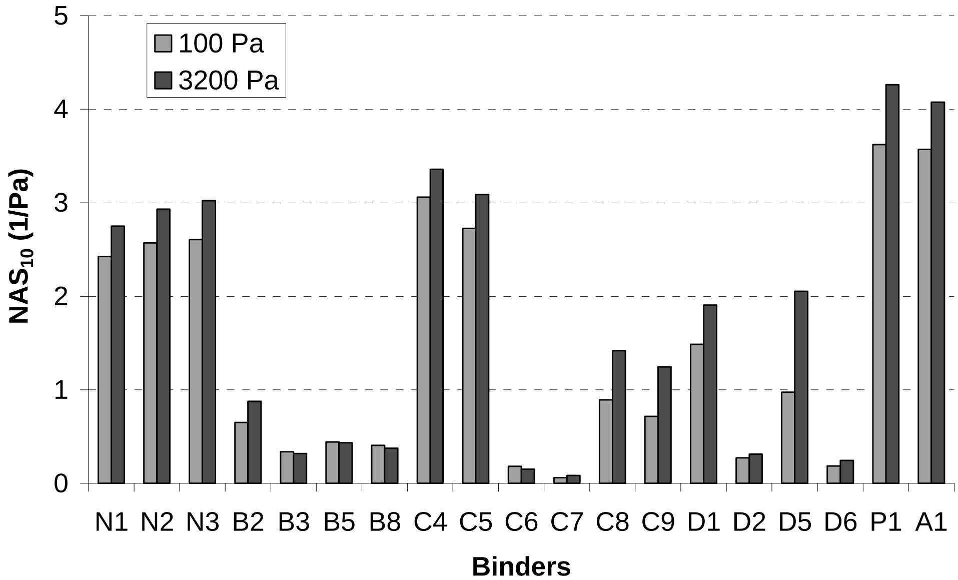

Figure 20. Comparison of NAS_{10}at HT/PG° at 100 Pa and 3,200 Pa.

Linear Viscoelastic Limits based on Stress Sweep Testing

Stress dependency of asphalt binders was also studied using the stress sweep testing. Previous research showed that binders that were able to withstand higher stresses without significant decreases in $|G^*|$ (or η_0) showed better rutting performance (*32, 33*). To study this effect further, a subgroup of 7 binders of the same PG grade was selected, tested and the results compared. Figures 21, 22 and 23 show the stress sweep results for those 7 binders (2 samples per binder). Figure 21 shows the results for 0.01 Hz, while Figure 22 presents the results for 1 Hz, and Figure 23 the results for 25 Hz. These plots illustrate how the ranking of the binders in terms of stiffness varies depending on the stress level applied. In Figure 21, for example, binder D2 (PG 64-34 SB) has a higher $|G^*|$ at low stress levels than B5 (PG64-34 Elvaloy). However, for stresses above 1,500 Pa, B5 is stiffer than D2. Similar situations can be observed in Figures 21 and 22. For 1 Hz (Figure 18), for example, B2 (64-28 Elvaloy) is stiffer than D5 (64-40 SB) for stresses lower than about 2,300 Pa, but the opposite is true for higher stresses. For 25 Hz (Figure 22), D2 (PG 64-34 SB) and D5 (64-40 SB) are in the lower range of stiffness for low stresses levels, but these are the only binders that are able to withstand more than 6,000 Pa without collapsing.

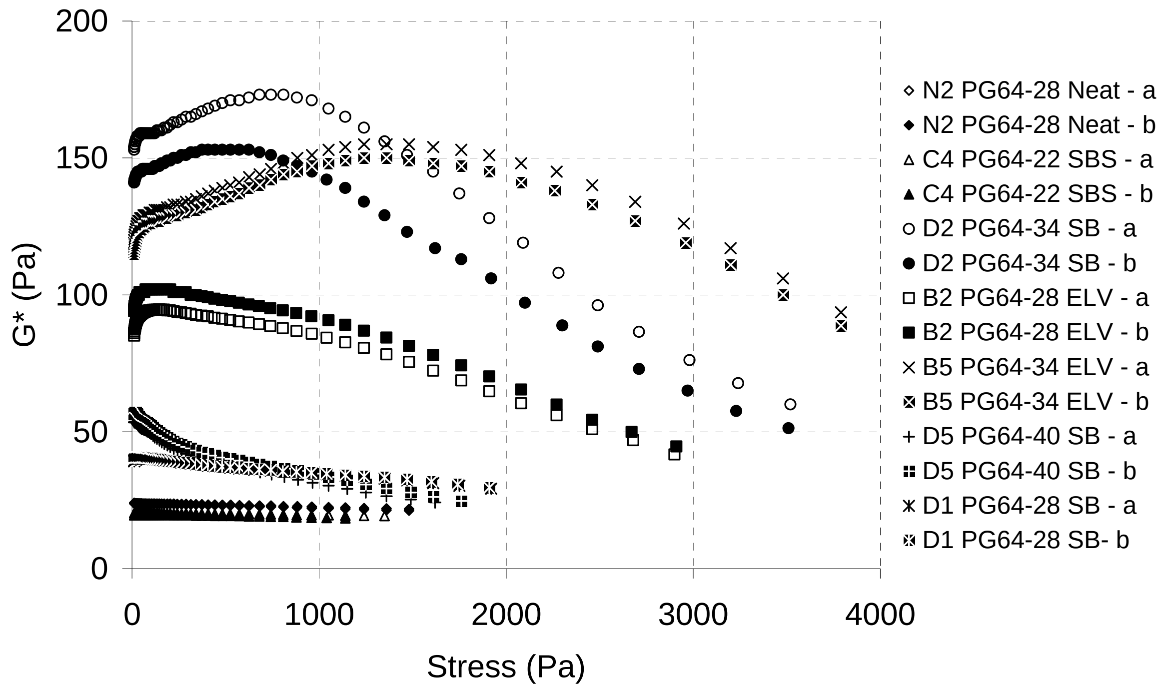

Figure 21. |*G| at 0.01 Hz v/s Stress, PG64-XX Binders.**

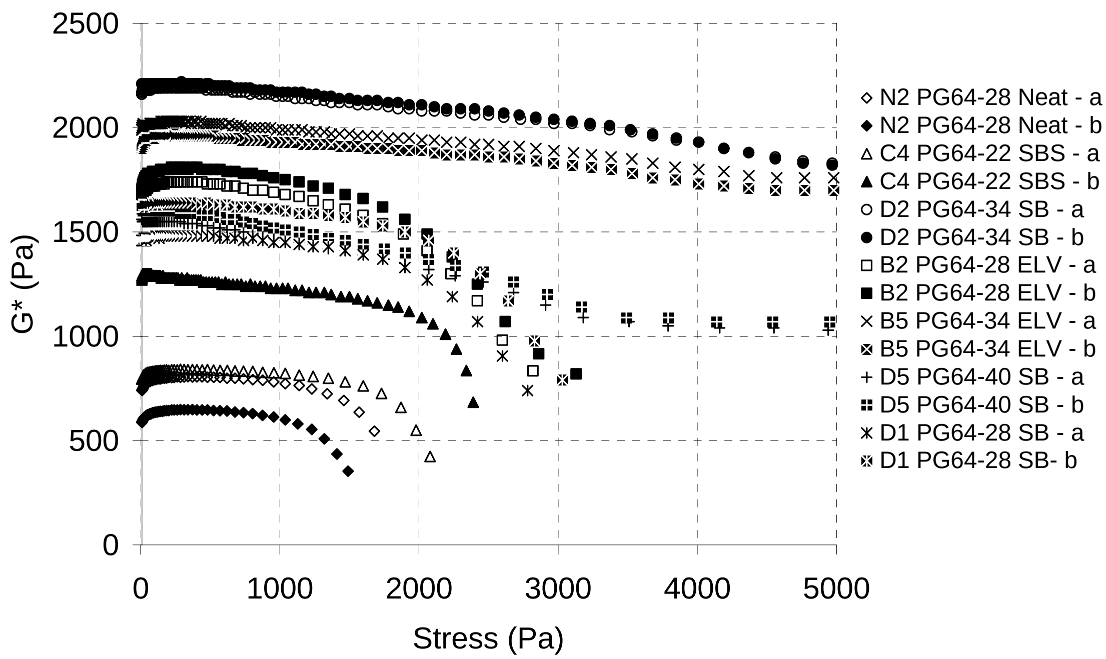

Figure 22. |*G| at 1 Hz v/s Stress, PG64-XX Binders.**

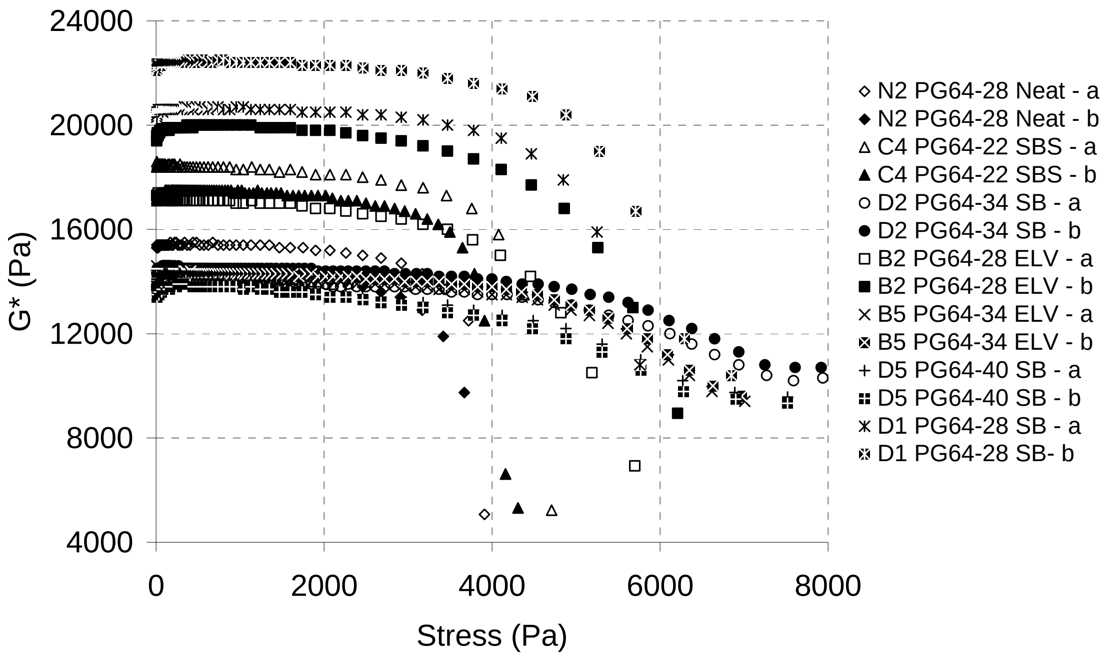

Figure 23. |*G| at 25 Hz v/s Stress, PG64-XX Binders.**

As mentioned previously in this report, stress and strain levels at which |*G**| decreases by various percentages were determined. Figures 24 and 25 show the strain level for 10 % decrease in |*G**| and for 50 % decrease in |*G**|, respectively. The values represent the average of the two samples tested for each binder. It is clear that the strain level required to produce a given decrease in |G*| is strongly dependent on the loading frequency; as frequency increases, the strain level decreases. Figure 24 can be thought of as a rough "map" of the practical linear region for the binders tested—strains lower than the plotted points will tend to provide a more or less linear response, while higher strains will result in an increasingly non-linear response. At strains of about 1 Hz and higher, there is a relatively small amount of scatter in Figure 24. However, as frequency decreases, the amount of scatter increases until it is quite large at 0.01 Hz. It is possible that some of this scatter is not due to differences in the behavior of the binders, but is the result of limitations in the test method—at low frequencies, the modulus of the binders is lower, and the response (stress) during loading can be difficult to measure precisely. The situation seen in Figure 25 is somewhat different. This plot shows the strain level required to cause the |*G**| value to drop to 50 % of its initial value; in this case, the scatter appears highest at intermediate frequencies, where the precision of the measurements is likely to be the highest. It can be concluded that there are significant differences in the high-temperature strain susceptibility of different asphalt binders, even when the high-temperature PG grades are identical.

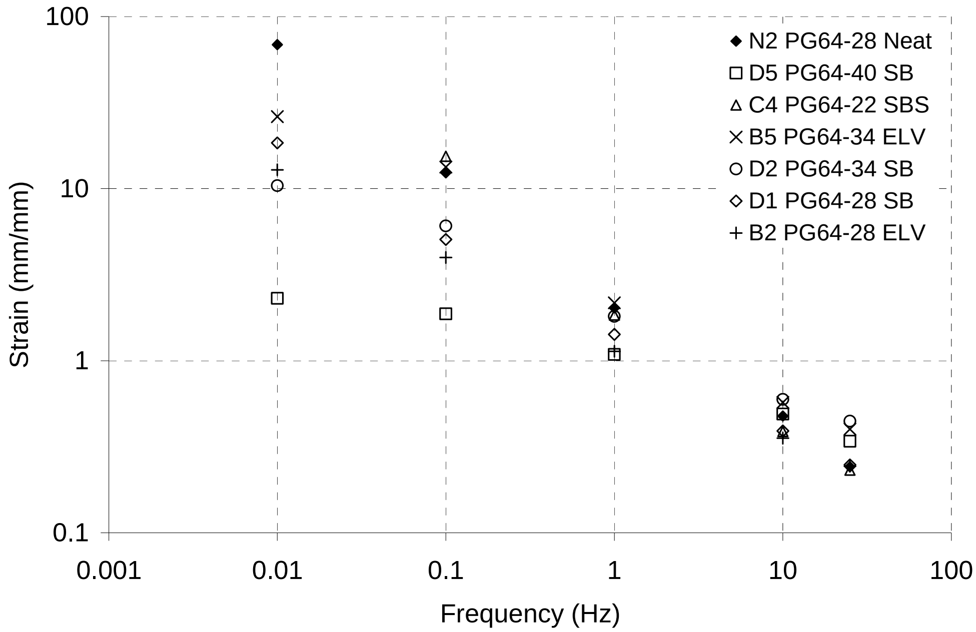

Figure 24. Strain Required for 10 % Decrease in |*G|, all Frequencies.**

Figures 26 and 27 are similar to Figures 23 and 24, but in this case the binders were tested in a stress-controlled mode, rather than in a strain-controlled mode. The figures there show the stress levels at which a given percentage decrease in |*G**| occurs. Figures 26 shows the stress level required to cause a 10 % decrease in |*G**|, while Figure 27shows the stress level required to cause a 50 % decrease in |*G**|. As in the previous series of plots, the values presented correspond to the average of the two samples. Again, although there is a clear trend toward increasing stress sensitivity with increasing frequency, there are significant differences in the stress sensitivity of the materials tested, even though they all are PG 64-XX binders.

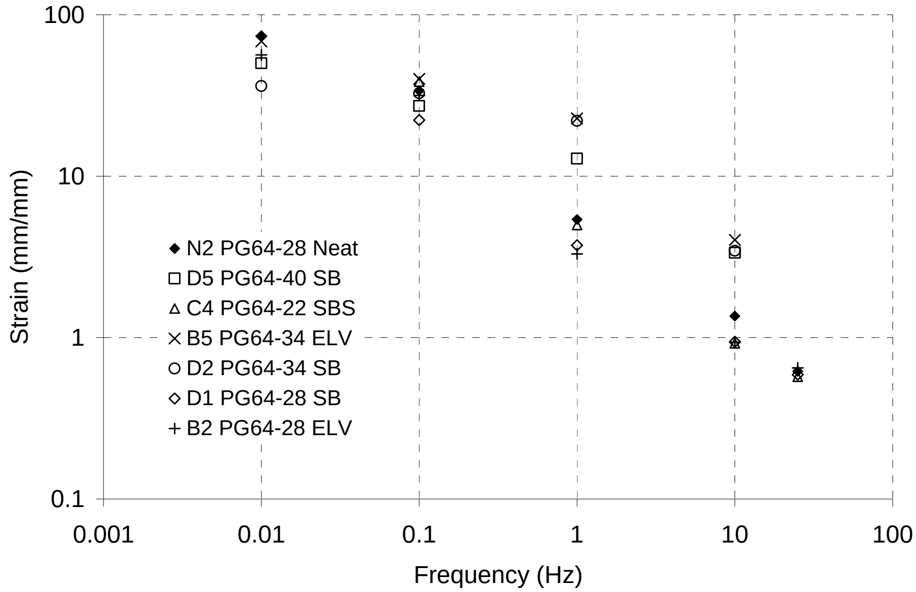

Figure 25. Strain Required for 50 % Decrease in |*G|, all Frequencies.**

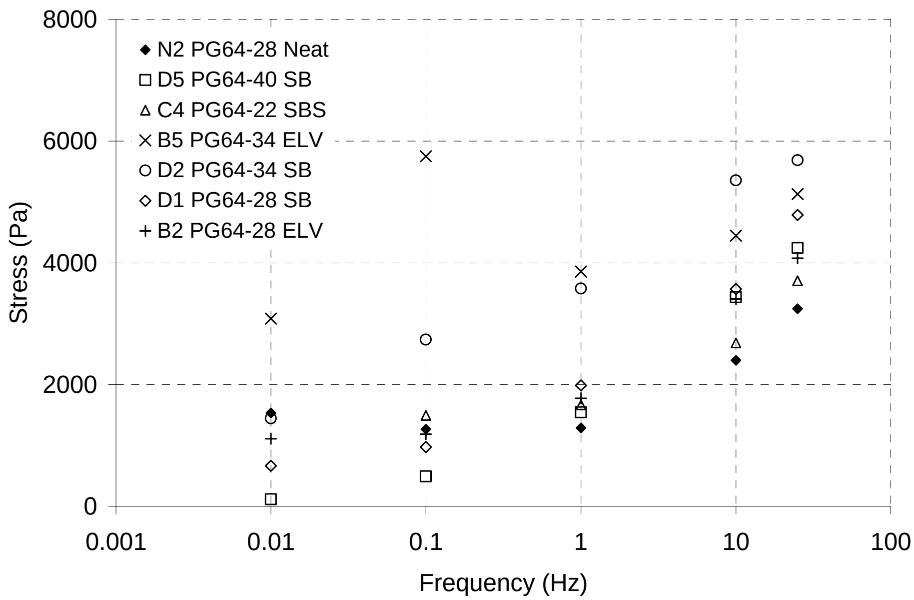

Figure 26. Stress Required for 10 % Decrease in |*G|, all Frequencies.**

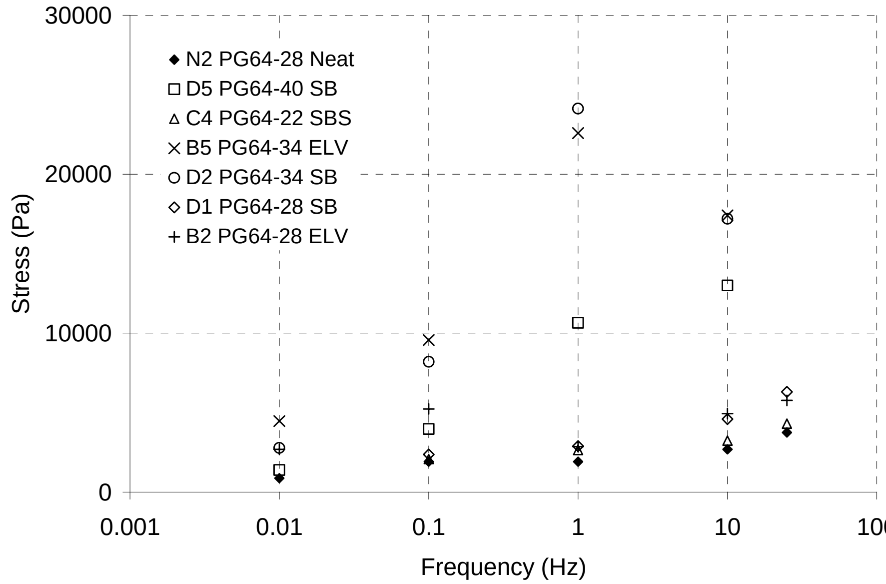

Figure 27. Stress Required for 10 % Decrease in |*G|, all frequencies.**

Mixture Repeated Load Tests

Binder Selection

Out of the 19 binders previously tested, two binders were selected for mixture rutting test at different stress conditions: a PG70-22 Neat (N3) and a PG64-34 (B5). The criteria for the binder selection considered the following:

- One neat binder and one polymer modified binder, with the objective of comparing the stress dependency of both kinds of asphalts.
- One binder with high elastic recovery and one binder with low elastic recovery, to evaluate the influence of this parameter in the rutting

The selection of a stiffer neat binder PG70-22 and a softer polymer modified binder (PG64-34) also allows the comparison of the benefits of the modification and the recoverability of polymer modified binders compared with the grade bumping for the high temperature of the PG grade.

The elastic recovery of the selected binders, measured using the ductilimeter and the MSCR test with the DSR, are presented in Table 14.

Table 14. Test Results for the Binders used in Tested Mixtures.

Code	Binder	ER (Ductilimeter)	ER/MSCR at HT of PG Grade		Accumulated Strain 10 Cycles of MSCR	
			100 Pa	**3,200 Pa**	**100 Pa**	**3,200 Pa**
N3	70-22 Neat	9 %	4 %	0 %	260 %	9,670 %
B5	64-34 Elvaloy	83 %	70 %	67 %	44 %	1,391 %

Aggregate Gradation

Two different gradations were selected for the mixture rutting testing. Previous research has demonstrated that the distribution of binder strains inside the mixture depends on the aggregate gradation (*34*). For this reason, a coarse gradation and a fine gradation were selected for the study of the stress susceptibility of both binders for rutting performance. The gradations are the standard Asphalt Institute gradations and they are shown in Table 15.

The fine gradation meets the requirements of UFGS-32 12 15 (formerly UFGS-02749). The coarse gradation does not, since the UFGS standards only consider fine mixes. The coarse gradation was included in this study despite this fact, because it is important to evaluate how the different strains that the binder is subjected in both kinds of mixtures affect the rutting performance at the high stress levels that the airplane tires apply on the pavement.

The aggregate used was crushed limestone. Two different sources of similar characteristics were used in the sample preparation. One of the sources was the standard aggregates used by the Asphalt Institute (Limestone 2) and the other a limestone from a Wisconsin source (Limestone 1).

Table 15. Aggregate Gradation.

Sieve Size mm	Percentage Passing	
	Fine	Coarse
25.0	100	100
19.0	100	100
12.5	95	98
9.5	85	87
4.75	66	44
2.36	50	28
1.18	38	20
0.600	27	14
0.300	15	8
0.150	6	5
0.075	3	4

Experimental Design

The experimental design considers two kinds of binders, two kinds of gradations and three different stress levels (100 lb/in^2, 200 lb/in^2 and 300 lb/in^2). That makes a total of 12 testing conditions. In order to allow 3 replicates per each testing condition, 36 samples were prepared. The samples were prepared using the Superpave gyratory compactor in batches of 8 samples or 4 samples. Tables 16 and 17 show the sample information for the fine mixtures and coarse mixtures respectively. In these tables the samples are labeled with the type of mixture first (F for fine and C for coarse), then the binder (B5 or N3), the stress level in lb/in^2 and the replicate identification (A, B & C).

Table 16. Fine Mixture Samples.

Sample ID	Gmm	% Air Voids, SGD Sample (before Coring)	Compaction Batch	Aggregate
F-N3-100-A	2.552	7.6%	IV	Limestone 2
F-N3-100-B	2.580	6.9%	III	Limestone 1
F-N3-100-C	2.580	7.1%	V	Limestone 1
F-N3-200-A	2.580	6.1%	III	Limestone 1
F-N3-200-B	2.580	6.1%	I	Limestone 1
F-N3-200-C	2.580	6.8%	II	Limestone 1
F-N3-300-A	2.580	6.9%	IV	Limestone 1
F-N3-300-B	2.580	5.9%	I	Limestone 1
F-N3-300-C	2.552	6.1%	V	Limestone 2
F-B5-100-A	2.574	7.9%	IV	Limestone 1
F-B5-100-B	2.574	8.1%	III	Limestone 1
F-B5-100-C	2.550	7.3%	V	Limestone 2
F-B5-200-A	2.574	6.3%	III	Limestone 1
F-B5-200-B	2.574	6.9%	I	Limestone 1
F-B5-200-C	2.574	7.2%	II	Limestone 1
F-B5-300-A	2.550	6.7%	IV	Limestone 2
F-B5-300-B	2.574	7.1%	I	Limestone 1
F-B5-300-C	2.574	7.6%	V	Limestone 1

Table 17. Coarse Mixture Samples.

Sample ID	Gmm	% Air Voids, SGC Sample (before Coring)	Compaction Batch	Source
C-N3-100-A	2.582	7.3%	IV	Limestone1
C-N3-100-B	2.582	6.6%	III	Limestone 1
C-N3-100-C	2.551	9.6%	V	Limestone2
C-N3-200-A	2.582	5.0%	III	Limestone 1
C-N3-200-B	2.582	6.1%	I	Limestone 1
C-N3-200-C	2.582	7.3%	II	Limestone 1
C-N3-300-A	2.551	10.1%	IV	Limestone 2
C-N3-300-B	2.582	6.3%	I	Limestone 1
C-N3-300-C	2.582	8.0%	V	Limestone 1
C-B5-100-A	2.547	6.6%	IV	Limestone 2
C-B5-100-B	2.573	7.1%	III	Limestone 1
C-B5-100-C	2.573	7.4%	V	Limestone 1
C-B5-200-A	2.573	6.3%	III	Limestone 1
C-B5-200-B	2.573	5.6%	I	Limestone 1
C-B5-200-C	2.573	7.1%	II	Limestone 1
C-B5-300-A	2.573	7.3%	IV	Limestone 1
C-B5-300-B	2.573	6.5%	I	Limestone 1
C-B5-300-C	2.547	8.1%	V	Limestone 2

Test Results—Mixture rutting test was performed at the Advanced Asphalt Technologies laboratory and the results sent back to University of Wisconsin Madison for analysis and evaluation of binder rutting performance. The mixture rutting test performed was repeated creep and recovery for determining the flow number Fn. The temperature of testing was 46ºC. Out of the testing stresses initially selected, only 100 lb/in^2 and 200 lb/in^2 were used. The flow numbers obtained for 200 lb/in^2 were very low and it was decided not to use 300 lb/in^2. Instead, an intermediate stress level of 150 lb/in^2 was used. Table 18 lists the flow number test results. The results are shown graphically in Figure 28. The stress level has a very large effect on the flow number, and it appears that the PG 64-34 binder has somewhat less resistance than the PG 70-22 binder. To better quantify the results of these tests, an analysis of variance was performed on the data. The factors included in the study were asphalt binder and aggregate gradation; air voids and the log of the stress level were used as covariates. The log of the flow number was the dependent variable. The results of this analysis are given in Table 19. All factors were highly significant in this analysis; the r^2 value for the model was moderate at 82 %. The effect of increasing air voids and increasing stress were both as expected—both caused a decrease in flow number. However, the coefficient for log stress was -4.26, whereas the expected value—the stress exponent used in the MEDG models—should be about -2. It is not clear why the stress exponent in this study is much larger than anticipated, and not in agreement with the MEDG model. One possibility is that the stress levels were simply too high for these materials. Flow numbers below 1,000 are very low and tend to be highly variable. Also, the damage mechanism under this type of loading could be considerably different than what occurs in the field. Although the stress levels are similar to the tire pressures used in many aircraft, these tests are unconfined, and so the distortional stress is much higher than what would exist in most airfield pavements. Lower stresses were not used because it was feared that testing to failure would take so long as to be impractical. Therefore, although this aspect of the test program was disappointing, the stress exponent as derived from the MEDG rutting model should still be considered to be reasonably accurate in addressing the higher stresses existing in some airfield pavements.

Table 18. Flow Number Test Results.

Sample ID	Stress Level	Sample ID	Fn
F-N3-100-A	100	C-N3-100-A	994
F-N3-100-B	100	C-N3-100-B	3,330
F-N3-100-C	100	C-N3-100-C	627
F-N3-300-A	150	C-N3-300-A	260
F-N3-300-B	150	C-N3-300-B	485
F-N3-300-C	150	C-N3-300-C	416
F-N3-200-A	200	C-N3-200-A	829
F-N3-200-B	200	C-N3-200-B	264
F-N3-200-C	200	C-N3-200-C	149
F-B5-100-A	100	C-B5-100-A	1,719
F-B5-100-B	100	C-B5-100-B	2,016
F-B5-100-C	100	C-B5-100-C	735
F-B5-300-A	150	C-B5-300-A	85
F-B5-300-B	150	C-B5-300-B	142
F-B5-300-C	150	C-B5-300-C	62
F-B5-200-A	200	C-B5-200-A	116
F-B5-200-B	200	C-B5-200-B	26
F-B5-200-C	200	C-B5-200-C	21

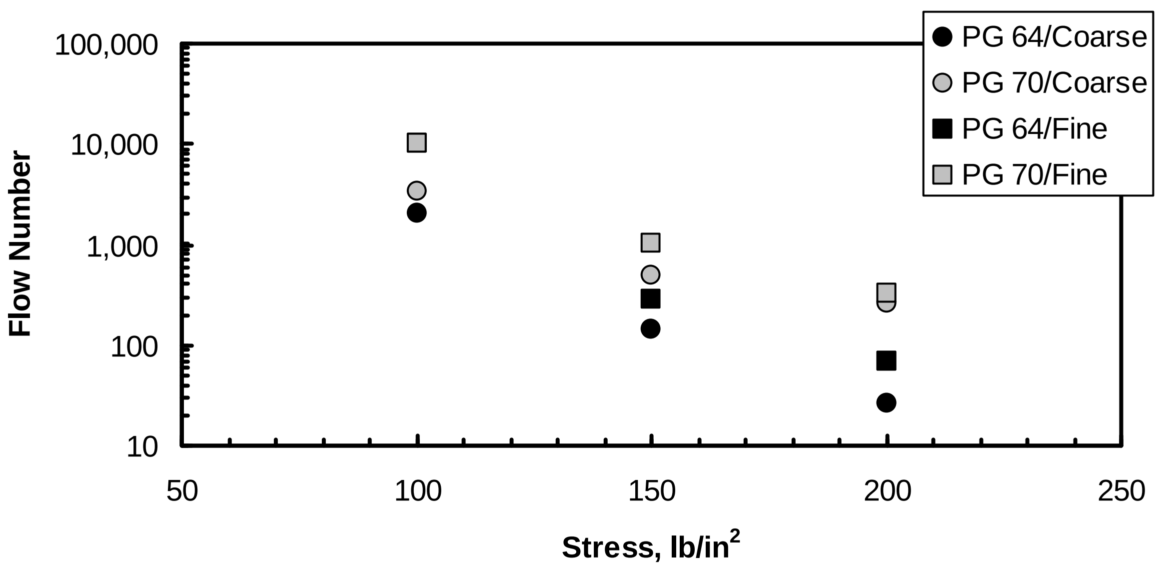

Figure 28. Flow Number as a Function of Stress Level for Four Different Mixtures.

Table 19. Summary of Results of Analysis of Variance of Flow Number Data.

Source	Degrees of Freedom	Coefficient	Sequential Sum of Squares	Adjusted Sum of Squares	Adjusted Mean Square	F	P'
Air Voids	1	-0.158	0.4908	0.5788	0.5788	6.49	0.016
Log Stress	1	-4.26	7.6955	8.3725	8.3725	93.94	0.000
Binder	1	---	1.5999	1.6400	1.6400	18.40	0.000
Aggregate	1	---	1.8032	1.8032	1.8032	20.23	0.000
Error	31	---	2.7630	2.7630	0.0891		
Total	35	---	14.3525				

Laboratory Test Program: Findings

It appears that the MSCR test has good potential as a specification test that addresses the performance characteristics of both modified and unmodified binders. It should be performed at the PG high grading temperature, at the higher stress level (3,200 Pa). PMAs are well suited for use in HMA pavement in airfields subject to heavy and/or slow moving air traffic. The MSCR test, once implemented, will be an effective means of specifying PMAs for airfield pavements. Unfortunately, at this time the MSCR test has not yet been widely implemented in the highway community, and applying it to the specification of PMAs for use in airfield pavements would be difficult and costly. An effective interim specification test is the elastic recovery test, which is widely used by many agencies to specify PMAs, and correlates reasonably well to the results of the MSCR test. Stress sweeps show large differences in the behavior of different binders, but it is unclear how this test could be used in specifying binders for either highway or airfield pavements.

The flow number tests performed on four different mixes made with two binders showed a greater degree of stress dependency that expected based upon rutting models included in the recently developed MEDG. However, this study was limited and it is possible the anomalous results were the result of very high stress levels without applying any confinement. It is concluded that the stress exponent developed on the basis of the MEDG rutting models should still be considered valid.

SPECIFYING POLYMER MODIFIED BINDERS FOR USE IN AIRFIELD PAVEMENTS

As discussed above, polymer modified asphalt binders (PMAs) have become widely used in HMA for highway pavements, especially for applications involving heavy and/or slow moving traffic. Highway engineers are in general pleased with the performance of PMAs and are increasing their use on interstate highways and similar applications. There appears to be no reason PMAs should not be used for HMA on airfield pavements subject to heavy, slow moving aircraft. However, there are a number of issues that need to be addressed in developing an effective specification for PMAs for use in HMA on airfield pavements:

- Under what conditions should PMAs be suggested? Under what conditions should PMAs be required?
- It is generally acknowledged that the current PG grading system is not effective in differentiating PMAs from non-modified binder. How can a PMA specification properly identify PMAs suitable for use in HMA for airfield pavements?
- It is also widely recognized that current PG grading system does not adequately address the improved rut resistance provided by many PMAs. How can a PMA specification for HMA for airfield pavements account for this performance benefit?
- How can an effective PMA specification for airfield pavements—addressing the three issues mentioned above—be kept simple enough to be easy to implement in both civilian and military airfield paving applications?

The back discussion on PMAs presented earlier in this report provided significant information useful in answering these questions. The sections below further address these issues and present specific recommendations for developing an effective PMA specification for HMA in airfield pavements.

When Should PMAs be Specified in Airfield Pavements?

FAA P-401 and the Unified Facility Guide Specification (UFGS 02749) both suggest that PMAs have performed well on taxiways and runway ends subject to significant aircraft stacking. However, this specification stops short of requiring PMAs for these applications (there is no mention of a particular test or specification for identifying an appropriate PMA). There is overwhelming evidence that PMAs should be required in the most severe of such applications—taxiways and runway ends with EHEs ≥ 300,000 subject to frequent aircraft stacking. Requiring PMAs in these applications will help ensure that there is not excessive rutting and will also help minimize cracking. Furthermore, as shown in Table 11 above, such applications will require a high-temperature grade adjustment of +20°C, on top of a traffic adjustment likely to be 6 to 7°C. This will generally result in a specified binder grade of PG 76-XX or PG 82-XX—binder grades that in most parts of the U.S. will be polymer modified. Therefore, requiring PMAs for these applications will in general not represent an unusual binder selection and/or unnecessary cost. Many state highway agencies require that PG 76-XX binders be polymer modified, since these are the binders specified for the most demanding and critical applications.

For similar reasons, it is suggested that PMAs be required for HMA in airfield pavements subject to some aircraft stacking and with design EHEs ≥ 10,000,000. This situation could occur on taxiways/runways subject to a moderate number of very large aircraft or aircraft with very high tire pressures. The resulting mix of traffic might not result in frequent stacking, but would nevertheless represent a condition likely to result in excessive rutting unless a suitable PMA is used in the HMA design. The specification should suggest that using suitable PMAs in HMA for airfield pavements with EHEs ≥ 3,000,000, or at lower traffic levels when some stacking of aircraft is expected, will provide significant additional assurance against excessive rutting and fatigue cracking. The specification should also note that PMAs should be specified in HMA airfield pavements that have shown a history of excessive rutting unrelated to improper construction, regardless of the level of air traffic and/or frequency of stacking. This statement would cover unusual situations leading to excessive rutting, such as very high tire pressures, unusual landing gear configurations and/or unusually heavy stacking of aircraft. The recommendations concerning specification of PMAs in HMA for airfield pavements are summarized in Table 20.

Table 20. Recommended PMA Usage in HMA for Airfield Pavements.

Design Traffic Level *EHEs*	**Aircraft Stacking**	**Polymer Modified Binder Use in HMA**
< 10 million	None	Not required
	Some	Suggested
	Frequent	Required
≥ 10 million	None	Suggested
	Some	Required
	Frequent	Required

Note: PMAs should be specified in HMA for airfield pavements that have exhibited a history of excessive rutting unrelated to improper construction, regardless of the specific loading conditions.

Differentiating PMAs from Non-Modified Binders

As discussed in Section 2.1 of this report, the most common specification test for differentiating PMA from non-modified binders is the elastic recovery test at 25 °C. Although this is an empirical test, it is relatively simple to use and obviously widely performed. An important question is whether or not the elastic recovery test can serve as an effective surrogate for the MSCR test until such time as that test is widely implemented in the paving community. Figure 15, presented previously, is a plot of percent elastic strain as determined from the MSCR test performed at the PG grading high temperature as a function of elastic recovery at 25 °C. The relationship is strong (r^2 = 91 %), although significant scatter is evident. It would appear that these tests provide similar information on the characteristics of PMAs, and that the elastic recovery test at 25 °C can be used as a surrogate for the MSCR percent elastic strain.

In establishing a minimum value or values for the elastic recovery test, there are a number of considerations. The requirements should be similar to those in existing Superpave plus specifications, to make sure that the specification is not too restrictive and that binders meeting this requirement will be widely available. At the same time, the requirements should be strict enough to ensure that the resulting PMAs will exhibit performance significantly better than non-modified binders. Table 21 is a summary of elastic recovery requirements for states using

AASHTO T-301 at 25 °C, for common PG grades of polymer modified binders. The minimum requirements vary from 40 to 75 %, with an average of about 60 %. For airfield applications, it is anticipated that the most widely used grades of modified binders would be PG 76-22 and PG 82-22; for these grades, the average minimum elastic recovery value is also about 60 %. It is therefore recommended that for PMAs for airfield applications the required minimum value for elastic recovery as determined following AASHTO T-301 be set at 60 %. In addition, it is recommended that the specification should include a short note explaining that the AASHTO T-301 elastic recovery test is meant only to be an interim requirement for binders used in airfield pavements; once the MSCR test is implemented in an improved PG grading system, the AASTHO T-301 ductilemeter/elastic recovery test should no longer be needed.

Table 21. Summary Data for Elastic Recovery Requirement in States Using AASHTO T-301 at 25 °C, for Common Modified Binder Grades.

Binder PG Grade						
High Temp.	**70**	**70**	**70**	**76**	**76**	**82**
Low Temp.	**-22**	**-28**	**-34**	**-22**	**-28**	**-22**
State:	*Required Elastic Recovery, Minimum %:*					
AS	40			50		
MI	40	40		50	50	
KY				75		
LA	40	70		60		
NE						
NV/ Clark County				58		
NY	60			70		
SD		60	60			
TX	30	50	60	50	60	60
UT	65	70	75	70	75	
VA				70		
WV				70		
Average:	**46**	**58**	**65**	**62**	**62**	**60**

Addressing the Improved Performance of HMA Made with PMA

The third important item that must be addressed in specifying PMAs for HMA in airfield pavements is the increased performance observed in HMA made with these binders. In most highway agencies that specify PMAs, this is addressed indirectly, by requiring PMAs for the most demanding and critical applications, such as interstate highways and similar applications. In some cases specification of PMAs is based on design traffic level. In the grade selection procedure described above, the grade selection is initially based on local climate and EHEs, with further adjustments based on traffic speed and pavement location/configuration. PMAs are required in critical applications—such as taxiways and runway ends subject to frequent aircraft stacking, and recommended in similar near-critical applications. No part of this selection process has addressed in any way the special properties of modified binders. If implemented as is, the resulting requirement would most likely be extremely conservative, resulting in the specification of binder grades and types with significantly higher levels of performance than required for a given application. To improve the efficiency and cost effectiveness of the specification, it should address the improved performance typical for PMAs.

Unfortunately, there are few studies that have attempted to quantify the performance benefits of HMAs made with PMAs. The rutting/resistivity model discussed previously in this report includes a factor to account for the improved performance of HMA made with polymer modified binders; this model indicates that on average, HMA with PMA can withstand 7.1 times as much traffic without excessive rutting compared to HMA made with a non-modified asphalt of the same PG grade (*29*). Data included in a recent report by the Asphalt Institute on the performance of PMAs shows a wide range in benefit compared to non-modified asphalt binder; the rutting in pavement sections made with PMA averages about one-half that of companion sections made without modified binders (*35*). Because pavement rutting typically is proportional to the square root of applied loading cycles (*36*), this decrease of 50 % in rutting rate translates to a factor of 4 increase in allowable traffic. Therefore, the Asphalt Institute report suggests that using PMA in HMA pavements typically increases allowable traffic by a factor of four.

In order to apply these estimates of improved rut resistance to binder grade selection, they must be put into terms of an equivalent adjustment in high temperature grade. This requires a relationship is between temperature change and increased level of allowable traffic. From Equations 16 and 27, such a relationship can be developed:

$$\frac{EHE_1}{EHE_2} = \left[\frac{\left(|G^*|/\sin\delta\right)_1}{\left(|G^*|/\sin\delta\right)_2} \right]^{1.373} = \left\{\exp\left[-0.1349\left(T_1 - T_2\right)\right]\right\}^{1.373} = \exp\left[-0.1852\left(T_1 - T_2\right)\right] \quad (32)$$

$$\Delta T = T_1 - T_2 = 5.4 \ln\left(\frac{EHE_1}{EHE_2}\right) \quad (33)$$

The rutting/resistivity model suggested that HMA made using PMA can withstand 7.1 times as much traffic as HMA made with non-modified binders. Setting (EHE_1/EHE_2) = 7.1 in Equation 33 results in an estimated equivalent high-temperature grade increase of 10.4 °C. The Asphalt Institute report suggests that PMA increases allowable traffic in HMA pavements by about a factor of four; again applying Equation 33, this gives an estimated equivalent increase of 7.5 °C in the high-temperature PG grade.

The data collected as part of Project 04-02—presented in the previous section of this report—also provides some indication of the performance benefit of PMA, but in an indirect way. Because elastic deformation in general should not contribute to rutting in HMA, the increase in elastic recovery observed for PMAs in the MSCR test (ER/MSCR) provides a means of estimating the effect of modification on rut resistance. For the recommended minimum ER/ductilimeter value of 60 %, the corresponding average ER/MSCR value would be 43 %. Because non-modified binders when tested at the high grading temperature typically show an ER/MSCR value close to 0 %, this means that the non-recoverable strain for asphalt binders should be reduced by at least 43 % by use of PMAs under the proposed specification.

Determining the high-temperature PG grade increase equivalent to a 43 % decrease in permanent deformation can be done using an approximate approach. The decrease in permanent deformation would be equivalent to an increase in modulus ($|G^*|$) of about 1/(1-.43) = 1.75 times. Although, the PG grading parameter $|G^*|/\sin\delta$ is not exactly equal to $|G^*|$, at a typical phase angle of 75 ° for modified binders at high-temperature grading conditions, this difference is less than 4 %. Therefore, Equation 20 can be rearranged and applied to determine the grade change equivalent to a modulus increase of 1.75:

$$\Delta T = T_1 - T_2 = 7.4 \ln\left(\frac{\left(|G^*|/\sin\delta\right)_1}{\left(|G^*|/\sin\delta\right)_2} \right) = 7.4 \ln(1.75) = 4.1 \tag{34}$$

Therefore, the increased proposed minimum ER/ductilimeter value of 60 % should result in PMAs with an effective binder grade about 4 °C higher than similar non-modified binders. This is however a conservative value, since it should be expected that most PMAs used under the proposed specification would have an ER/ductilimeter values significantly higher than the minimum value of 60 %.

Taken together the three analyses given here would suggest PMAs provide a typical performance benefit ranging from about 5 to 10 °C, in terms of a high-temperature PG grade. It is proposed that the procedure for selecting binder for HMA for airfield pavements include a performance benefit for PMAs of one-half a grade, or 3 °C. This conservative approach will encourage the use of PMAs, while ensuring that the actual performance of the binder will almost always meet minimum requirements. This will also normally provide a significant performance "reserve," which will help provide good performance even for the most severe applications. Table 22 is the proposed modification of the binder grade adjustments given earlier in Table 11, but including the suggested provisions for polymer modified asphalt binder, including a note establishing the minimum ER/ductilimeter value of 60 % and a note concerning the potential implementation of the MSCR test. It also includes the information given previously in Table 20, concerning situations in which PMAs are suggested and/or required. This will simplify implementation of the specification—only Figures 7 and 8 (or Equation 22), and Table 22 are needed to fully describe the technical details of the proposed procedure for selecting PG binders for airfield pavements. As emphasized at several other points in this report, the high-temperature grade adjustments listed in Table 22 should be applied to the continuous base grade as determined using LTPPBind version 3.1 and the appropriate traffic level given in terms of EHEs. The final high-temperature grade is then found by rounding upwards to the nearest standard grade.

Table 22. High-Temperature PG Grade Adjustments for Aircraft Speed/Stacking and Pavement Location, Including Provisions for Polymer Modified Asphalt Binders.

Aircraft Stacking	Typical Speed *Mph*		Design Traffic *EHEs*	Grade Adjustment *°C*	
	Runway Centers	**Taxiways/ Runway Ends**		**Non-Modified Binders**	**Polymer Modified Binders***
None	≥ 45	15 to < 45	< 300,000	0	
Little or none	≥ 45	15 to < 45	300,000 to < 3 million	+7	*Not Required* +4
			3 million to < 10 million	+7	*Suggested* +4
			≥ 10 million	---	*Required* +4
Occasional	---	5 to < 15	< 10 million	+14	*Suggested* +11
			≥ 10 million	---	*Required* +11
Frequent	---	< 5	Any	---	*Required* +17

NOTE: Various highway agencies are currently evaluating the multiple stress creep and recovery (MSCR) test for use in the PG binder grading system. This test will better address the unique characteristics of modified binder than the current DSR tests at high temperature. Once the MSCR is implemented, only the grade adjustments given under "Non-Modified Binders" should be used.

REVIEW OF CURRENT AIRFIELD PRACTICE

The purpose of the review of current practice is to compare PG grade used on actual airfield pavements with grades selected on the basis of the proposed procedure. This is an evaluation meant to determine if the procedure provides reasonable grades compared with current practice. This evaluation must also consider, if possible, the performance of the pavement being used in the comparison. Another aspect of this review is to compare PG grades determined using current standards with those determined using the proposed procedure. These comparisons are given below.

Comparison of Proposed Procedure with Current Standards

There are two widely used existing FAA standards that contain procedures for selecting binder PG grades for airfield pavements: (1) Items P-401/403 as contained in FAA Circular 150/5370-10C; and (2) "Notice 15," the Northwest Mountain Region revision to P-401/403. These standards were summarized previously in this report. In order to compare binder grading under these two systems and under the proposed system, three model airfields will be used, representing small GA, medium and large airfields. The characteristics for the three model airfields are listed in Table 23. Binder grading information for three states—Alabama, Colorado and Kentucky—is given in Table 24. These states were selected for this comparison because after a long search, few states could be found for which published guidelines for PG grade selection could be located, and almost all were located in the South; Alabama, Colorado and Kentucky represented the largest range in climate for states for which PG grade requirements were located. Information in these two tables was used to select PG grades, using the proposed system, and using the procedures given in P-401/403 and Notice 15. Use was made where possible of the list of commonly available PG grades given previously (Table 3). PG grades in which the sum of the two grading numbers exceed 90 were assumed to be modified. Under P-401/403, high-temperature PG grade bumping can be based either on aircraft tire pressure or gross weight; this analysis includes both grade bumping approaches. The procedure given in Notice 15 was only applied to Colorado, since this procedure was developed for the Rocky Mountain states only, and should not be applied to other locations. The results of the comparison are summarized in Table 25 (runways) and Table 26 (taxiways). This comparison indicates that the proposed procedure in general provides similar high-temperatures grades for taxiways, but in some cases softer grades for runways, compared to those given by the existing procedures. The proposed procedure also tends to give softer grades for taxiways for small airfields. The differences appear to be in part because of the relatively simple approach in P-401 and Notice 15—in many cases, these procedures do not differentiate between runways and taxiways, and also do not provide as much refinement in addressing differences in traffic as the proposed procedure. Because durability is considered more of a problem for HMA pavements on airfields than rutting, the fact that the proposed procedure often provides slightly softer PG grades may be desirable. This is especially true for GA airfields, where the very low traffic volume could contribute to durability problems unless a relatively soft binder is used. It should be emphasized that this comparison is only based on existing standards, and not actual airfield pavements—this more realistic and important comparison is made in the next section, and should help determine if the proposed system is in fact an improvement over the existing procedures.

Table 23. Three Model Airfields used In Comparison of PG Grade Selection Methods.

Airfield Size	Annual Departures	Design Aircraft Tire Pressure *lb/in²*	Typical Gross Aircraft Weight *lb*	Taxiway Config.	Design EHEs	Stacking
GA	5,000	50	50,000	Central	< 100,000	None
Medium	20,000	150	150,000	Parallel	800,000	Some
Large	100,000	210	600,000	Parallel	8 million	Frequent

Table 24. Binder Grading Information for Alabama, Colorado and Kentucky.

Traffic Level	Alabama	Colorado	Kentucky
Continuous high Temp. grade, LTPPBind, < 3 million ESALs	63.2	52.6	59.8
Continuous high Temp. grade, LTPPBind, 3 to < 10 million ESALs	69.7	60.4	66.9
Binder grade from agency, < 10 million ESALs	PG 67-22	PG 64-22	PG 70-22
Binder grade from agency, > 10 million ESALs	PG 76-22M	PG 64-22	PG 76-22M

Table 25. Recommended PG Grades for Airfield Runways Using Various Procedures.

Airport Size	State	Proposed	P-401, Tire Pressure	P-401, GAW	Notice 15
Small	**AL**	64-22	70-22	70-22	---
	CO	58-22	64-22	64-22	64-22
	KY	64-22	70-22	70-22	---
Medium	**AL**	76-22M	76-22M	76-22M	---
	CO	64-22	70-28M	70-28M	76-22M
	KY	70-22	76-22M	76-22M	---
Large	**AL**	76-22M	82-22M	76-22M	---
	CO	70-28M	76-28M	70-28M	76-22M
	KY	70-22M	82-22M	76-22M	---

Table 26. Recommended PG Grades for Airfield Taxiways Using Various Procedures.

Airport Size	State	Proposed	P-401, Tire Pressure	P-401, GAW	Notice 15
Small	AL	64-22	70-22	70-22	---
	CO	58-22	64-22	64-22	64-22
	KY	64-22	70-22	70-22	---
Medium	AL	76-22M	76-22M	76-22M	---
	CO	70-28M	70-28M	70-28M	76-22M
	KY	76-22M	76-22M	76-22M	---
Large	AL	82-22M	82-22M	76-22M	---
	CO	70-28M	76-28M	70-28M	76-22M
	KY	82-22M	82-22M	76-22M	---

Comparison of Proposed Grade Selection Procedure with Existing Airfield Pavements

The database of airfield HMA pavement construction projects is included in this report as Appendix A; this database was collected both to gather information on modified binder usage, and to help evaluate the proposed binder grade selection procedure. The database includes eight projects. In the section below, the binder grades needed for these projects are predicted using the proposed system, and compared to those actually used. Two of the projects in the database were not included in these comparisons because the design traffic level was not clear, making a good comparison impossible. In most cases, traffic level for the projects was given in equivalent annual departures of the design aircraft, which will normally be significantly less than the total annual departures. To estimate total annual departures, the equivalent annual departures were multiplied by two. Because specific traffic distributions were not given in the survey responses, some judgment was needed in selecting the value of GAW to use in determining EHEs. None of the projects discussed aircraft stacking on the runways; it was assumed in this analysis that for total annual departures less than 40,000, little or no stacking would occur. For annual departures between 40,000 and 80,000, occasional stacking was assumed to occur. Above 80,000 total annual departures, frequent aircraft stacking was assumed to occur. None of these projects differentiated between the central portion of the runway and the runway ends. Therefore, the more critical situation—the runway ends—was used in the analysis. In some cases, it was necessary to refer to the list of normally available binder grades in different states, given previously in Table 3 of this report.

Rantoul National Aviation Center, Runway 18/36, Rantoul, IL

This airfield handles very low traffic, equivalent to a GA facility. Therefore, the binder grade as given in LTPPBind v. 3 for the lowest traffic level (up to 3 million ESALs) would be recommended—PG 58-28. The actual binder grade used was an AC-10, estimated to be equivalent to a PG 58-22. Because the low temperature properties of AC-graded asphalts are quite variable, it is quite possible that the equivalent grade was PG 58-28. The pavements has performed very well; this should be considered good confirmation of the proposed system.

Memphis International Airport, Runway 9-27, Memphis, TN

This runway handles heavy air carrier and cargo aircraft. The highest gross aircraft weight for aircraft using this pavement is estimated to be 900,000 lb. The equivalent annual departures are about 20,000, and the total annual departures are estimated at 40,000. This results in an estimated 3.7 million EHEs. The continuous grades given by LTPPBind v. 3 are 62.7 and -14.9 °C. Assuming occasional aircraft stacking, the grade adjustment would be +11 °C, and a modified binder is suggested. Therefore, the recommended binder grade is a PG 76-16M, however, this binder grade is not normally available in Tennessee (see Table 3). The only acceptable binder grade normally available in this locations would be a PG 76-22M. The binder used was in fact a PG 76-22M. Significant rutting was observed on this runway, but forensic investigations attributed to a variety of causes, including low air voids, and a binder that did not meet all the requirements of a PG 76-22. Although there was rutting in this pavement, the forensic investigation did not suggest that it was because of an inappropriate binder grade selection. Therefore, this site should also be considered to provide confirmation of the proposed binder selection procedure.

Bowman Field, Runway 6-24, Louisville, KY

This is a GA airfield handling a very low level of traffic. Therefore, the binder grade as given in LTPPbind v. 3 for up to 3 million ESALs would be selected; for Louisville, KY, this is a PG 64-22 binder. The actual binder used was an AC-20, usually equivalent to a PG 64-22. Therefore, this site confirms the proposed procedure.

Lexington Blue Grass Airport, Runway 6-24, Lexington, KY

This runway handles a mix of commuter aircraft; the maximum GAW for aircraft using this pavement is estimated to be 170,000 lb. The equivalent annual departures is about 3,700, with an estimated total annual departures of 7,500. The resulting design traffic level is 260,000 EHEs. The continuous binder grade given by LTPPBind v. 3 for these conditions is 59.3-22.4. At 280,000 EHEs, no other grade adjustment is needed, resulting in a final grade of PG 64-22, assuming a -22.4 lower grade at 98 % reliability would be rounded to -22, and not to -28. The actual grade used was a PG 64-22, which has performed well. The proposed procedure provides exact agreement with the observed PG binder grade.

Houston Hobby Airport, Runway 12R-30L, Houston, TX

This pavement handles B-727, B-737 and MD-80 aircraft. The estimated maximum GAW is estimated to be 170,000. Assuming 60,000 total annual departures, this results in about 2.4 million EHEs. For Houston, LTPPbind v. 3 gives a required binder grade of 64.7 for up to 3 million ESALs. For occasional stacking, an upward adjustment of 11 °C would be needed, and use of a modified binder is recommended, resulting in a required grade of PG 76-10M. However, referring to Table 3, this is not a standard PG binder grade; in Texas, the closest grade meeting these requirements that is normally available is a PG 76-16M. The actual grade used was a PG 76-16M. Some groove closure was seen on the runway after one year, but this was attributed to contractor error and not to the binder grade selection, which appears to be appropriate. This site confirms the proposed procedure.

Niagara Falls International Airport, Runway 10L-28R, Niagara Falls, NY

This runway handles a mix of commuter aircraft. The maximum GAW is estimated to be 170,000, and the traffic level is 8,840 equivalent annual departures of this aircraft, equivalent to about 18,000 total annual departures. This results in a calculation of 650,000 EHEs. For Niagra Falls, LTPPBind v. 3 gives a required binder grade for this traffic level of 52.4-21.7. Assuming there is little or no aircraft stacking on this runway, the grade would be adjusted upward 7 °C, resulting in a final required grade of PG 64-22, which is the grade used for this project. There was some weathering and raveling observed on this pavement, but it was determined unrelated to the binder grade selection. This project therefore confirms the proposed binder grade selection process.

JFK International Airport, Runway 13R-31L, New York, NY

This project was not included in the database, but is included in the traffic mix data used to develop the grade selection procedure (see Table 9), and in the process of researching other aspects of this project, the binder grade used for this runway was discovered to be a PG 82-22. This provides an excellent opportunity to verify the procedure (note that only the traffic mix for this project was used in the analysis underlying the grade selection procedure, and not any information pertaining to the binder grade used). The total annual departures for this runway is 89,783. The maximum GAW for aircraft using this pavement and representing more than 10 % of the total departures is 400,000 lb, producing 5.5 million EHEs. LTPPBind v. 3 gives a required continuous binder grade of 61.8-16.3 for these conditions. Assuming frequent stacking of aircraft on this runway, this grade should be adjusted upward by 17 °C and a modified binder is required; the resulting binder grade would be 82-22M, which is the same as the binder grade used on the project, which has performed well. This provides very strong confirmation of the proposed grade selection procedure.

The results of these seven comparisons are summarized in Table 27. In all cases, the proposed procedure provided the exact binder grade that was selected for the project. This provides excellent confirmation of the proposed method for selecting PG binder grades for airfield pavements.

Some discussion is in order concerning the apparent discrepancy between existing procedures for binder PG grade selection for airfield pavements and the proposed procedure and the grades actually used in practice, as illustrated in the projects listed in Table 27. The existing procedures, as described in P-401/403 and Notice 15, appear to recommend significantly stiffer binders than required for pavements at GA airfields and commercial airfields handling very low to low traffic. This could contribute significantly to durability problems at these facilities, since softer binders will be more ductile and might also exhibit greater healing potential. At the same time, the existing procedures also seem to recommend binder PG grades that are too soft for pavements subject to very heavy traffic, which could lead to pavements prone to excessive rutting. Overall, it appears that the proposed procedure should provide proper binder grades for the complete range of airfield pavements, providing adequate rut resistance without specifying overly stiff binders.

Table 27. Summary of Comparison of Predicted and Actual Binder PG Grades for Seven Airfield Paving Projects.

Facility	Runway	Predicted Grade	Actual Grade	Comments
Rantoul National Aviation Center, Rantoul, IL	18-36	PG 58-28	PG 58-28	Exact agreement
Memphis International Airport, Memphis, TN	9-27	PG 76-22M	PG 76-22M	Exact agreement
Bowman Field, Louisville KY	6-24	PG 64-22	PG 64-22	Exact agreement
Lexington Bluegrass Airport, Lexington, KY	6-24	PG 64-22	PG 64-22	Exact agreement
Houston Hobby Airport, Houston, TX	12R-30L	PG 76-16M	PG 76-16M	Exact agreement
Niagra Falls International Airport, Niagra Falls, NY	10L-28R	PG 64-22	PG 64-22	Exact agreement
JFK International Airport, New York, NY	13R-31L	PG 82-22M	PG 82-22M	Exact agreement

Final Grade Selection from Available Binder Grades

A final consideration in the grade selection process is comparing the binder grade recommended by the proposed procedure to the binders likely to be available in a given region. For example, as discussed above, for two projects listed in Table 27, the grade selected using the proposed method was not one normally available in the given state, but appropriate binder grades were available in both cases, with somewhat better low temperature performance than required. In the final specification, Table 3 (showing commonly available PG grades in each state) will be included. Once determining the required PG grade, the available PG grades will be reviewed and the final selection made using the following rules;

- The high temperature grade must be equal to or greater than the required high temperature grade; and
- The low temperature grade must be equal to or lower than the required high temperature grade.

The final grade would be that of the commonly available grades in the given state which meets these two requirements and most closely matches the required grade. The specification should include a note that the PG grades available in different regions is likely to change from time to time, and the list of available grades should be revised every two to three years.

CHAPTER 3
DISCUSSION OF RESULTS

The binder PG grade selection described in Chapter 2 of this report is relatively simple, and appears to be very effective in selecting appropriate binder grades for a wide range of airfield pavements. However, in view of the results of the comparisons with current practice, and after review of the pertinent FAA specifications, it is believed that one minor simplification of the proposed procedure is needed prior to implementation. Specifically, the chart for determining EHEs for runways and taxiways where the taxiway is in a central configuration (Figure 8) should be removed. It is likely that the only airfields for which this configuration is used will be GA and other small airfields, for which the design traffic level will be much less than the 3 million EHEs needed before a high-temperature grade adjustment is needed. Using only a single chart—Figure 7 for runways and taxiways in a parallel configuration—significantly simplifies the specification and reduces the chances for error. Using this figure for runways and taxiways where the taxiway is in a central configuration will have no significant effect on the final binder grade selection, because the traffic for such airfields will not be high enough to require any grade adjustment.

KEY TECHNICAL FEATURES OF PG BINDER GRADE SELECTION PROCEDURE

The proposed procedure for selecting PG binder grades for airfield pavements involves the following key features:

- The procedure uses the program LTPPBind version 3.1 to determine the base binder grade for a given location and traffic level (98 % reliability level). Research performed as part of NCHRP Projects 9-25, 9-31 and 9-33 have confirmed that this program provides accurate, damaged-based selections of PG grades for highway pavements.
- In order to use LTPPBind for high temperature binder grade selection, equivalent highway ESALs (EHEs) are calculated, using a simple semi-empirical method requiring as input only total annual departures and the GAW for the largest aircraft making significant use of the runway/taxiway. The procedure accounts for all major factors influencing high temperature grade selection, including differences in mixture composition and construction between highway and

airfield pavements; increased tire pressure for many aircraft compared to that for commercial trucks; the much greater wander of aircraft over taxiways and especially runways compared to the wander that occurs on highways; and differences among aircraft in the landing gear configuration.

- Adjustments to the high temperature PG grade for airfield type (GA, small commercial, etc.), aircraft speed and aircraft stacking have been based on a variety of empirical models. The adjustments are implemented in the form of a simple table containing appropriate adjustments to the high temperature PG grade.
- Low-temperature grades are as given by LTPPBind v. 3.1. There appears to be little reason for changing this aspect of the PG grade selection process for airfields. Furthermore, if different low temperature grades were selected for airfield pavements, it would in many cases probably be difficult to find these grades, as the selection of low temperature grades in a given region tends to be limited.
- The procedure has been compared to existing FAA procedures for binder PG grade selection, and with binder grades used for seven airfield pavement projects. The binder grades determined with the proposed procedure agreed very closely with those used in the actual paving projects, but there were significant differences between the proposed procedures and those currently in use by the FAA. It appears that the propose procedure provides significantly more accurate selections of binder PG grades for a wide range of airfield pavements compared to existing FAA procedures.

DESCRIPTION OF THE PROPOSED PROCEDURE

The proposed procedure is very simple. The user first identifies the total annual departures for the runway and/or taxiway in question. The maximum GAW for aircraft representing more than 10 % of the total annual departures is then determined. The design traffic level, in terms of EHEs, is then found using Figure 7. Once the design traffic level for the pavement is determined, LTPPBind v. 3 is used to determine the base PG grade at a 98 % reliability level for the given project. The user then adjusts the high-temperature PG grade according to the airfield type and aircraft speed and stacking, using Table 22. In the final step in the procedure he/she compares the resulting binder grade with those commonly available in the state in which the project is being constructed, and selects the most appropriate PG grade.

Appendix B is a concise statement of the proposed final procedure for binder PG grade selection for airfield pavements. It is formatted as a revision of section 2.3 of Item P-401 “Plant Mix Bituminous Pavements (Surface Courses).” This is identical to section 2.3 of Item P-403 “Plant Mix Bituminous Pavements (Base and Leveling Courses).” As noted above, the final procedure has been simplified somewhat from that presented in Chapter 2 of this Report:

IMPLEMENTATION OF THE PROPOSED PROCEDURE

There are at least four different ways in which the proposed procedure can be implemented:

1. As described above—that is, EHEs are determined using Figure 7, the PG grade is determined using LTPPBind version 3.1, and high-temperature grade adjustments are made to account for aircraft speed.
2. Using separately developed software. The LTPPBind software could be modified to produce a package specifically designed for selection of PG binder grades for airfield pavements.
3. A booklet could be developed listing all airfields and their base PG grades. Charts would then be used to adjust these grades for traffic level and aircraft speed, using the concept of EHEs.
4. The entire procedure could be built into the next generation of pavement design software for airfields.

Of these three alternatives, the first is the simplest and least costly, although there is a certain potential for user error in the binder grade selection process. The specification would have to be updated on a regular basis to remain current with the latest binder selection procedures and available binder slates. Alternative two (stand-alone software) would be the most expensive, but would also be very reliable and flexible. However, the software would have to be updated on a regular basis. There would probably also need to be some means for providing training and support for the software. The third alternative (booklet) would involve some additional cost, but significantly less than required for new software development. It would be relatively simple to use, but like the other two alternatives, would require periodic updating to ensure accuracy. The fourth alternative (inclusion in pavement design software) has many advantages—it would be a simple and reliable means of implementing the procedure, and the additional cost (compared to development of the software without the PG grade selection feature) would be relatively small. The main drawback to this alternative is that implementation would have to wait until development of the next version of pavement design software, although alternative 1 could be used in the interim.

An important consideration during implementation of this procedure is the precise nature of the mix design procedure being used for the design of HMA for airfield pavements at the time of implementation. Changes in design compaction, design air void content, typical field air void content, target VMA, and average mineral filler content will potentially have an effect on PG binder grade selection. This report includes all calculations necessary to make adjustments in the selection process if needed. At the time of implementation (and periodically thereafter) HMA design procedures and typical construction methods should be reviewed and the PG binder grade selection procedure revised as needed.

CHAPTER 4
CONCLUSIONS AND RECOMMENDATIONS

This Report documents all significant work performed during AAPTP Project 04-02. It includes a detailed description of various analyses and tests performed during the project, and discussion of the rational used in developing the proposed procedure for selecting binder PG grades for airfield pavements. Appendix B of this report is a clear and concise description of the proposed procedure, written as a revision of section 2.3 of Item P-401/P-403 "Plant Mix Bituminous Pavements."

The procedure itself is quite simple and well suited for use by practicing engineers. It involves the use of a single chart and table, along with the computer program LTPPBind version 3.1, which is available free from an FWHA website. Evaluation of the procedure performed as part of this project indicates that it provides appropriate binder PG grades for a wide range of airfield paving projects, and is more effective than existing procedures for selecting PG grades for such applications.

It is recommended that the proposed procedure should be circulated for comment among engineers involved in the design and construction of HMA airfield pavements for a wide range of conditions and climates. It is also essential that this report be reviewed by researchers involved in AAPTP Project 04-03 *Implementation of Superpave Mix Design for Airfield Pavements*. It cannot be emphasized enough that the proposed binder grade selection procedure was developed using certain assumptions concerning typical HMA mix design and construction practice; if Project 04-03 proposes significant changes to these assumptions, the proposed procedure for binder grade selection must be reviewed and modified as needed. This report includes all technical information needed to perform such a review and modification. After review and revision by the airfield pavement engineering community and the AAPTP Project 04-03 researchers, the procedure will be ready for implementation as part of Items P-401 and P-403 and related standards.

An alternate but potentially effective means of implementing the procedure given in this report would be to modify the program LTPPBind to provide the appropriate PG grades for airfield pavements directly. This would require only a few simple modifications, primarily inclusion of Equation 25 in the program, along with the information contained in Table 22. The program could also be modified to include the list of commonly used binders for each state. This approach, though involving an additional modest investment, would further ease implementation and make errors in applying the procedure less likely. Another way of implementing the proposed procedure would be to develop a booklet containing base PG grades for all airfields in the U. S. and U.S. dependencies, and include in the booklet the various charts and tables needed for PG binder selection, along with needed instruction. This method of implementation would be less costly than development of new software, but would represent a somewhat more tedious procedure for the end user. Another very effective way of implementing the proposed procedure would be to include it in the next generation of airfield pavement design software. Until the next version of the software is developed with the PG grade selection feature, the simplified approach could be used, which would also help in evaluating and refining the procedure.

CHAPTER 5
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APPENDIX A: DATABASE OF AIRFIELD HMA PAVING PROJECTS

Rantoul National Aviation Center, Rantoul, Il	
Facility	Runway 18/36
Construction Date	Summer 1999
Mixture Type	P-401
Binder Grade	Section 1: AC-10 (Typically PG58-22); Section 2 PMA PG64-28
Modifier	Elastomer (SBS-10)
Grade of Modification	Unknown
Grade of Neat Asphalt	75 – 110 pen
Governing Specifications	State of Illinois
%AC	Unknown
%PMA Added	Unknown
Polymer and AC suppliers:	Emulsicoat, Urbana, IL
Engineer of Record/Designer	Stan Herrin Crawford, Murphy & Tilly, Inc. 2750 W. Washington Springfield, IL. 217-787-8050
Design Standard Used	FAA
Aircraft Fleet Mix	12,500 lb single wheeled aircraft
HMA and Pavement Structure Thickness	varies 2" - 5"
Factors that influenced the use of PMA and choice of grad and/or polymer type	Comparison section of an AC with Polymer to a section without Polymer. The sections are side-by-side
Contractor	Champaign Asphalt
Describe Binder-Aggregate Mixing Process	N/A
Pavement Compaction	Minimum 92% of Max Density; typically about 95%
Experience with the Pavement Performance	No, an inspection of the condition in June 2006 revealed that the section without polymer is performing similar to the section with polymer
Possible Causes of Distress	N/A

Memphis International Airport	
Facility	Runway 9-27
Construction Date	Summer 2004
Mixture Type	P-401
Binder Grade	PG 76-22
Modifier	Elastomer (SBS)
Grade of Modification	High
Grade of Neat Asphalt	Unknown
Governing Specifications	FAA P-401, as contained in Advisory Circular 150/5370-10A
%AC	5.5
%PMA Added	Unknown
Polymer/AC suppliers:	Marathon Ashland Petroleum
Engineer of Record/Designer	Engineer of Record/Designer: = Engineer of Record: HNTB--Todd Knuckey. Pavement Design Consultant: Roy D. McQueen & Associates--Roy D. McQueen
Design Standard Used	FAA Advisory Circular 150/5300-13
Aircraft Fleet Mix	Heavy air carrier and cargo aircraft, including B-727, B-757, B-767, B-747, B-777, A-300, A-330, and MD-11. The critical (most damaging aircraft was the MD-11 at 607,000 lb Gross weight and about 20,000 equivalent annual departures
HMA and Pavement Structure Thickness	3- inch Bituminous Surface Course
Factors that influenced the use of PMA and choice of grad and/or polymer type	Designer Recommendation
Contractor	APAC--Tennessee
Describe Binder-Aggregate Mixing Process	No plant problems identified during production. Product met all specified criteria. Conventional Double Drum Astec (10') plant w/horizontal storage tanks, volumetric A/C metering pump, and computer controls
Pavement Compaction	Standard steel drum rollers. Roller pattern unknown at this late date. Compaction Standard: FAA mat density 96.3% and joint density 93.3%, as a percentage of 75-blow Marshall density, for percent within limits (PWL) computations. All tests indicated satisfactory. To meet the FAA's 90 PWL requirement with these lower limits, the averages need to be about 98% and 96% for mat and joint densities, respectively, based on "normal" standard deviations. No failing tests.
Experience with the Pavement Performance	Experience with the Pavement Performance: initially unsatisfactory. Rutting was identified almost immediately at taxiway crossings where FedEx aircraft crossed regularly during construction, but after cool down and initial cure. When grooving started, new pavement also rutted very dramatically under the weight of the

Experience with the Pavement Performance (Memphis Airport continued)	grooving machine wheels. Whenever the sun was shining, the asphalt softened and had to be cooled with water. Eventually had to restrict grooving to off--daylight hours to reduce problem. Deformation on the taxiway crossing was a result of the heavy MD-11 aircraft being channelized on the HMA that was paved the previous day. In other words, there was only a 24-hour "cure time. The deformation from the grooving machine happened during daytime grooving in late July. The steel wheels on the grooving equipment exert 500 psi pressures. For this reason (and operational), grooving is normally done at night, but due to FEDX nightly operations, this was not possible at Memphis.
Possible Causes of Distress	Extensive testing and evaluation revealed no identifiable cause. Speculation by engineers centered on excessive moisture in the aggregate at the time of asphalt production. Runway surface is now two years old and is being monitored for continued rutting. Forensic analysis revealed additional possible causes, including: a. low in-place air voids b. asphalt cement that didn't fully comply with PG 76-22 c. possible tender mix tendencies with the gradations Rate of rut increase dropped off dramatically after the first year. Next inspection scheduled for July 2006.

Tucson International Airport	
Facility	Runway 11L/29R overlay
Construction Date	Sept. 2006
Mixture Type	P-401
Binder Grade	PG 76-22
Modifier	Unknown
Grade of Modification	Unknown
Grade of Neat Asphalt	Unknown
Governing Specifications	AASHTO MP 320
%AC	Unknown
%PMA Added	Unknown
Polymer and AC suppliers:	Unknown
Engineer of Record/Designer	Kimley-Horn and Assoc.,Att:Leon Vicars P.E. 520-615-9191
Design Standard Used	FAA P-401
Aircraft Fleet Mix	737, 757, MD-80, RJ, 727, A320
HMA and Pavement Structure Thickness	5 inches
Factors that influenced the use of PMA and choice of grad and/or polymer type	Pg76-22 binder was used because of the extreme heat and rutting of the existing pavement
Contractor	Ashton construction
Describe Binder-Aggregate Mixing Process	Unknown
Pavement Compaction	N/A at this time
Experience with the Pavement Performance	Existing asphalt was P401. Rutting became evident after 12 years
Possible Causes of Distress	High temperatures

Bowman Field, Louisville, KY	
Facility	Reconstruct RW 6-24
Construction Date	2001
Mixture Type	P-401, 50-blow Marshall
Binder Grade	AC-20 (non modified)
Modifier	Unknown
Grade of Modification	Unknown
Grade of Neat Asphalt	Unknown
Governing Specifications	Unknown
%AC	Unknown
%PMA Added	Unknown
Polymer and AC suppliers:	Marathon Oil (AC-20)
Engineer of Record/Designer	Tetratech, Inc (formerly PDR)
Design Standard Used	Advisory Circular 150/5320-6D
Aircraft Fleet Mix	General Aviation and Business Jets
HMA and Pavement Structure Thickness	3 to 4-in HMA on 6-in CAB
Factors that influenced the use of PMA and choice of grad and/or polymer type	Normal grade for geographic area
Contractor	Gohman Brothers, Inc
Describe Binder-Aggregate Mixing Process	Drum Mix
Pavement Compaction	Unknown - no reported compaction problems
Experience with the Pavement Performance	No problems after 5-years, PCI~90. Some problems with low air voids during construction. Also, fractured aggregate reported, believed to be as a result of lift thicknesses that were too thin. Defective areas were removed and replaced.
Possible Causes of Distress	No major distress

Lexington Blue Grass Airport, Lexington, KY	
Facility	Overlay RW 6-24
Construction Date	1994
Mixture Type	P-401, 75-blow Marshall
Binder Grade	AC-20
Modifier	Unknown
Grade of Modification	Unknown
Grade of Neat Asphalt	Unknown
Governing Specifications	Unknown
%AC	optimum =5.6%
%PMA Added	none
Polymer and AC suppliers:	Shell Oil for AC-20
Engineer of Record/Designer	Tetratech, Inc., formerly PDR, Inc
Design Standard Used	Advisory Circular 150/5320-6D
Aircraft Fleet Mix	MD-80, B737, B727, BAE, F28, Commuters. Pavement design based on 3,700 equivalent annual departures of B727 at 190,500 lb.
HMA and Pavement Structure Thickness	3-in HMA overlay on variable thickness AC/9-in PCC
Factors that influenced the use of PMA and choice of grad and/or polymer type	Normal grade of AC for geographic area.
Contractor	Central Kentucky Asphalt - Allen Company, JV
Describe Binder-Aggregate Mixing Process	Four drum mix plants. Project involved placement of 24,000 tons of HMA during 42-hour weekend shutdown period.
Pavement Compaction	4 paving trains matched to each plant. Vibratory steel wheel and pneumatic rollers used. Compaction requirements of specification were met.
Experience with the Pavement Performance	Overall pavement performance is good. Primary distress was weathering and raveling of surface. PCI's in the 60 to 70 range.
Possible Causes of Distress	Weathering primarily believed to be the result of shot blasting used for rubber removal - not believed to be associated with mix or grade of AC. Milling and replacement of surface scheduled for 2006 to coincide with runway extension.

Houston Hobby Airport, TX	
Facility	Overlay Runway 12R-30L
Construction Date	1994
Mixture Type	P-401 (75-blow Marshall)
Binder Grade	Novaphalt Blend, PG 76-16; performance similar to PG 82-16 SBS modified
Modifier	Plastomer (Novaphalt)
Grade of Modification	High
Grade of Neat Asphalt	ask AAT
Governing Specifications	AAT
%AC	AAT
%PMA Added	AAT
Polymer and AC suppliers:	AAT for Novaphalt
Engineer of Record/Designer	Brown & Root, Inc
Design Standard Used	Advisory Circular 150/5320-6D
Aircraft Fleet Mix	B727, B-737, MD-80. Pavement design based on 29,000 equivalent annual departures of B727 at 190,500 lb.
HMA and Pavement Structure Thickness	Mill 2-in and 3-in to 8-in overlay on 4"AC/9"PCC/6"PCC
Factors that influenced the use of PMA and choice of grad and/or polymer type	Desire to increase hot weather stiffness and good performance with Novaphalt on prior projects.
Contractor	Contact AAT
Describe Binder-Aggregate Mixing Process	Contact AAT
Pavement Compaction	Unknown. No reported compaction problems.
Experience with the Pavement Performance	A 2,000-ft section of the runway experienced plastic deformation (groove closure) after about 1-year. This section was subsequently removed in replaced. After removal and replacement PCIs of the runway were in the 80s in 2002.
Possible Causes of Distress	Analysis of the area that experienced plastic deformation indicated tender mix tendencies due to poor contractor quality control. Problem appeared to be unrelated to choice of asphalt binder.

Buffalo-Niagara International Airport	
Facility	Overlay Runway 5-23
Construction Date	1975
Mixture Type	P-401 (75-blow Marshall)
Binder Grade	Probably AC-10
Modifier	Unknown
Grade of Modification	Unknown
Grade of Neat Asphalt	Unknown
Governing Specifications	Unknown
%AC	Unknown
%PMA Added	Unknown
Polymer and AC suppliers:	Unknown
Engineer of Record/Designer	HNTB
Design Standard Used	Advisory Circular 150/5320-6B
Aircraft Fleet Mix	Unknown. Probably B 727 aircraft.
HMA and Pavement Structure Thickness	8 to 12-in HMA overlay on existing 3-in HMA/9-in PCC
Factors that influenced the use of PMA and choice of grad and/or polymer type	AC grade probably selected based on normal usage in area in 1975.
Contractor	Unknown
Describe Binder-Aggregate Mixing Process	Since construction was in 1975 - Batch Plant.
Pavement Compaction	Vibratory steel wheel and pneumatic rollers. No reported compaction problems.
Experience with the Pavement Performance	The overlay performed extremely well over 30-years. In 2004, the pavement was still rated as structurally adequate. Functional condition was also good considering age, with low severity weathering and longitudinal joint cracking. PCIs for the runway were in the 60's after nearly 30-years. Pavement is scheduled for 3-in mill and replacement of surface in 2006.
Possible Causes of Distress	No major problems. In 1986, 2 longitudinal joints required repair due to lack of maintenance from reflection cracking. Since the repair and with timely maintenance, performance has been very good. This runway exemplifies the fact that properly designed and constructed HMA overlays can last 20+ years with effective maintenance.

Niagara Falls Int'l Airport	
Facility	Rehabilitation of Runway 10L-28R
Construction Date	2002
Mixture Type	P-401 (75-blow Marshall, with VMA's lowed 2% from Standard)
Binder Grade	PG 64-22
Modifier	Unknown
Grade of Modification	Unknown
Grade of Neat Asphalt	Unknown
Governing Specifications	Unknown
%AC	Unknown
%PMA Added	Unknown
Polymer and AC suppliers:	Marathon Ashland Petroleum
Engineer of Record/Designer	URS, Inc
Design Standard Used	Advisory Circular 150/5320-6D
Aircraft Fleet Mix	Commuter, B767, C-130, KC-135. Pavement design based on 8,840 equivalent annual departures of KC-135 at 322,000 lb.
HMA and Pavement Structure Thickness	5-in HMA on 9-in rubblized PCC on 18-in CAB
Factors that influenced the use of PMA and choice of grad and/or polymer type	PG grade based on climatic conditions and normal usage in area. PMA not used.
Contractor	Producer: Lafarge North America
Describe Binder-Aggregate Mixing Process	Gencor counterflow Drum Mix, rated at 400 tph
Pavement Compaction	IR DD 130, Bomag 202, IR pneumatic. Cedar Rapids CR 551 Paver.
Experience with the Pavement Performance	Severe weathering and raveling began approximately 2-years after construction.
Possible Causes of Distress	Primary cause was believed to be stripping due to low VMA, high fines, low %AC, low volume of AC and low film thickness. Problem unrelated to binder, but due to faulty spec (lowered VMA) and poor quality control.

APPENDIX B: PROCEDURE FOR SELCTING PG BINDER GRADES FOR AIRFIELD PAVEMENTS

401-2.3 BITUMINOUS MATERIAL. Bituminous material shall conform to the following requirements: **[ ]**.

* *

Asphalt cement binder shall conform to AASHTO M320 Performance Grade (PG) [_____]. Test data indicating grade certification shall be provided by the supplier at the time of delivery of each load to the mix plant. Copies of these certifications shall be submitted to the Engineer. The Engineer shall specify the grade of bituminous material, based on geographical location, climatic conditions, and anticipated loading conditions. Asphalt Institute Superpave Series No. 1 (SP-1) provides guidance on the selection of performance graded binders for highway paving applications. The selection of a PG grade for a specific airfield pavement application shall be done following the procedure described below. The Engineer should be aware that PG asphalt binders may contain modifiers that require elevated mixing and compaction temperatures that exceed the temperatures specified in Item P-401.

Procedure for Selecting Asphalt Binder PG Grade for Airfield Pavements:

For the given pavement, determine the total annual departures and the maximum gross aircraft weight (GAW) among aircraft representing more than 10 % of the total departures on the runway and/or taxiway. In cases where the aircraft types are evenly distributed so that few if any represent 10 % of the total departures, the maximum GAW among all aircraft should be used. With this information, use Figure 1 to determine the equivalent highway ESALs (EHEs) for the pavement. Use the software program LTPPBind, Version 3.1, to find the recommended continuous PG binder grade for the given location and traffic level, using EHEs in place of ESALs and a 98 % reliability level. The program can be downloaded from the website http://ltpp-products.com/OtherProducts.asp. The continuous high-temperature binder grade given by LTPPBind shall then be adjusted according to the traffic level and anticipated conditions following the guidelines given in Table A. The final binder grade should be selected from commonly used binder grades in the state in which the project is located, as listed in Table B. The high temperature limit for the final PG grade selected from Table B shall be as low as possible, but equal to or greater than the continuous high temperature grade required for the project. The final low temperature limit for the final PG grade selected from Table B shall be as high as possible, but equal to or less than the continuous high temperature grade required for the project.

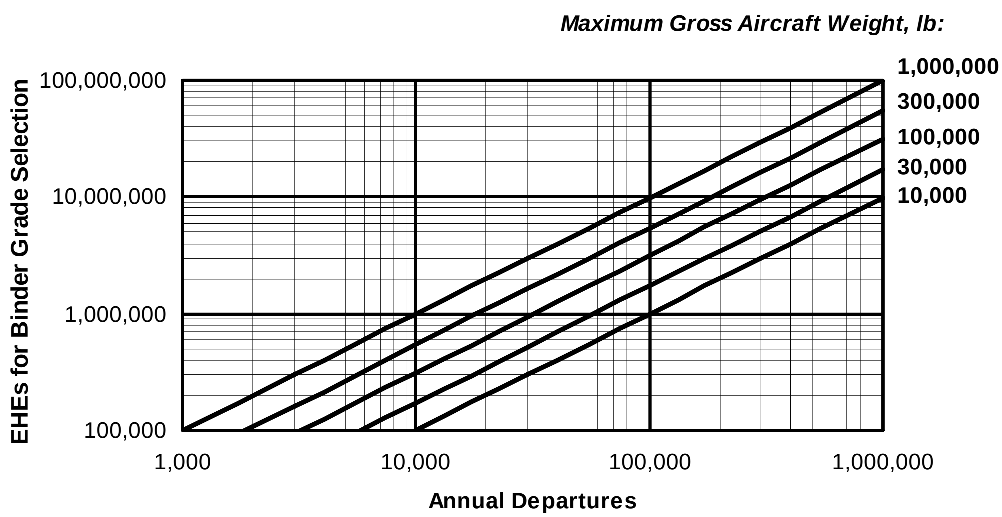

Figure 1. EHEs for High-Temperature Binder Grade Selection as a Function of Annual Departures of the Maximum Gross Aircraft Weight.

Table A. High-Temperature PG Grade Adjustments for Airfield Type and Aircraft Speed and Stacking, Including Provisions for Polymer Modified Asphalt Binders.

Aircraft Stacking	**Typical Speed** *Mph*		**Design Traffic** *EHEs*	**Grade Adjustment** *°C*	
	Runway Centers	**Taxiways/ Runway Ends**		**Non-Modified Binders**	**Polymer Modified Binders***
None	≥ 45	15 to < 45	< 300,000	0	
Little or none	≥ 45	15 to < 45	300,000 to < 3 million	+7	*Not Required* +4
			3 million to < 10 million	+7	*Suggested* +4
			≥ 10 million	---	*Required* +4
Occasional	---	5 to < 15	< 10 million	+14	*Suggested* +11
			≥ 10 million	---	*Required* +11
Frequent	---	< 5	Any	---	*Required* +17

**Polymer modified binders must have a minimum elastic recovery value of 60 % at 25 °C, following procedures described in AASHTO 301.*

NOTE: Various highway agencies are currently evaluating the multiple stress creep and recovery (MSCR) test for use in the PG binder grading system. This test will better address the unique characteristics of modified binder than the current DSR tests at high temperature. Once the MSCR is implemented in the PG binder grading system, the elastic recovery test will no longer be needed in specifying polymer modified binders for airfield use. In addition, the grade adjustments given in the table above will need to be modified to reflect the changes in the PG binder grading system.

Table B. Commonly Used Binder PG Grades by State (Part 1).

State	Common Binder PG Grades																					
	46	52		58			64				67	70					76				82		
	-28	-34	-28	-34	-28	-22	-34	-28	-22	-16	-22	-34	-28	-22	-16	-10	-16	-28	-22	-16	-28	-22	-16
Alabama	--	--	--	--	--	Y	--	--	Y	--	Y	--	--	--	--	--	--	--	Y	--	--	--	--
Alaska	--	--	--	--	Y	--	--	Y	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Arizona	--	--	--	--	--	Y	--	--	Y	Y	--	--	--	--	--	Y	--	--	Y	Y	--	--	--
Arkansas	--	--	--	--	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
Colorado	--	--	--	Y	Y	Y	--	Y	Y	--	--	--	Y	--	--	--	--	Y	--	--	--	--	--
Connecticut	--	--	--	--	Y	--	--	Y	Y	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Delaware	--	--	--	--	Y		--	--	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
Florida	--	--	--	--	--	--	--	--	Y	--	Y	--	--	--	--	--	--	--	Y	--	--	--	--
Georgia	--	--	--	--	--	Y	--	--	Y	--	Y	--	--	--	--	--	--	--	Y	--	--	--	--
Hawaii	--	--	--	--	--	--	--	--	--	Y	--	--	--	--	--	--	--	--	--	--	--	--	--
Idaho	--	--	--	Y	Y	--	Y	Y	Y	--	--	--	Y	--	--	--	--	Y	--	--	--	--	--
Illinois	Y	--	Y	--	Y	Y	--	Y	Y	--	--	--	Y	Y	--	--	--	Y	Y	--	--	--	--
Indiana	--	--	--	--	Y	--	--	Y	Y	--	--	--	Y	Y	--	--	--	--	Y	--	--	--	--
Iowa	--	Y	Y	--	Y	Y	--	Y	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
Kansas	--	--	--	--	--	Y	--	Y	Y	--	--	Y	Y	Y	--	--	--	Y	Y	--	Y	Y	--
Kentucky	--	--	--	--	--	Y	--	--	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
Louisiana	--	--	--	--	--	Y	--	--	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
Maine	--	--	--	Y	--	--	--	Y	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Maryland	--	--	--	--	--	--	--	Y	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
Massachusetts	--	--	--	Y	--	--	--	Y	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Michigan	--	Y	Y	Y	Y	Y	Y	Y	Y	--	--	--	Y	Y	--	--	--	Y	Y	--	--	--	--
Minnesota	--	--	--	Y	Y	--	Y	Y	--	--	--	Y	Y	--	--	--	--	Y	--	--	--	--	--
Mississippi	--	--	--	--	Y	--	--	--	--	--	Y	--	--	--	--	--	--	--	Y	--	--	Y	--
Missouri	--	--	--	--	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
Montana	--	--	Y	--	--	--	Y	Y	Y	--	--	--	Y	--	--	--	--	--	--	--	--	--	--
Nebraska	--	--	--	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--	--

Table B. Commonly Used Binder PG Grades by State (Part 2).

State	Common Binder PG Grades																					
	46	52		58			64				67	70					76				82		
	-28	-34	-28	-34	-28	-22	-34	-28	-22	-16	-22	-34	-28	-22	-16	-10	-16	-28	-22	-16	-28	-22	-16
Nevada	--	--	--	--	--	--	Y	Y	Y	--	--	--	--	--	--	--	--	--	Y	--	--	--	--
New Hampshire	--	--	--	--	--	--	--	Y	Y	--	--	--	--	Y	--	--	--	Y	--	--	--	--	--
New Jersey	--	--	--	--	--	--	--	--	Y	--	--	--	--	--	--	--	--	--	Y	--	--	--	--
New Mexico	--	--	--	--	Y	--	--	Y	Y	--	--	--	Y	--	--	--	--	--	Y	--	--	Y	--
New York	--	--	--	Y	Y	--	--	Y	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
North Carolina	--	--	--	--	--	--	--	--	Y	--	--	--	Y	Y	--	--	--	--	Y	--	--	--	--
North Dakota	--	--	--	Y	Y	--	--	Y	--	--	--	--	Y	--	--	--	--	--	--	--	--	--	--
Ohio	--	--	--	--	Y	--	--	Y	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
Oklahoma	--	--	--	--	--	--	--	--	Y	--	--	--	Y	--	--	--	--	Y	--	--	--	--	--
Oregon	--	--	--	--	--	--	--	Y	Y	--	--	--	Y	Y	--	--	--	--	Y	--	--	--	--
Pennsylvania	--	--	--	--	Y	--	--	--	Y	--	--	--	--	--	--	--	--	--	Y	--	--	--	--
Puerto Rico	--	--	--	--	--	--	--	--	Y	--	--	--	--	Y	Y	--	--	--	--	--	--	--	--
Rhode Island	--	--	--	--	--	--	--	Y	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
South Carolina	--	--	--	--	--	--	--	--	Y	--	--	--	--	--	--	--	--	--	Y	--	--	--	--
South Dakota	--	--	--	Y	--	--	Y	Y	Y	--	--	Y	Y	--	--	--	--	--	--	--	--	--	--
Tennessee	--	--	--	--	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
Texas	--	--	--	Y	Y	Y	Y	Y	Y	Y	--	Y	Y	Y	Y	--	--	Y	Y	Y	Y	Y	Y
Utah	--	--	--	Y	--	--	Y	Y	--	--	--	Y	Y	Y	--	--	--	Y	Y	--	--	--	--
Vermont	--	--	--	Y	Y	--	Y	Y	--	--	--	--	Y	--	--	--	--	--	--	--	--	--	--
Virginia	--	--	--	--	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
Washington	--	--	--	Y	Y	Y	Y	Y	Y	--	--	Y	Y	Y	--	--	--	Y	Y	--	--	--	--
West Virginia	--	--	--	--	Y	--	--	Y	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--
Wisconsin	--	--	--	Y	Y	--	Y	Y	Y	--	--	--	Y	--	--	--	--	Y	--	--	--	--	--
Wyoming	--	--	--	Y	Y	--	Y	Y	Y	--	--	--	--	Y	--	--	--	--	Y	--	--	--	--

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The Contractor shall furnish vendor's certified test reports for each lot of bituminous material shipped to the project. The vendor's certified test report for the bituminous material can be used for acceptance or tested independently by the Engineer.