VERIFICATION OF THE PERFORMANCE OF THERMOPLASTIC PLANT MIX ADDITIVE USED TO PRODUCE BRIDGE DECK WATERPROOFING MATERIALS

Dr. Geoffrey M. Rowe*
Abatech Inc.
PO Box 356
Blooming Glen, PA 18911
+1 (267) 261-8481
growe@abatech.com

Mr. Phillip Blankenship
The Asphalt Institute
2696 Research Park Drive
Lexington, KY 40511
+1 (859) 288-4986
pblankenship@AsphaltInstitute.org

Doug Zuberer
Director - Chase Specialty Coatings
Chase Construction Products
295 University Ave
Westwood, MA 02090
Tel: +1(508)341-4961
dzuberer@chasecorp.com

Mr. Mark J. Sharrock
Abatech Inc.
22 Andover Road North
Winchester
SO 26NW
United Kingdom
Mark.Sharrock@Btconnect.Com
+44-1962-880678

***Corresponding Author**

July 28, 2010
Revised November 12, 2010

Word count: 7,341 (5,341+2,000 figures and tables)

ABSTRACT
Plant mixed modifier (PMM) has been used for the past 25-years to produce waterproofing asphalt materials for bridge deck applications as a polymerized "Dry Mix" modifier. These offer significant advantages over conventional polymer modified binders (PMBs) since much high polymer loading can be used in the final material without the risk of storage separation and/or pumping and handling issues associated with these high polymer loads. However, with the advent of Superpave it has become the norm for many specifying agencies to include the Superpave binder specification tests as "performance related" controls for the specification. Unfortunately, with plant mix additives it is not possible to obtain a sample of the binder in the conventional manner that occurs with the use of PG binders thus making this route for quality assessment not feasible. Nevertheless, it is possible to evaluate mixture performance using a suite of tests that relate to low-temperature cracking, fatigue performance and permanent deformation – thus capturing the same end performance requirements considered in the binder but by testing the mixture. Conceptually, this is better since mix tests should more closely relate to field performance than binder tests. The use of these tests to develop rational specification parameters is discussed for a bridge-deck thermoplastic PMM water proofing material which is used by various state DOTs and other agencies. Recommendations are made that could form the basis for a performance related specification for these bridge deck waterproofing materials utilized as an alternative to torch or spray applied systems, epoxy overlays or latex modified concrete overlays.

INTRODUCTION

Bridge deck surfacings have made use of the highest quality asphalt materials to meet the specialized requirements that are needed. Traffic on bridge decks is constrained between physical limits to a much greater extent than typical highways resulting in a much greater degree of channelization of traffic flow. This in turn results in a much greater degree of loading in wheel tracks that in turn can result in deformation if a material is not designed with extreme care. In addition, these materials have to be waterproof to ensure that salts and other harmful effects of water penetration do not result in deterioration to the bridge structure and flexible to cope with the movements that occur on different types of bridge decks.

The need to provide waterproofing results in the HMA material requiring a very low void content, typically in the range 1 to 2 percent. The low air voids reduces interconnecting voids cutting off the path for water to travel through a mixture. This generally ensures that the hydraulic conductivity of material will be less that $1x10^{-7}$ cm/sec when assessed with the ASTM D5084 (1) test method which effectively classifies the material as impermeable. This low void requirement would for conventional asphalt binder result in a material more prone to deformation. Consequently, the adopted materials have made extensive use of thermoplastic additives, resulting in materials that exhibit viscoelastic solid behavior at normal working temperatures.

Considerable experience has been obtained over some 25 years with a system of modification which consists of adding 45lbs of thermoplastic PMM to a ton of hot mix. The material has an excellent performance history (2) but the data obtained over time has been largely based upon quantification of empirical properties.

In recent years it has become increasingly important to evaluate material properties in terms of fundamental characteristics since these are required by specifying agencies and are an essential part of risk reduction through assessment of material performance. While asphalt binders can be assessed by testing in accordance with Performance Graded (PG) tests (3), these tests cannot be simply performed on samples taken from site when evaluating PMM materials. Consequently, mixture evaluations have included a suite of tests which has become the norm in some testing laboratories to evaluate new materials. These performance and performance-related tests, as specified by ASSHTO and ASTM, can include the Asphalt Pavement Analyzer (APA) (4), Hamburg Wheel Tracker (HWT) (5) device, Indirect Tensile (IDT) device (low temperature cracking) (6) flexural fatigue device (7,8), Superpave Shear Tester for modulus and permanent deformation testing (9), dynamic modulus (10) and flow number testing (11). Such tests can be used equally to assess PMM materials used on bridge decks and in highway surfacing materials. For the materials in this paper we used the APA, flexural fatigue device, and IDT tests.

The objectives of this paper are; 1) to review typical performance related parameters of asphalt materials when used on bridge deck structures, 2) to present the properties of the PMM modified asphalt materials, and 3) to make suggestions for specification parameters related to various key aspects of performance.

BRIDGE DECK PERFORMANCE REQUIRMENTS

The need for high performance materials for use in bridge deck surfacing is well establish (Hicks (12)) and asphalt materials have been used for over 100 years in prominent bridge structures, Boorman (13). These have included a variety of materials including Mastic Asphalt, Guasphalt, Hot Rolled Asphalt, Asphalt Concrete and Epoxy Asphalt to name a few. Some of these materials such as Mastic Asphalt and Guasphalt have good waterproofing properties but if used with conventional binders can have significant problems with deformation performance if in high temperature location or used with very heavy traffic. Other systems such as Hot Rolled Asphalt, Epoxy Asphalt and Asphalt Concrete have been traditionally used with other layers which impart waterproofing properties to the combined layers over the bridge deck.

Bridge decks have traffic which is generally channelized into narrower widths thus promoting application of repeated loading over a narrower width. In addition, steel decks will result in a greater need for flexure and fatigue performance. Further, to protect the decks from salt and the harmful effects of water intrusion it is important that the deck surfacing materials have a very low void content thus rendering effective impermeability. With conventional asphalt materials high deformation resistance results partially from a good aggregate skeleton in the mixture. However, when the void content is reduced to less than 3 percent the aggregate skeleton is significantly reduced. The thermoplastic PMM effectively modifies a standard viscoelastic binder with liquid like properties into a binder which has properties that are closer in performance to a visco-elastic-plastic solid material.

The performance requirements of a mixture for a bridge deck are therefore summarized by three main requirements, flexibility, deformation resistance and low hydraulic conductivity. Flexibility is considered in two manners; 1) resistance to load associated cracking and 2) resistance to thermally induced fatigue cracking. For fatigue, if a detailed evaluation is considered it is preferable to construct a fatigue curve in which life is expressed as a function of strain level or strain and stiffness. Alternatively life can be assessed at a single strain level for agency specification purpose. Thermal cracking performance is assessed according mixture performance in the IDT test device and this is related to the climatic data for a particular location. Deformation properties at high temperature are considered using wheel tracking tests.

Fatigue performance requirements for materials vary with different types of bridge decks, resulting in differing fatigue and flexibility demand. Generally, the flexure that occurs on concrete bridge decks is relatively small when compared to steel decks and quite different demands on the material performance exist when comparing the two types of deck response. Typically steel bridge decks can have a wide range of strain response as illustrated by the strain gauge results shown in FIGURE 1 which is the response to a 45-ton truck on an orthotropic steel deck which was instrumented in manner to capture various strains at critical locations in the steel deck (De Backer, (14)). The maximum magnitude of strain is approximately 500με in this figure. Medani (15) conducted detailed Finite Element analysis of orthotropic steel deck bridges to study the need for correct modeling to understand stress and strain states that occur in the deck and asphalt materials. The response under a 14.5 ton duel wheel load is illustrated in FIGURE 2 with maximum tensile strains around 900με. In other work, for example that conducted by Houel et al. (16), where specialized devices have been fabricated to conduct tests that closely resemble the geometry of asphalt surfacing, initial strain amplitudes in the range 500 to 1500με have been indicated. The evolution of damage in this more sophisticated device appears similar to that which would be expected in a controlled load bending beam fatigue test.

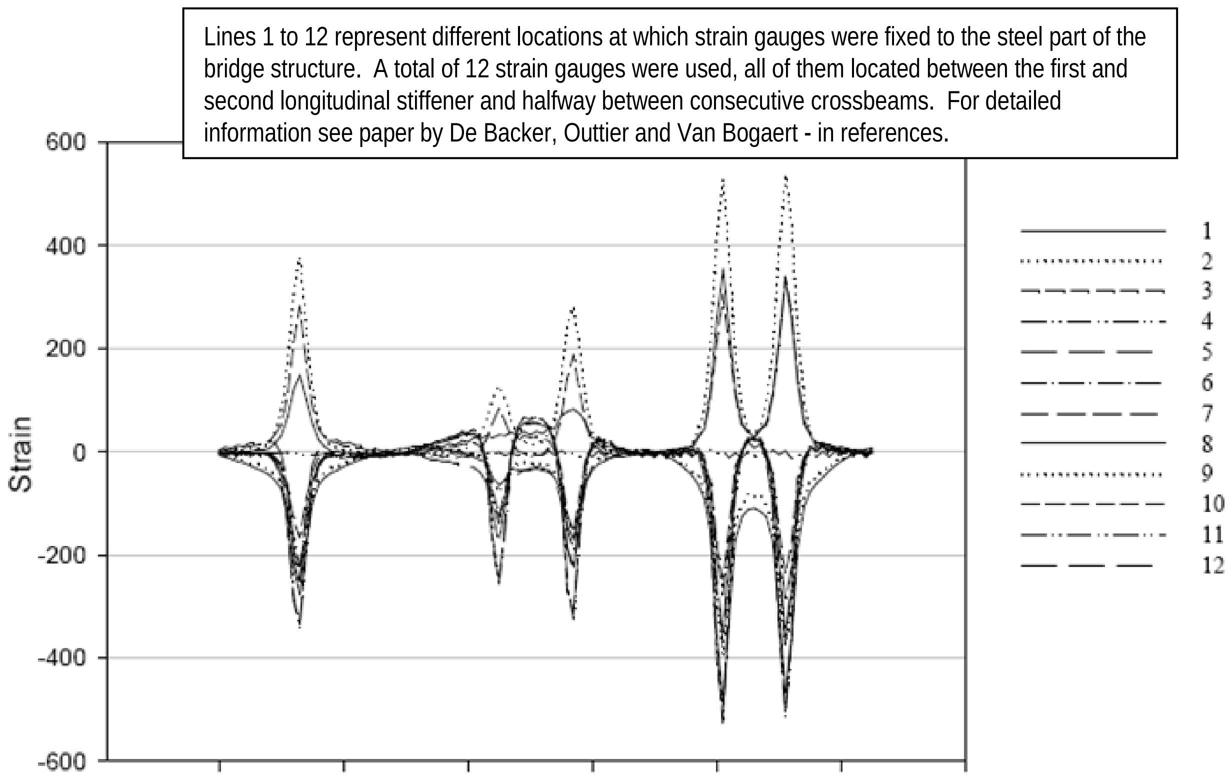


FIGURE 1 Strain response of orthotropic steel deck bridge to a 45-ton truck (after De Backer et al. (141))

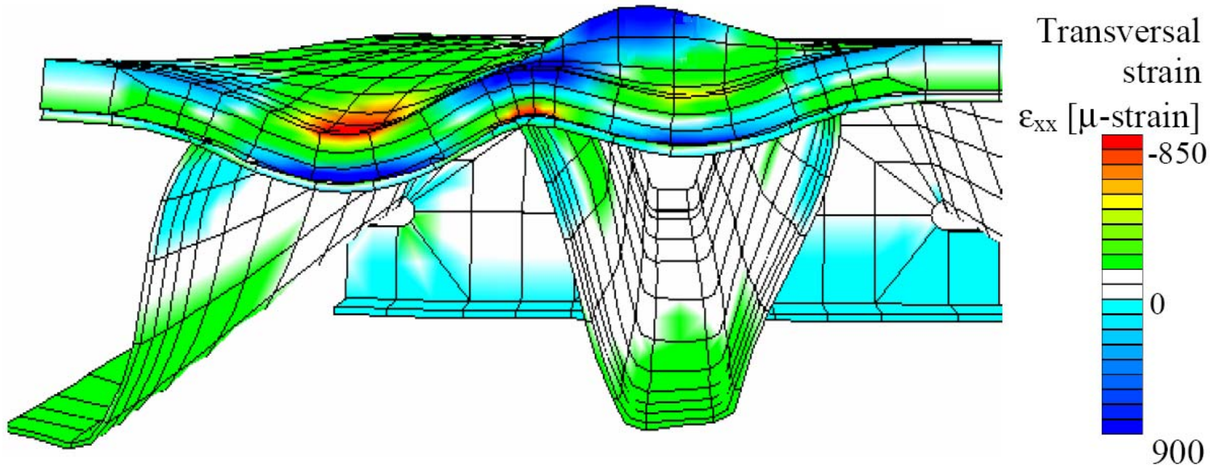


FIGURE 2 Deformed bridge deck (250x) with transversal strain under a 14.5 tons (3mm water-proof layer an 50mm mastic asphalt) (after Medani (15))

In the USA data collected by CAIT (17) for a study of materials laid on an orthotropic bridge deck in NY State used a strain of 900με to evaluate materials in a four point controlled strain bending beam test. It should be noted that the materials being used in bridge decks tend to have a fatigue relationship which can be typically represented by a linear log-log relation between tensile strain and fatigue life. While different agencies have used differing strain values for the evaluation of materials we would note that the performance of the materials in steel deck structures would suggest that values of strain are generally below 1,000με. Consequently, for thermoplastic PMM materials we have generally adopted a standard testing level of 750με consistent with most current DOT specifications. In addition, this level is consistent with the experience gained by others as discussed above. Life at other strain values can be estimated by interpolation in tests at different strain levels.

MATERIALS EVALUATED

The thermoplastic PMM is supplied in a powder form and added to the asphalt mixture at a rate that approximates 2.25 percent of the total mixture. A typical mixture suitable for modification will have a 9.5mm (⅜-inch) maximum aggregate size and the resulting mixture will, when compacted, have a void content less than 2%. The material is supplied in various forms but generally either in polyethylene bags and/or super-sack or bulk tanker. Bag form is generally preferred for batch plant and bulk supply in the form of tanker loads of the product is the preferred method with drum mix plants.

For this paper various tests have been conducted using a standard mixture made with a PG 64-22 binder mixed with trap rock aggregate. The modification of a typical mixture such as this results in significant changes to the volumetric structure of the mixture (see Rowe et al. (12)) increasing the VMA and resulting in a larger volume of binder. The change in the aggregate structure results in a mixture that can not be considered to behave as a traditional asphalt concrete which relies upon much of its strength from an aggregate skeleton within the mix. Rather the material relies upon a minimal aggregate skeleton and more significantly upon the mastic of modified binder and fine aggregate which has approached a saturation level. This mastic is effectively working as a material which closely approximates a viscoelastic solid structure between the larger aggregate particles thus preventing flow and deformation.

The modified materials have also been assessed from pavement cores with differing aggregate types to yield additional material samples so that field compacted materials can be compared to the laboratory prepared materials. A total of three sets of pavements cores from sites in different parts of the country have been evaluated, 1) Tully Construction, Willets Point, NY, 2) PJ Keating, Dracut, MA, and 3) Payne & Dolan, Waukesha, WI. These mixes had a 9.5mm nominal maximum stone size and contained PG64-22 as the base binder.

BINDER PERFORMANCE

Testing of binder performance has been conducted by various laboratories over the past 10 years with evaluation of the PG grade using laboratory blended samples to produce an equivalent PMM modified binder. The resulting binder has then been evaluated by the methods specified within AASHTO M320 (1). PG grades as high as PG94-34 have been reported in past testing (Buchanan, (19)) but it should be noted that the expected performance grade will depend upon the source of the binder and the original grade being modified. It should be noted that, as is common with other heavily modified binders, this material is somewhat difficult to age in a Rolling Thin-Film Oven (RTFO) bottle. One of the laboratories conducting evaluations noted some significant "balling up" with material being expelled from the RTFO bottle while the aging process was being performed. However, regardless of these issues it is possible to evaluate the grade using AASHTO M320 (2) criteria if care is taken with the aging process. Regardless of the base binder grade the effect of modification will be an improvement to both high and low temperature performance. Having evaluated different base grades the level of improvement can be equated to a minimum of +2 grade bump improvement at the high temperature end of the specification and -1 grade improvement at the low temperature end when considering the current AASHTO M320 Tables 1 or 2 specification, although this may even be greater (e.g. as high as +5 grade bump has been achieved in the past).

In addition, testing has also been performed in the newer Multiple Stress Creep and Recovery (MSCR) (ASTM D7405 (20) or AASHTO TP70 (21)) test as recently introduced to better define the binder performance in permanent deformation with the evaluation of the Jnr parameter (D'Angelo et al. (22)). The concept of this parameter is very important for ensuring that the material adopted tends to maintain good behavior characteristics as the magnitude of stress increases. When evaluating bridge deck materials in accordance with this parameter it is apparent that the modification results in a material which more closely approximates a viscoelastic solid due to the very high degree of elastic recovery which is obtained, as shown in TABLE 1. The normal specification criterion for a conventional binder is the material shall have a value of Jnr ≤4 (1/kPa) with this value reducing to 2, 1 and 0.5 for heavy duty, very heavy and extreme grades respectively. It can be seen that at 70°C the PG 64-22 binder fails the standard requirement as would be expected since this binder is designed to pass at 64°C. However, when modified the binders performance exceeds that of the extreme grade at the 70°C temperature.

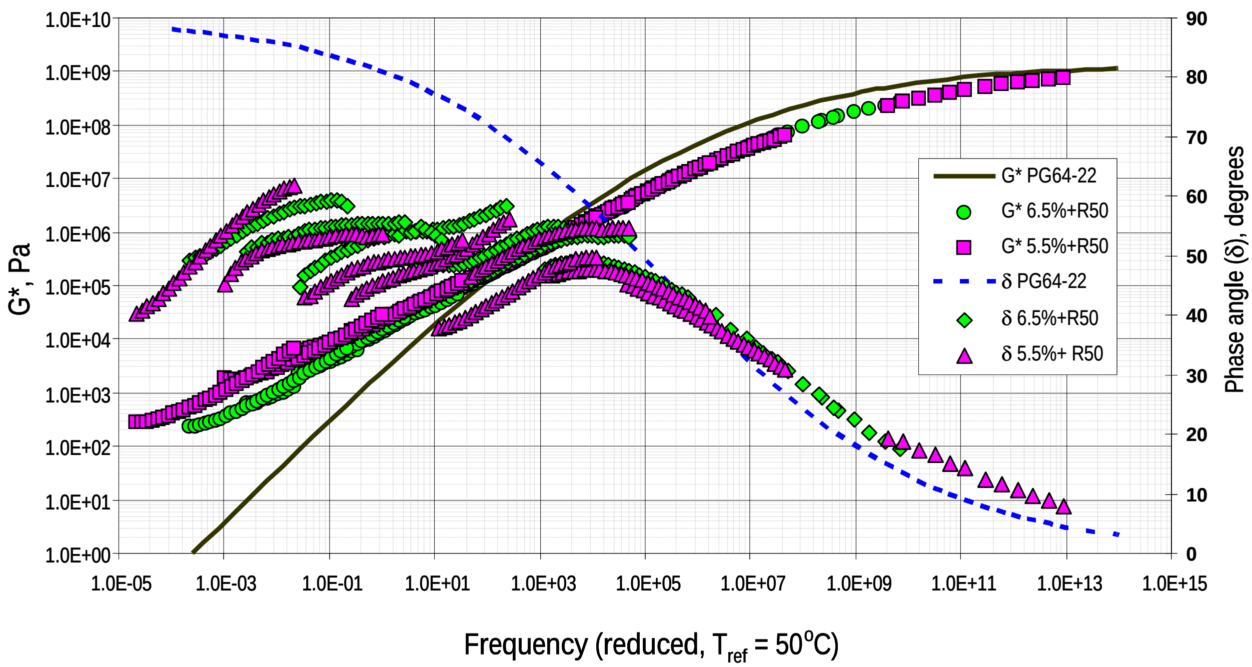
TABLE 1 Performance of PG 64-22 modified at two different concentration levels, MSCR, 70°C

Performance measure	Stress level	PG 64-22	5.5% PG64-22 + 2.25% PMM	6.5% PG64-22 + 2.25% PMM
Jnr (non-recoverable creep compliance), 1/kPa	100 Pa	5.39	0.0002	0.008
	3200 Pa	6.09	0.027	0.122
Elastic recovery, %	100 Pa	1	100	93
	3200 Pa	0	75	59
Total permanent strain, %	100 Pa	543	0.103	0.793
	3200 Pa	20,144	95.7	374
Percent of strain compared to unmodified PG 64-22, %	100 Pa	100	0.0	0.1
	3200 Pa	100	0.5	1.9

Note: The materials represented by 5.5% and 6.5% of PG64-22 +2.25% PMM represent the typical range in binder content (expressed as a percentage of the total mix) and PMM concentration found in the PMM modified mixtures (normally added at an addition rate of 45lbs/ton of mix). For the Trap Rock mix design that was used in the study the target binder content was 6.5% whereas in other mixes used in the past 6.5% represents a binder content towards the higher end of that used. The use of these two binder contents allows the range in performance to be demonstrated. The PMM content of the total binder is 29.0 and 25.7% for the 5.5% and 6.5% binder contents.

The performance change can in part be explained by inspecting the curves of stiffness produced when testing the modified materials over a range of frequencies and temperatures. A standard technique (Rowe and Sharrock, (23)) is used to convert the test data to a "master curve" of stiffness and phase angle which represents the performance over a wide range of frequencies and temperatures. For convenience the data is all reported at a single temperature called the reference temperature with the high stiffness being associated with the low temperature tests and the low stiffnesses being those evaluated at high temperatures. The data collected for the thermoplastic PMM modified materials are compared to a standard PG 64-22 binder used in the testing. From inspection of the data in this master curve representation it can be clearly seen that the stiffness (complex shear modulus, G*) of the binder is reduced at the high frequency end of the master curve (low temperature tests) but increased at the low frequency end of the master curve (high temperature tests). While the changes may appear relatively small on the graph it should be noted that the G* is plotted on a logarithmic scale and consequently the stiffness changes, particularly at the high temperature, end are very significant.

While the change in performance can be demonstrated in the frequency sweep master curve results the key performance at high temperatures can be best demonstrated by the MSCR tests since this captures the response at higher stress and strain levels than are used in the frequency sweep testing. In this case we have evaluated the materials at 70°C in the multi-stress creep recovery tests, see TABLE 1. This is an important step in verifying the performance since the binders' sensitivity to stress can then be determined. However, the true mix behavior can only be fully understood by conducting mixture tests as described in the next section of this paper. It should be noted that traditional binder testing with the PMM additives used in this study is complex since the material is added to the hot aggregate, not the liquid binder, in the mixing process thus resulting in PMM being better defined as a mix modifier rather than an asphalt modifier.



Modified materials denoted by 5.5%+R50 and 6.5%+R50. The 5.5 and 6.5 refer to the binder content (PG64-22) in the unmodified mixture. A 6.5% blend with R50 (added at a 2.25%/45lb per ton level) results in a PMM concentration of 25.7% of the total binder.

FIGURE 3 Rheology of PG 64-22 modified with thermoplastic PMM modifier

MIXTURE TEST METHODS

All field sampled mixtures were removed from 5-gallon sample buckets and divided into pans by use of minimal heating and covered with aluminum foil to minimize further aging. The pans were heated to compaction temperature of 171°C (340°F). The mixture maximum gravities (Gmm) were measured and 150mm diameter gyratory samples and 380mm long beams were compacted. All samples, except for the APA samples, were trimmed and mixture bulk gravities (Gmb) were measured to ensure that test specimens had 1 to 2 percent air voids.

The mix samples have been evaluated for hydraulic conductivity, fatigue endurance and permanent deformation characteristics. The hydraulic conductivity tests were performed using the procedures described in ASTM D5084 using the constant head method on specimens removed from the trial pavement areas and this data is presented in FIGURE 4. This data is consistent with other studies, for example Mallick and Bergendahl (24), who observed that the material had a very low coefficient of permeability ($K=2.15\times10^{-5}$ $m.s^{-1}$). In the calculations contained with their report they showed that water would theoretically penetrate a 2-inch layer of Rosphalt with a 2-inch head of water (considered reasonable for a puddle depth) if this existed for a period of 22-months. Clearly, the concept of standing water existing on a bridge deck for such a long duration is not possible and this effectively demonstrates that materials with these levels of hydraulic conductivity or permeability (depending upon test procedures) can effectively be used as water-proofing materials for bridge decks.

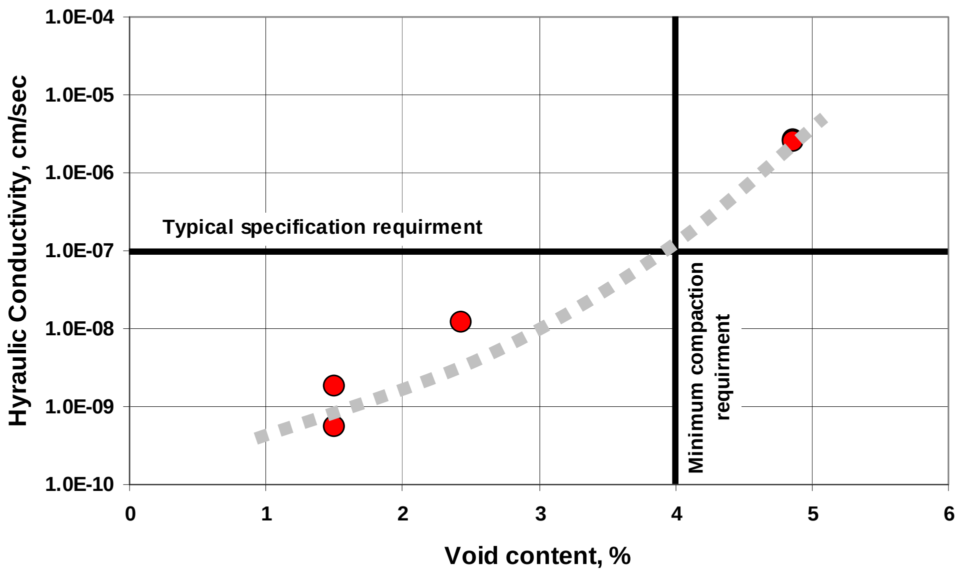


FIGURE 4 Data from paving trial showing typical hydraulic conductivity relationship with void content

Low temperature creep tests were conducted at -40, -30 and -20°C, after which specimens were strength tested at -30°C. Strains were kept in the linear viscoelastic range, in most cases below 100με, as per AASHTO T322 (6). In addition, specimens cut from gyratory compacted specimens made with Trap Rock aggregate were also evaluated. Tensile strength tests were conducted at -30°C, following creep testing to determine the tensile strength of the materials. The tensile strengths obtained were generally higher that those obtained with non-modified materials. The creep compliance data for the materials evaluated are illustrated in FIGURE 5 which shows the master-curves developed at a reference temperature of -40°C. This data was then used with the method published in the SHRP A-357 report to estimate the thermal cracking (Lytton et al. (25)). From the fitted compliance mastercurve function an array of creep compliances has been generated over an appropriate range of time to enable the calculations to be performed. Hopkins & Hamming's (26) method was then used to obtain the numerical inverse of this array in the form of relaxation moduli. A generalized hyperbolic power function was then fitted to describe the relaxation modulus values, as follows:

$$E(t) = \frac{E_0}{\left(1 + (t/\lambda)^{\beta}\right)^{\frac{\delta}{\beta}}}$$

The software MONARCH (developed by Abatech) was used for this evaluation. The thermal Stress calculation involves the constitutive relation for a one-dimensional restrained structure subjected to a thermally induced strain which can be written as:

$$\sigma(\xi) = \int_0^{\infty} E(\xi - \xi') \frac{\partial(\varepsilon - \varepsilon^{th})}{\partial \xi'} d\xi'$$

where:

Reduced time $\xi = t/a_T$,

Thermal strain = ε^{th}

Shift factor = a_T

The shift factors and relaxation function obtained as described above were finally employed with user-specified values of initial temperature, rate of cooling and linear thermal expansion, to enable numerical integration of the constitutive relation. The thermal stresses versus temperature thus computed are compared with observed fracture strengths versus temperature, and if possible a critical cracking temperature is interpolated.

The computed thermal stress curves and the tensile strengths information have been superimposed in FIGURE 5. This data shows that the predicted critical cracking temperature computed for these various projects varies from -28 to -38°C, with an average performance of -33°C. The performance grade of the binders used in these evaluations was -22°C and consequently the improvement in low temperature performance ranged from 6 to 16°C. This represents a minimum of 1 grade improvement to as high as nearly three grades of improvement at the low end of the performance spectrum.

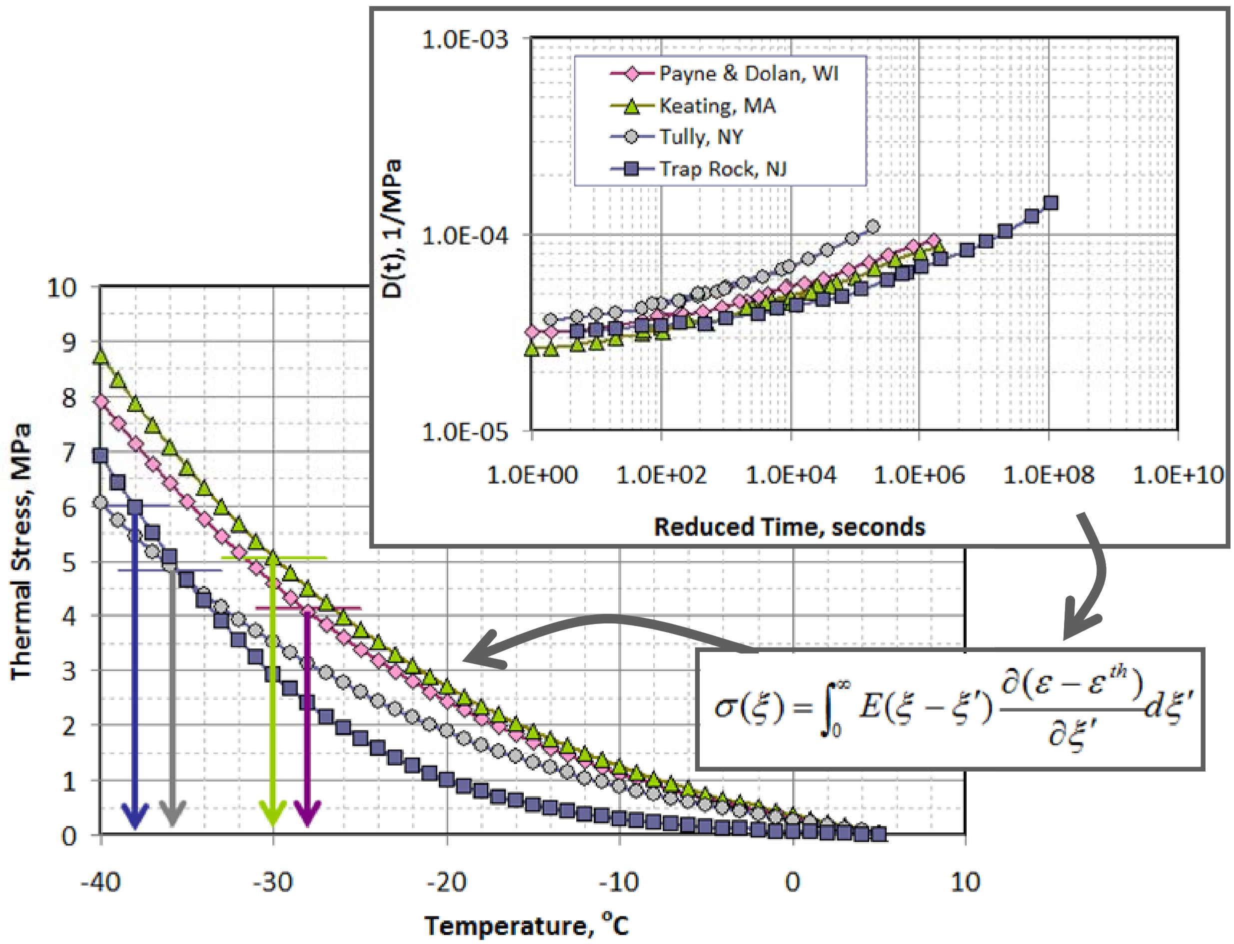


FIGURE 5 Creep compliance data (at T_{ref} = -40°C) obtained from core and gyratory compacted specimens (top right) used to compute estimated thermal stress (bottom left) for various mixes (horizontal lines in bottom left represent tensile strength evaluated at -30°C)

Fatigue testing was conducted using a bending beam protocol in accordance with AASHTO-T321/ASTM D7460. Testing was continued beyond the 50 percent reduction in stiffness thus enabling analysis with both the ASSHTO T321 method and ASTM D7460. The ASTM method provides a more accurate failure point (27) that that given by the ASSTHO test methods and this is more important with PMM modified materials since polymer materials typically fail at 30 to 45 percent of initial stiffness as compared to non-modified materials. The fatigue response has then been compared to a conventional material (Kentucky Class 2 mixture which is a non-modified mixture used on roads carrying up to 3 million Equivalent Single Axle Loads). At a strain level of 750με the performance is increased from 20,000 load cycles to over 5,000,000 load cycles (2,000,000 if regression is based on Trap Rock data alone).

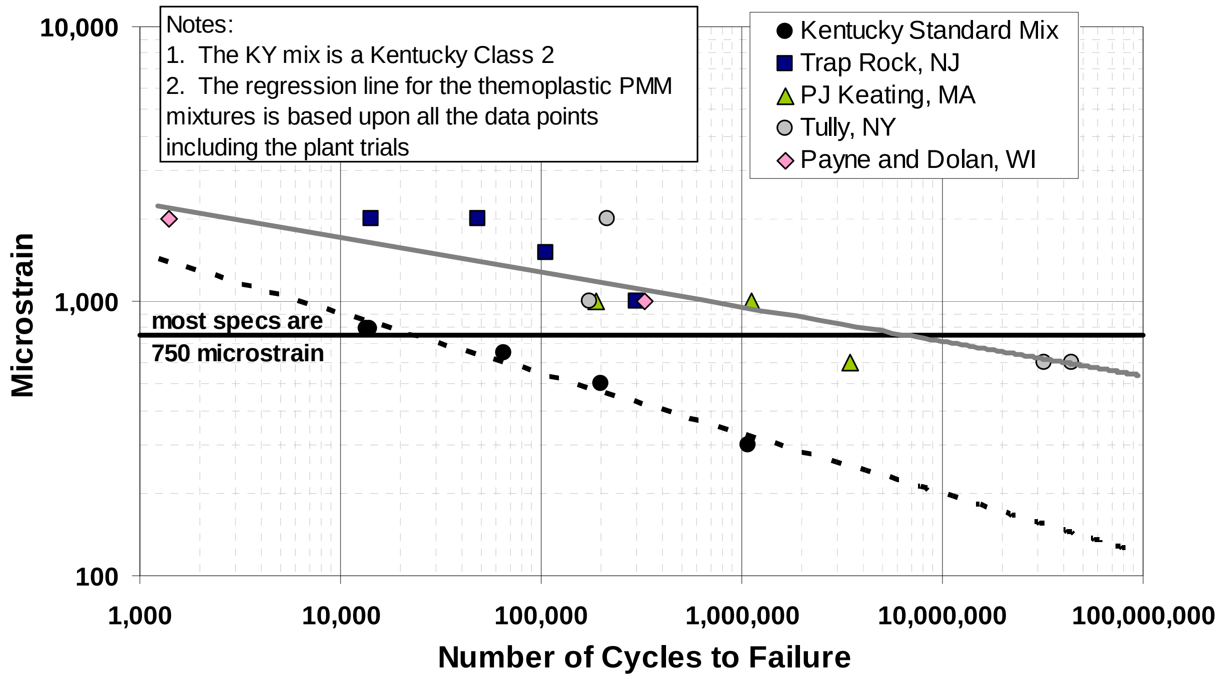


FIGURE 6 Fatigue performance of various thermoplastic PMM compared to conventional HMA manufactured with PG 64-22 binder

Permanent deformation tests were conducted using both laboratory prepared specimens and specimens removed from the pavement structures by coring. Initially in the study the Hamburg Wheel Tracking (5) test was used at 50°C but it was decided that it would be more prudent to conduct tests at the high PG grade temperature. Since the majority of states where the thermoplastic PMM materials are used tend to make use of the Asphalt Pavement Analyzer (APA) this was adopted for testing of cores from various sections. Tests were conducted at 64°C in this device and typically very low deformation rates were noted, as illustrated in FIGURE 7.

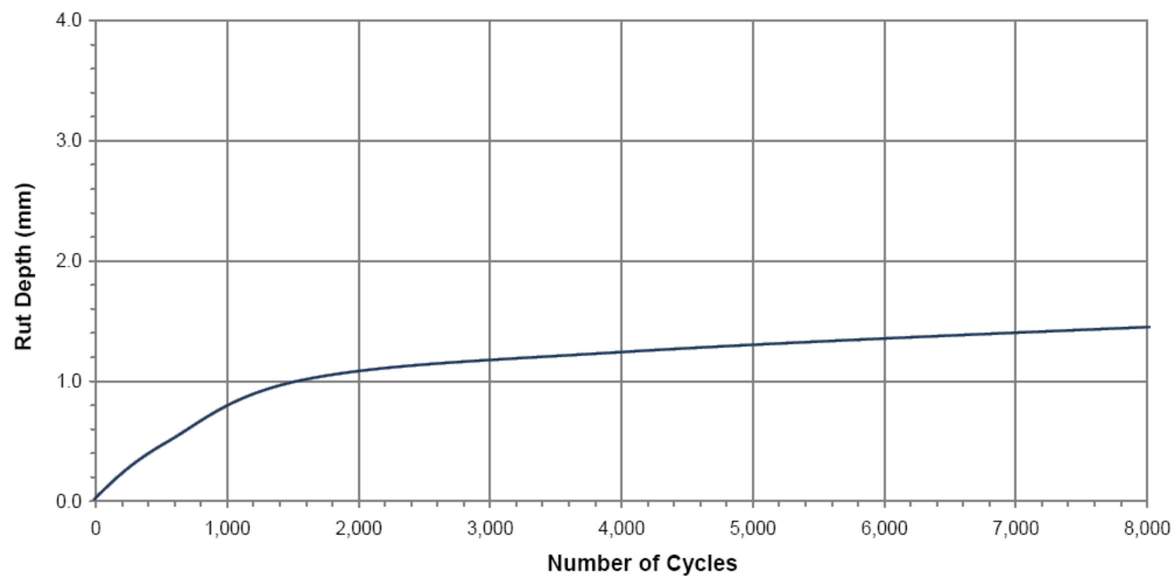


FIGURE 7 Typical APA performance of core specimen made with thermoplastic PMM

DISCUSSION

The performance of the thermoplastic PMM modified material compared to a conventional asphalt concrete material was evaluated at two specific stages of the work conducted; 1) mix design and 2) with material placed in paving trials. In addition, we have compared the data obtained with other historical data collected by PRI Asphalt Technologies (28) and CAIT (17). The improvement in fatigue is supported by observations of performance on steel structures such as the George Washington Bridge, New York were material that was placed in the 2006 is still performing in a satisfactory manner in one of the most heavily trafficked bridges in the world with approximately 1,000,000 vehicles passing over the structure every month. Based upon these observations a reasonable specification requirement for the performance of materials for orthotropic steel bridge decks would be the requirement to achieve 1,000,000 load applications at a 750 microstrain level. For concrete decks the requirement for flexure is lower and this value could be considerably reduced.

The stiffness obtained from the creep test was used to calculate the estimated stresses in the mixture when subjected to a standard cooling rate. The temperatures are significantly lower than that of the unmodified binder which was graded as a -22. The material characteristics that impacted this calculation significantly are the lower stiffness and the higher tensile strength that the thermoplastic PMM achieves. While a modification level of 45lbs/ton of mix results in a minimum improvement of one PG grade at the low temperature part of the specification it is noted that the average improvement equates to nearly 2 grades. The implementation of a mix design process in which the critical cracking temperature is determined via AASHTO testing can be rapidly implemented. It should be noted that the calculation procedure performed is effectively implemented in the AASHTO specification for binders (AASHTO PP-42 (29)) but with the mastercurve of binder stiffness replaced by the mix mastercurve and no correction factor applied as used with the binder calculation.

The deformation performance of asphalt materials is very difficult to assess due to the complex interactions that exist between loading speed, stress applied, state of confinement of test specimens and other factors. Consequently, many agencies prefer to evaluate materials in wheel tracking experiments that appear intuitively to better represent the actual loading on site. In the work with thermoplastic PMM materials a wide variety of wheel tracking experiments have been conducted. Lai (30) assessed the performance of the material in the Georgia Wheel Tracking (GWT) test for use in Racetracks whereas Mallick et al. (24) conducted tests in a “model mobile load simulator.” More recently, we have extended this data set by performing tests in the Asphalt Pavement Analyzer (which is the commercial development of the GWT) and the Hamburg Wheel Tracking (HWT) tests. The HWT test was conducted on a laboratory prepared specimen at 50^{o}C in the “wet condition” with a total deformation of 6.2mm after 20,000 load passes. The result in the APA on actual cores taken from the pavement areas gave an average deformation of 2.4mm at 8000 cycles (100 psi, Load 100 lbs, test temperature 64^{o}C). Both these results indicate that the material has a good propensity to withstand permanent deformation. The key factor in this excellent performance is the modification of the binder that results in practically all of the strain associated with loading being recoverable.

SUMMARY

The evaluation of the thermoplastic PMM as an alternate bridge deck waterproofing system has demonstrated the use of extensive laboratory and field evaluations. The key functionality requirements after the material has been placed are the ability of the material to act as a waterproofing layer, demonstrate good flexibility and resist permanent deformation. The thermoplastic PMM achieves all three of these performance criteria via a unique “dry-process” modification. Each of these requirements relies upon a characteristic of the mixture or binder modification to achieve the desired functionality. The testing and evaluation of these materials can be performed rapidly with mixture specimens produced within the laboratory environment and verified by testing of field samples. Standard test methods now exist for low temperature cracking, fatigue performance and evaluation of rutting potential. This is a relatively new development in the paving industry in the USA which previously meant that engineers had to rely upon tests of the individual components rather than the final mixture. It is the authors’ view that mixture tests will provide a much more meaningful evaluation and assessment of future performance since the correlations and calculations that rely on binder and aggregate properties are simply not needed. For achievement of adequate performance on bridge decks we have recommended performance parameters as follows:

- Fatigue and Flexure, ASTM D7460 - ≥1,000,000 cycles, 20^{o}C, 750$\mu\varepsilon$. The reduction in binder stiffness through modification and the use of thermoplastic elastomeric modifiers enables an increase of fatigue and flexibility when this material is compared to conventional asphalt mixtures. ASTM D 7460 is preferred by the authors over AASHTO T321 due to the better definition of failure life.

- Low temperature performance, AASHTO T322 (and calculations), ≤-30°C. The modification of a -22 grade results in a grade which is typically lower than -30 due to the lower stiffness and higher strength of the modified materials.
- Permanent deformation, AASHTO TP 63 - ≤10mm, 8,000 cycles, 64°C. The stiffness and elastic recovery of the binder modification at a high temperature and low loading speed enables deformation to be recovered after each loading pass whereas a conventional binder would develop significant deformation.

In addition, hydraulic conductivity below $1x10^{-7}$ cm/sec (ASTM D-5084) is recommended to ensure that durability and waterproofing requirements are met. The thermoplastic PMM materials enable an alternate solution for bridge deck waterproofing that can be easily specified and implemented. The use of plant mix additives allows HMA manufacturers increased flexibility when producing materials for multiple projects in that liquid hot storage tanks are not needed and no minimum amount of modified binder is needed. In addition, significantly higher modification levels can be used than those which can be achieved with conventional plant and equipment which generally has limitations on pumping viscosity. This method offers significant additional benefits of ease of maintenance and rapid construction time and can assist with the need for effective project delivery in today's market.

ACKNOWLEDGEMENTS

The authors acknowledge the significant help of the laboratory personal in the preparation of the test data and in particular the staff of Chase Corporation, the Asphalt Institute; Professor Bill Butler and Mr. Sarfaz Ahmed of the University of Illinois, PRI Asphalt Technologies and Dongre Testing Laboratories. We also acknowledge the work conducted by the PANYNJ and the evaluations they have conducted with Dr. Tom Bennert at the Center for Advanced Infrastructure Testing at Rutgers University.

REFERENCES

1 ASTM, "*Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter*," Test method ASTM D5084, ASTM International, 100 Barr Harbor Drive, West Conshohocken, Pennsylvania, USA.

2 Valsangker, A.N., "*Rosphalt 50 Pavement on Bridge Decks in New Brunswick,*" Report prepared for New Brunswick Ministry of Transportation, by J.W. Bird and Company Limited, 2001.

3 AASHTO, "*Standard Specification for Performance-Graded Asphalt Binder*," Materials Standard M320, American Association of State Highway and Transportation Officials.

4 AASHTO, "*Determining Rutting Susceptibility of Asphalt Paving Mixtures Using the Asphalt Pavement Analyzer (APA)*," Test Procedure - TP63-03, American Association of State Highway and Transportation Officials.

5 AASHTO, "Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot-Mix Asphalt (HMA), AASHTO Test Procedure T324, American Association of State Highway and Transportation Officials.

6 AASHTO, "*Standard Method of Test for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device*," Test Procedure - T322, American Association of State Highway and Transportation Officials.

7 AASHTO, "*Determining the Fatigue Life of Compacted Hot-Mix Asphalt (HMA) Subjected to Repeated Flexural Bending*," Test Procedure - T321, American Association of State Highway and Transportation Officials.

8 ASTM, "Standard Test Method for Determining Fatigue Failure of Compacted Asphalt Concrete Subjected to Repeated Flexural Bending," Test method ASTM D7460, ASTM International, 100 Barr Harbor Drive, West Conshohocken, Pennsylvania, USA.

9 AASHTO, "*Determining Shear Strain and Stiffness of Asphalt Mixtures Using the Superpave Shear Test*," Test Procedure - T320, American Association of State Highway and Transportation Officials.

10 AASHTO, "*Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures*," AASHTO Designation T62, American Association of State Highway and Transportation Officials.

11 AASHTO, "*Standard Method of Test for Determining the Creep Compliance and Strength of Hot-Mix Asphalt (HMA) Using the Indirect Tensile Test Device*," AASHTO Standard Method of Test T322, American Association of State Highway and Transportation Officials.

12 Hicks, RG., Dussek, I.J. and Siem, C., "*Asphalt Surfaces on Steel Deck Bridges*," Transportation Annual Meeting, Paper 00-0389, Washington, D.C., 2000.

13 Boorman, T.H., "*Asphalts, Their Sources and Utilizations, Asphalt for Dustless Roads, Recent Improvements in Asphalt Industries*," Comstock, New York, 1908.

14 De Backer, H., Outtier, A. and Van Bogaert, P., "*Alternatives for Bridge Surfacings with Orthotropic Plated Deck: A Fatigue Point of View*," Foundations of Civil and Environmental Engineering, No. 11, Poznań, 2008.

15 Medani, T.O., "*Design Principles of Surfacings on Orthotropic Steel Bridge Decks*," University of Delft, PhD Thesis, 2006.

16 Houel, A., N'Guyen, T.L. and Arnaud, L., "*Monitoring and designing of wearing courses for orthotropic steel decks throughout the five-point bending test*," Advanced Testing and Characterization of Bituminous Materials – Loizos, Partl, Scarpas & Al-Qadi (eds), Taylor & Francis Group, London, ISBN 978-0-415-55854-9, 2009.

17 Center for Advanced Infrastructure Testing (CAIT), "*The Advanced Characterization Testing of the Port Authority of NY/NJ's Hot Mix Asphalt Materials - Rosphalt Material Test Results*," Report submitted to The Port Authority of NY/NJ, Materials Engineering Division, Port Authority Technical Center, 241 Erie Street, Jersey City, New Jersey. 2006.

18 Rowe, G.M., Blankenship, P. and Zuberer, D., "*Evaluation of Rheology and Engineering Properties of a Bridge Deck Thermo-Plastic Waterproofing Material*," 2010 FHWA Bridge Engineering Conference, April 8 and 9, 2010 Hyatt Regency, Grand Cypress Hotel, Orlando, Florida, April 8-9, 2010.

19 Buchanan, S., "*SHRP Asphalt Grading*," Report on testing by National Center for Asphalt Technology, October, 1999.

20 ASTM, "*Standard Test Method for Multiple Stress Creep and Recovery (MSCR) of Asphalt Binder Using a Dynamic Shear Rheometer*," Test method ASTM D7405 - 10a, ASTM International, 100 Barr Harbor Drive, West Conshohocken, Pennsylvania, USA.

21 ASSHTO, "*Multiple Stress Creep and Recovery Test of Asphalt Binder Using a Dynamic Shear Rheometer*" Test Procedure - TP70, American Association of State Highway and Transportation Officials.

22 D'Angelo, J., Kluttz, Robert Q, Dongre, Raj, and Stephens Keith., "*Revision of the Superpave High Temperature Binder Specification: The Multiple Stress Creep Recovery Test*," Journal of The Association of Asphalt Paving Technologists, Vol. 76, pp. 123, 2007.

23 Rowe G.M., and Sharrock, M.J., "*Development of Standard Techniques for the Calculation of Master Curves for Linear-Visco Elastic Materials*," The 1st International Symposium on Binder Rheology and Pavement Performance, University of Calgary, Alberta, Canada, August 14 - 15, 2000.

24 Mallick, R.B. and Bergendahl, J.A., "*An Evaluation of Rutting and Shoving Potential of, and Chloride Diffusion through Hot Mix Asphalt (HMA) With Rosphalt*," Civil and Environmental Engineering Department, Worcester Polytechnic Institute, April 2004.

25 Lytton, R.L., Uzan, J., Fernando, E.G., Roque, R., Hiltunen, D. and Stoffels, S., "*Development and Validation of Performance Prediction Model and Specifications for Asphalt Binders and Paving Mixes*," Report SHRP-A-357, The Strategic Highway Research Program, Washington DC 1993.

26 Hopkins, I.L. and Hamming, R.W., "*On Creep and Relaxation*," Jour. Appl. Phys., Vol.28, No.8, pp.906, 1957.

27 Rowe, G.M. and Bouldin, M.G., "*Improved Techniques to Evaluate the Fatigue Performance of Asphaltic Mixtures*," Eurobitume - Book 1, September 2000, pp.754-763.

28 PRI Asphalt Technologies, "*Test & Evaluation Report, Maybrook Materials*," Report prepared for Chase Construction Company, Project ROY 20-02-01, December 2006.

29 AASHTO, "*Standard Practice for Determination of Low-Temperature Performance Grade (PG) of Asphalt Binders*," AASHTO Practice - PP42, American Association of State Highway and Transportation Officials.

30 Lai, J.S., "*Assessment of the Suitability of Using Rosphalt-50 Modified Asphalt Mixes for Auto Race Track Pavement Surface*," Report submitted to Royston Laboratories Division, Chase Corporation by Pavtec Engineering Technology, Inc, Georgia, July 1996.