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Application of Asphalt Mix Performance-Based Specifications

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General Issues in Asphalt Technology Committee
Characteristics of Asphalt–Aggregate Combinations to Meet Surface Requirements Committee
Characteristics of Asphalt Paving Mixtures to Meet Structural Requirements Committee
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Preface

This circular contains papers based on presentations made at the 93rd Annual Meeting of the Transportation Research Board in a session titled Application of Asphalt Mix Performance-Based Specifications. The session illustrated performance-based asphalt mix (PBAM) specifications that currently are being used by various agencies. It provided a review of the concepts behind the development of the PBAM, as well as the application of PBAM to field projects. In addition to laboratory results, the session presented data on pavement performance and discussion about the interaction required between the agency, the suppliers, and the contractor to complete a successful project.

—Frank Fee
Frank Fee, LLC

PUBLISHER'S NOTE

The views expressed in the papers contained in this publication are those of the authors and do not necessarily reflect the views of the Transportation Research Board, the National Research Council, or the sponsors of the conference. The papers have not been subjected to the formal TRB peer review process.

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Performance-Based Specifications
California Experience to Date

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INTRODUCTION

Performance-based specifications (PBSs) have been defined as

> Quality assurance specifications that describe the desired levels of fundamental engineering properties (e.g. resilient modulus, creep properties, and fatigue) that are predictors of performance and appear in primary prediction relationships (i.e., models that can be used to predict stress, distress, or performance from combinations of predictors that represent traffic, environment, supporting materials, and structural conditions). (*1*)

The advantages of using PBS based on mechanistic–empirical (ME) design are clear. PBSs permit the designer to assume that materials constructed on the grade will have similar properties to those that are being used in the ME design structural analyses. They also permit the tailoring of specific materials requirements, such as stiffness, rutting and cracking properties, to unique features of a given project. These unique features include the particular traffic, climate, subgrade and existing pavement layers, and to locally available materials including local reclaimed asphalt pavement (RAP). PBS also allow the designer to "raise the bar" with regard to specific expectations for performance related mix properties compared to what is possible with specifications that rely on aggregate and binder specifications, volumetric mix design, and empirical mix tests.

The development of PBS for pavement and asphalt has been a subject of a great deal of research, including the first Strategic Highway Research Program (SHRP) which included the development of two approaches to ME performance models and testing methods for PBSs for asphalt binders and mixtures to control three distress modes: rutting, fatigue cracking, and thermal cracking (*2*, *3*). There was significant early work in this area in the Netherlands (*4*), particularly with regard to development and use of four-point bending for stiffness and fatigue. There has been ongoing work in Europe, mostly through RILEM, towards development of performance-based testing methods and specifications going back to the 1960s (*5–7* provide snapshots as of 1997, 2003, and 2009) towards the development of international standards for characterizing and specifying mix performance properties. Several European countries are regularly using PBSs for asphalt, primarily for design–build (DB) and design–build–maintain (DBM) projects where the designer has access to precise understanding of the materials to be used and some control over their properties as part of the design process. There has been extensive work in Australia and New Zealand towards developing tests and PBS for granular bases (*8–10*). In addition to go–no-go specifications, performance-based incentive–disincentive pay factors for asphalt have been developed based on ME performance estimates (*11*).

While the benefits of implementation of PBSs are clear, there are a number of issues that have been identified throughout the literature, and in discussions with early implementers. One example was identified in *Transportation Research Circular Number E-C037: Glossary of Quality Assurance Terms* (*1*): "…because most fundamental engineering properties associated with pavements are currently not amenable to timely acceptance testing, performance-based specifications have not found application in highway construction".

The purpose of this paper is to provide a summary of California's experience regarding development and implementation of PBSs, challenges that have been identified, and ideas for overcoming those challenges from an owner's headquarters perspective.

SUMMARY OF CALIFORNIA PRACTICE AND EXPERIENCE

California's initial implementation of PBSs based on ME design began in the late 1990s when the asphalt industry was faced with the challenge of building long-life asphalt pavements (LLAP). Together, industry, the California Department of Transportation (Caltrans), and the University of California Pavement Research Center (UCPRC) determined that existing mix and pavement design methods and specification frameworks were not adequate to achieve desired goals.

The initial project was for the long-life rehabilitation of I-710 in Long Beach in southern California, designed to handle more than 200 million 80 kN (18 kip) equivalent single axles (ESALs) over a design period of 30 years, including overlays of existing concrete pavement and full-depth asphalt pavement beneath overpasses. The concepts of (*a*) increased compaction, (*b*) use of stiffer binders in thick sections and polymer-modified binders in the surface layer, (*c*) rich bottom layers with slightly more binder to facilitate better compactionfor bottom-up fatigue cracking and moisture sensitivity, and (*d*) flexural beam and repeated simple shear test (RSST) laboratory testing were implemented in the pavement designs and specifications from previous UCPRC and SHRP research (*12*). The designs and specifications were based on: 50% loss of stiffness in the flexural fatigue test; repetitions to 5% permanent shear strain in the RSST; and flexural stiffness at 20°C, 10 Hz (*13*). The laboratory-to-field shift factors were based on

- Fatigue through comparison with designs from the Caltrans empirical pavement design method based on knowledge of that methods original calibration and analysis of results from a large sensitivity analysis using typical materials in the state and
- Rutting through the calibration performed as part of the SHRP A-003A project (*14*).

The baseline materials were high quality 100% crushed alluvial aggregate, standard AR-8000 asphalt, and special polymer-modified asphalt binders that were locally available, but selected to provide improved performance.

The use of these concepts permitted a reduction in thickness of the asphalt layers in the full-depth section of more than 35%, which was essential for meeting the required construction schedule with 55-h weekend traffic closures. Phase 1 construction was completed in 2002, followed by two more phases resulting in about 150 lane-km rehabilitated. Surveys of change in backcalculated stiffness after more than 5 years showed little damage, and no distresses other than some localized raveling in the sacrificial open-graded wearing course (*15*).

Beginning in 2000, UCPRC, Dynatest Consulting, Inc., and Caltrans developed the CalME flexible pavement design software that is based on incremental-recursive damage models and materials parameters from repeated load tests for fatigue and rutting (currently flexural beam and RSST, respectively), and frequency sweeps for stiffness (currently flexural beam). CalME was calibrated using accelerated pavement testing from different studies and some field sections, and evaluates reliability using Monte Carlo analysis and statistical variability of existing layers quantified using the back-calculated stiffness measurements (*16*).

Ten years after the initial project in southern California, Caltrans decided to implement the ME design methods using CalME and PBS on three northern California Interstate highway rehabilitation projects, with heavy long-haul truck traffic, although fewer ESALs per year than on I-710. However, the design goals were at least 40-year fatigue (bottom-up or reflective) and rutting (asphalt and unbound layers) service lives. Each project involved a new and different contractor–materials producer, and two districts, both of which had not experience building long life hot-mix asphalt (HMA) pavements. These projects were also the first Caltrans projects to use 25% reclaimed asphalt pavement (RAP) in the HMA layers below the surface layer which was a significant increase over the previous maximum 15%. ME design provided the tool for consideration of the unfamiliar materials properties in the design.

All of the projects were delivered using the design–bid–build (DBB) low bid approach, with the designs and specifications prepared by the owner and construction bid submitted by the contractor–supplier. This presents additional challenges compared to practice in Europe, where PBSs have mostly been used for DB or DBM. There, the contractor prepares the design for their own materials, or can compare designs and costs for alternative materials that they can consider using. In DBM contractor develops the life-cycle cost, and can consider cash flow, balancing initial construction and future preservation or maintenance activities, as well as total net present value of cost. In California, the designer must prepare specifications which are biddable, and the contractor must bid, with neither knowing beforehand exactly what the contractor can or will deliver.

Materials and Structures

Pavement cross sections for the three northern California projects designed using CalME are shown in Table 1. Each project included milling off of thick layers of existing cracked, and at times moisture damaged asphalt to provide RAP. The thickness of the middle layer with 25% RAP was the main variable changed in the structural design.

Specifications

The RSST (based on AASHTO T 320, ASTM D7312) was used to select the design binder content for each of the mixes, except the rich bottom asphalt concrete mixes, where 0.7% was added to the binder content found with the RSST to facilitate better compaction. To determine mix fatigue response at the selected design binder content, the flexural fatigue test (AASHTO

TABLE 1 Pavement Rehabilitation Structural Sections

Red Bluff (I-5, Tehama County)	Weed (I-5, Siskiyou County)	Dixon (I-80, Solano County)
30 mm (0.1 ft) RHMA-O-HB[a]		30 mm (0.1 ft) RHMA-O-HB
90 mm (0.3 ft) PG 64-28PM 15% RAP[b]	60 mm (0.2 ft) PG 64-28PM 15% RAP	60 mm (0.2 ft) PG 64-28PM 15% RAP
60–200 mm (0.2–0.65 ft) PG 64-10 25% RAP[c]	110–180 mm (0.35–0.6 ft) PG 64-16 25% RAP	75–180 mm (0.25–0.6 ft) PG 64-10 25% RAP
60 mm (0.2 ft) PG 64-10 rich bottom 15% RAP[d]	60 mm (0.2 ft) PG 64-16 Rich Bottom 15% RAP	30 mm (0.1 ft) PG 64-10 25% RAP with asphalt impregnated fabric on top
110 mm (0.35 ft) existing CTB[e]	150–230 mm (0.5–0.75 ft) varying CTB, AB[f], CSJPC[g]	0.7 ft CSJPC

[a] Rubberized HMA open-graded high-binder content.
[b] Dense-graded polymer-modified HMA, 6% air voids.
[c] Dense-graded conventional HMA, 6% air voids.
[d] Dense-graded conventional HMA, rich bottom (+0.5% binder), 0% to 3% air voids.
[e] Cement-treated base.
[f] Aggregate base.
[g] Cracked and seated jointed plain portland cement concrete.

T 321, ASTM D7460) was utilized. The moisture sensitivity response of each of the mixes was evaluated using the Hamburg wheel tracking test (HWTT, AASHTO T 324). All of the specimens for the performance tests were prepared using rolling wheel compaction (RWC) because the aggregate structure prepared by this method is similar to that obtained in mixes during pavement construction. RWC was developed during SHRP (AASHTO PP3-94.4). In developing the test data used to define the performance requirements, the AASHTO procedures were subsequently modified published in the Caltrans Flexible Pavement Test Method LLP-AC1 (*17*, *18*).

Specification limits were selected based on the 95% confidence interval for the given property based on replicate tests as shown in Figure 1. Caltrans accepts 95% of the risk of laboratory test variability. The procedure for developing the specification limits was developed by Tsai et al. (*19*). An example of the PBSs is shown in Table 2. The specification requires that the PBSs be applied to plant-produced mix. Two contractors used plant mix and one contractor used laboratory mix to develop preliminary mix designs. All three contractors used plant mix for mix design acceptance testing as per the specification.

Conventional Hveem mix design requirements are also included in the specification, including air void content under Hveem kneading compaction (for bleeding), aggregate specifications, voids in the mineral aggregate, voids filled with asphalt, dust proportion and tensile strength ratio (untreated and lime treated). The district where the Red Bluff and Weed projects were built generally requires lime treatment because of historical moisture sensitivity problems. Quality control and quality assurance testing during construction was based on conventional tests listed above because of the time requirements for performance related repeated load tests. The contractor had to provide new specimens for testing if the aggregate, binder source or the job mix formula changed.

The Red Bluff and Weed projects were successfully completed in 2012 (*20*). The Dixon project started paving in 2013 and will be completed in 2014.

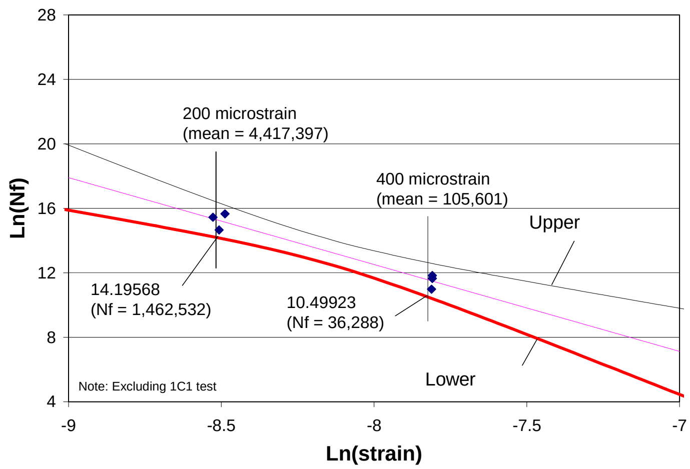

FIGURE 1 Fatigue 95% confidence band, PG 64-10, 25% RAP with lime [AC = 5.38% (by weight of virgin aggregate); AV = 6.0%].

Challenges

A number of challenges were encountered on these three projects, including:

1. Selection of baseline material to develop specifications that are locally achievable but get the best performance possible at the lowest cost.
2. Communication of what specifications mean to potential bidders.
3. Procurement of representative local materials for design properties, especially RAP.
4. Writing of PBSs, description of reliability and statement of quality requirements for different layers, and relationship to expected distress modes.
5. Communication of specification language to district materials engineers for writing of final specifications and bid package, and district construction engineers for administration of the process, including:
   – Mix properties with respect to distress modes,
   – Reliability, and
   – Reasons for selection of air-void contents for each material and test.
6. Procurement of lab testing services.
7. Comparison of laboratories for performance-related tests not included in AMRL (auditable reference testing system). A similar challenge has just been experienced with tests using the AMPT testing device.
8. Assistance in advising contractor during mix design with regard to
   – Producing specimens;
   – What tests mean and dealing with variability;
   – Performance-based mix design considering sensitivity of rutting, fatigue, and stiffness to changes in mix; and
   – Meeting values for conventional specifications at same time.

TABLE 2 Asphalt Mix PBSs for Red Bluff Project

Design Parameters	Test Method	Requirement
Permanent deformation (min.) PG 64-28PM (with lime)[a] PG 64-10 (with RAP and lime)[b]	AASHTO T 320 modified[c]	360,000 stress repetitions[d,e] 360,000 stress repetitions[d,e]
Fatigue (min.) PG 64-28PM (with lime)[f,g] PG 64-10 (with RAP and lime)[h,i] PG 64-10 RB[j] (with lime)[k,l]	AASHTO T 321 modified[c]	23,000,000[e,m] 345,000,000[e,n] 25,000 repetitions[e,m] 950,000 repetitions[e,n] 182,000 repetitions[e,m] 2,700,000 repetitions[e,n]
PG 64-10 (with RAP and lime)	AASHTO T 324 modified[c]	20,000 repetitions[o]

NOTE: min. = minimum.
[a] At proposed asphalt binder content (mix containing 1.2% lime) and with mix compacted to 3%+/-0.3% air voids.
[b] At proposed asphalt binder content (mix containing RAP and 1.2% lime) and with mix compacted to 3%+/-0.3% air voids.
[c] Included in the testing procedure, LLP-AC1 (rolling wheel compaction): Sample Preparation and Testing for I-710–Long-Life HMA.
[d] In repeated simple shear test at constant height (RSST-CH) at a temperature of 55°C at 100kPa.
[e] Minimum test value measured from tests on three specimens.
[f] At proposed asphalt binder content (mix containing 1.2% lime) and with mix compacted to 6%+/-0.3% air voids [determined using AASHTO 209 (Method A)].
[g] At proposed asphalt binder content, the average mix stiffness at 20°C and a 10 Hz load frequency must be in the range 2,859–3,349 MPa (415,000–486,000 psi). At proposed asphalt binder content, the minimum stiffness at 30°C and a 10 Hz load frequency must be equal to or greater than 1,516 MPa (220,000 psi).
[h] At proposed asphalt binder content (mix containing RAP and 1.2% lime) and with mix compacted to 6%+/-0.3% air voids (determined using AASHTO 209 [Method A])
[i] At proposed asphalt binder content (mix containing RAP and 1.2% lime), average stiffness at 20°C and a 10 Hz load frequency must be in the range 5,589–6,890 MPa (870,000–1,000,000 psi).
[j] The RB mix contains the same binder as the mix with RAP, i.e., the PG 64-10; the binder content of this mix is increased 0.5% (mix basis) above the binder content used for the mix containing RAP.
[k] At proposed asphalt binder content (mix containing 1.2% lime) and with mix compacted to 3%+/-0.3% air voids [determined using AASHTO 209 (Method A)].
[l] At proposed asphalt binder content (with 1.2% lime), average stiffness at 20°C and a 10 Hz load frequency must be in the range 5,443–6,890 MPa (790,000–1,000,000 psi.)
[m] At 400 x 10^{-6} strain, results shall be reported for this strain level but may be obtained by extrapolation. Minimum number of repetitions required prior to extrapolation defined within test procedure.
[n] At 200 x 10^{-6} strain, results shall be reported for this strain level but may be obtained by extrapolation. Minimum number of repetitions required prior to extrapolation defined within test procedure.
[o] Minimum number of repetitions for rut depth of 12.5 mm (0.5 in.) at 50°C (average of two specimens).

9. Performance-related testing values for laboratory versus plant produced mix.
10. Schedule pressures and time to perform performance-related tests.
11. Consideration of interaction of stiffness and fatigue test values from actual material on predicted structural life if materials exceeded one property by a wide margin but missed other property.

APPROACHES AND PROPOSED ALTERNATIVES TO DEAL WITH CHALLENGES

The approach used to meet the challenges listed in the previous section, or in some cases ideas for how to improve the PBS–ME design process are briefly discussed in this section.

Challenge 1

To obtain a better idea of what is available in the region, Caltrans–UCPRC will likely continue testing of more materials to establish regional databases. There is discussion internally and with the state industry association (CalAPA) regarding how high to set the bar within locally available materials. Experience to date shows that explicitly setting mechanistic properties will result in mix design changes that will improve those properties, while under the old system those properties were unknown for the materials purchased by the state.

Challenge 2

Considering the many alternatives for aggregate in a geologically diverse state and multiple (although diminishing) sources of binder, Caltrans and industry are working to provide more explicit direction to contractors prior to bidding, particularly to address major gaps in common knowledge in a low-bid system. For example, a statement similar to this may be included on a slide in the pre-bid meeting: "Binder source for a given PG grade can possibly have a large influence on the ability of HMA to meet stiffness and fatigue specification requirements. The PG specification only controls binder properties at the high and low temperatures, not the temperatures in between, and does not address fatigue."

Similarly, information will be provided regarding the improvement in chances of meeting stiffness and rutting requirements when using 100% crushed (>2 faces) coarse and fine aggregates. Getting the message out through industry/Caltrans meetings is also underway based on lessons learned from these three projects.

Bidders/contractors generally didn't seem to understand the "seriousness or severity" of the PBS requirements, and had no idea when preparing paving schedules whether mixes previously accepted by the state based on Hveem mix design would meet PBS by the date assumed. This became critical in project management after award of the contract more due to time constraints of changing plant operations and then testing time from iterations on the mix design rather than the cost of testing.

Challenges 1 and 2 Combined

Possible solutions to Challenges 1 and 2 combined that might be considered are

1. Set the bar low, designing the structure for the properties of the locally available materials that result in the thickest pavement. The result would be that if a material is delivered that exceed those requirements, Caltrans would be getting longer life, but paying a higher initial cost. This can also result in other problems, such as longer construction periods and issues with bridges, ramps, rails and other nonpavement infrastructure due to thicker sections.

2. Set the bar higher, but set up a pre-qualification process with shared cost between contractors and agencies so that contractors can get materials tested before preparing to bid and prepare informed bids.

Challenge 3

Obtaining regionally representative materials in a DBB environment for laboratory testing to establish mechanistic properties for design presented some challenges, but designers relied primarily on the experience of district materials engineers. Use of design properties from other regions is much more problematical. It was much easier to identify the effects of RAP on mix properties when the RAP samples could be milled from the existing project by district forces. On projects where the RAP was not coming from the existing pavement, obtaining representative RAP samples is more difficult, and there is risk for both the contractor and the state if RAP used is particularly different.

Overall, it is expected that as the effort to expand regional databases of properties continues there will be less need to do as much pre-testing for design (*21*). It is anticipated that contractors will become more aware of the properties of their mixes, and if there is sufficient opportunity to bid on and win PBS–ME projects this will incentivize innovation, the "if" condition being critical.

Challenge 4

Attention needs to be given to the testing and specification of properties for the polymer modified layer for top-down cracking. A bigger issue is that the current approach of specifying huge numbers of required repetitions based on extrapolation of results from reasonable testing times and load repetitions for fatigue and rutting repeated load tests to specified limits initially caused consternation on the part of both contractors and district engineers. The approach used for the Caltrans specifications is described in Caltrans' "Sample Preparation and Testing for Long-Life Asphalt Concrete Pavements" (*17*). It is also known that 50% loss of stiffness is a conservative criteria for many polymer- and rubber-modified binder mixes, and estimation of cracking initiation or some other "failure" criteria, as well as extrapolation is an area of additional investigation on the part of various researchers, as is discussed in Anderson et al. and Souliman et al. (*22*, *23*) which compare methods developed by Rowe, Franken, Hopman, Ghuzlan and Carpenter, and Pronk as well as a more recent comparison by Rowe et al (*24*). *CalME* uses a damage function fit to the entire damage curve from the test in incremental-recursive analysis, and 50% loss of stiffness is only used for specification. A better parameter for specification of fatigue and to a lesser extent rutting, based on the damage curves, needs to be developed.

Based on discussions of the Netherlands approach and other ideas at the recent 4-Point Bending Conference, a new simpler approach for classifying materials based on the three performance tests is also being considered. The approach would require a critical mass of projects (dollars and numbers of projects) each year over a 5-year or longer period, for contractors to justify the cost of testing, and for commercial laboratories to consider developing equipment and human resources. In this system there would be categories of performance for rutting [repeated load triaxial (RLT) or RSST], fatigue (flexural fatigue) and stiffness (flexural or compressive). Results for repeated load tests would be based on the log of the repetitions to failure to produce a linear scale of loss of stiffness for fatigue and permanent strain for RLT or RSST. How to handle two strains for fatigue needs to be determined, or a single point might be used, such as the strain that results in 1 million load cycles used in the Netherlands. On the order of five to 10 categories might be considered. A mix may then have an A through J category for fatigue, 1 through 10 for rutting, and a through j for stiffness.

Contractors could then test their current most used mixes in advance, and know whether their mix will meet the specifications, or be close enough that they can reasonably adjust the mix design to meet them. Designers would use regional materials in the ME analysis for several mix types that should be available in the region, such as an E2f or an F3e, and determine the mixes that will provide at least the minimum required performance in the specific structural design. While considering allowable differences in grade elevations for rehabilitation projects, alternative designs with different materials might be prepared for design by the state.

Challenge 5

Interaction between headquarters and the district for each project has been found to be the best way to communicate the intent and requirements of the PBS. Some prior training may be useful for basic background, but the experience of working through a first project with assistance is invaluable. Having sufficient headquarters resources to answer questions and address problems as they arise is critical.

Challenge 6

As mentioned previously, for the laboratory testing to be moved from research laboratories to commercial or even contractor laboratories will require a multiyear commitment of enough projects to amortize the equipment and recoup the investment in human resources with a profit. Concern about whether equipment manufacturers will or can produce equipment and provide long-term service at affordable prices is also an issue. For this reason, the recent wave of investment in AMPT equipment is leading to consideration of moving to RLT testing for rutting with that device, not because the RSST is not an excellent test (and can test field cores), but because it does not have a critical mass of numbers of deployed devices. There is a concern on the part of California that initial enthusiasm for the AMPT may wane, as it did for the RSST.

Challenge 7

Certification of any repeated load testing equipment will be an issue. Quality control procedures are available, such as standard materials with known properties (developed after SHRP for SST and flexural devices), as is round robin testing of the same materials. These again need a critical mass of projects and laboratories to be worthwhile. Based on experience comparing RSST results with the University of Nevada, Reno, for the Red Bluff project, and recently completing a round robin comparison of flow number and dynamic modulus results (AMPT) with three laboratories for NCHRP 9-52 shows that there will need to be clarification of steps and procedures in test methods as a part of this process.

Challenge 8

Production of rolling wheel core and beam specimens using the Caltrans method (*17*) was not found to be a problem using contractor built molds at the plants. Contractor training of their staff to strictly follow the specimen preparation process eliminated most problems. Similar experience has been found with Superpave gyratory specimens for RLT.

Although contractors have extensive experience with Hveem, and are learning Superpave volumetric mix design, there is not much experience balancing sometimes opposing specific performance related properties, namely fatigue and rutting. Applying in practice the "theoretical" ideas that most contractors are familiar with for balancing mix design to achieve these requirements requires additional experience. Working with contractor staff on the three recent projects showed that in a relatively short time that this experience was obtained. Having an experienced consultant (mix design and plant operations) for guidance and assistance communicating with the state also seemed to be helpful to the contractors.

Challenge 9

The time and materials required to produce plant mixed materials are considerable. However, for several mixes there was a notable difference between the properties from the plant and laboratory produced mixes. Although an exact cause was not determined, indications were that interactions of the lime treatment and mixing may have played a role, as well as binder aging. This challenge will require more investigation; however, the state wants to reduce its risk by requiring that final acceptance be based on plant mixed material which can add a significant amount of time to the testing process.

Challenge 10

It is apparent that Caltrans–UCPRC working with industry needs to improve the specifications and acceptance process, while maintaining the shared commitment to achieving the benefits of PBSs combined with ME design, or else there will not be future bidders. Going up the learning curve noted in this process, while faced with the schedule delays and cost of adjusting a mix to meet PBSs for the first time is a stressful experience that few contractors would want to repeat. The requirement that plant produced mix is used to pass the specification, and the length of time for low strain fatigue testing, were found to be the largest contributors to the schedule. Making adjustments to balance shear, fatigue, and laboratory compaction (three decision-making variables instead of just adjusting binder content) was the biggest mix design issue. The proposed specification scheme (Challenge 4), where contractors would test their mixes prior to bidding, is intended to help address this. However, few contractors at this time would be willing to go through that relatively expensive testing process without having already won the contract. The taking on of some additional risk by the owner by some reductions in the amount of fatigue testing, or increasing the strain levels, is one alternative that is being considered.

Because of schedule constraints for the flexural and shear tests used for acceptance of the mix design, quality control and assurance during construction relies on standard tests including checking of the job-mix formula proportions and standard aggregate and mix tests. Rapid tests that can be performed in the field and that are reasonably well calibrated with the repeated load tests used for design and mix acceptance are currently being investigated for Caltrans by the UCPRC and corresponding researchers (*25*).

Challenge 11

Different combinations of stiffness and fatigue behavior will produce a structure that meets the design fatigue requirements for a given project. In addition to providing a more transparent specification framework for contractors, the proposal described for Challenge 4 is intended to provide more flexibility for designers to consider alternative combinations of these properties.

CONCLUSIONS AND RECOMMENDATIONS

PBSs and ME designs provide a means to produce materials and designs that reduce life-cycle cost for the state, and a framework for competitive innovation to "raise the bar" for contractors and materials producers. Challenges have been identified, many particular to the DBB project delivery method, and lessons learned from the three projects described in this paper. These should result in changes to the current process to reduce risk for contractors and the state, and particularly to improve transparency and understanding of what they need to do to be successful for contractors.

It is recommended that Caltrans, industry, and academia work together, as they have in the past in California, to meet these challenges.

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Implementation of Performance-Based Specifications for Asphalt Mix Design and Production Quality Control for New Jersey

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Recently, the New Jersey Department of Transportation (DOT) has focused almost all of their pavement construction efforts towards pavement rehabilitation. This is not due to the lack of a need for more and larger roadways, but simply due to the fact that available space to construct new pavements is lacking in the most densely populated state in the United States. Therefore, a significant portion of the New Jersey DOT's pavement budget is allocated towards rehabilitating and maintaining its current transportation infrastructure. Unfortunately, in recent years, the New Jersey DOT has realized they are not getting the return on their investment as they had hoped. Current pavement rehabilitation efforts have resulted in pavement lives of approximately one-half of their intended design life. The primary distress found among most of the asphalt pavements in New Jersey is longitudinal cracking. Most of the asphalt mixtures placed in New Jersey are lean on asphalt content, resulting in stiff asphalt mixtures that cause issues with compaction and inevitably result in durability problems. In some cases, the issue can be classified as "…the wrong mix for the wrong application". And to make the matters worse, the New Jersey DOT has been continually under pressure by the asphalt industry to increase the amount of RAP utilized in their asphalt mixtures. Until recently, the New Jersey DOT has worried that the addition of recycled asphalt pavement (RAP) into already lean asphalt mixtures may result in pavement lives even shorter than what the New Jersey DOT is currently experiencing.

To help improve the performance of the asphalt mixtures being placed on New Jersey roadways, the New Jersey DOT has developed a Performance-Based Mixture Design and Quality Control program. The basis of the program is to "engineer" asphalt mixtures for specific performance needs. For example, general maintenance mixtures require lesser performance than asphalt mixtures placed on composite pavements or bridge deck overlays where horizontal and vertical movements are much greater. Therefore, the asphalt mixtures to be placed on these structures will have different asphalt contents, asphalt binder types, volumetric targets and even different levels of performance requirements. This approach is a drastic improvement over the current mentality that the same asphalt mixture can be placed on all applications and be expected to perform as intended.

NEW JERSEY DEPARTMENT OF TRANSPORTATION'S PERFORMANCE-BASED ACCEPTANCE PROCEDURE

The New Jersey DOT has established a general acceptance procedure that the asphalt plants–contractors are required to follow to be allowed to produce and place their respective performance-based asphalt mixture. The general procedure is as follows:

1. Step 1 requires that the asphalt plant conduct a volumetric design using the proposed materials and mixture design specifications. After the asphalt plant has successfully conducted their own volumetric design, the New Jersey DOT Regional Offices verify the volumetrics at their laboratory. Once the volumetrics have been verified and the constituents (aggregates and asphalt binder) of the asphalt mixture have been approved, the asphalt plant–contractor is allowed to proceed to Step 2.
2. In Step 2, the asphalt plant–contractor must submit either laboratory prepared loose mix or the virgin materials to a laboratory approved by the New Jersey DOT Bureau of Materials. The laboratory will then prepare the required test specimens for the respective performance tests. If the test specimens meet the specified performance criteria, the asphalt plant–contractor is then allowed to move to Step 3. Otherwise, the mixture must be redesigned.
3. In Step 3, the asphalt plant–contractor must produce the mixture through the asphalt plant and construct a test strip. The location of the test strip is preferred to be close to the actual location of construction (i.e., shoulder area), but it is at the discretion of the contractor as long as it is approved by the New Jersey DOT. Loose mix used to produce the test strip is sampled and supplied to a laboratory approved by the New Jersey DOT Bureau of Materials. The same test procedure and performance criteria from Step 2 must again be met with the plant produced material. If the test specimens fail, the asphalt plant–contractor must again produce the mixture through the plant and construct another test strip, essentially repeating Step 3 until the mixture passes the performance criteria established. Once the test strip material passes the loose mix criteria, the asphalt plant–contractor is allowed to produce and place the material on the project.
4. In Step 4, the contractor must sample material during production for continued performance testing to ensure the mixture properties still meet the required specifications. The frequency of sampling is dependent on the respective performance-based mixture being produced, as well as the quantity.

Three different hot-mix asphalt (HMA) performance test methods are utilized to test the performance-based mixtures in New Jersey. In most cases, both rutting and fatigue cracking are evaluated using one of the following test procedures:

- Asphalt pavement analyzer (APA) (AASHTO T 340: Determining Rutting Susceptibility of Hot-Mix Asphalt Using the Asphalt Pavement Analyzer);
- Flexural beam fatigue (AASHTO T 321: Determining the Fatigue Life of Compacted Hot-Mix Asphalt Subjected to Repeated Flexural Bending); and
- Overlay tester (Texas DOT TEX 248-F: Test Method for the Overlay Test).

The type of fatigue test utilized is dependent on whether the mode of cracking is dependent on the flexural properties of the pavement or the expansion–contraction of Portland cement concrete (PCC) slabs.

PERFORMANCE-BASED ASPHALT MIXTURES: SPECIFICATIONS AND FIELD INSTALLATION

Currently, the New Jersey DOT has five performance-based asphalt mixtures that require the testing and protocols previously mentioned. These five mixtures include:

1. High-performance thin overlay (HPTO);
2. Binder-rich intermediate course (BRIC);
3. Bridge deck waterproofing surface course (BDWSC);
4. Bottom-rich base course (BRBC); and
5. High RAP (HRAP).

Each one of these mixtures is explained in detail in the following sections.

High-Performance Thin Overlay

By Superpave® definition, the New Jersey DOT's HPTO is a fine-graded, 9.5-mm nominal maximum aggregate size (NMAS) mixture. The HPTO is used as a rut-resistant–durable thin lift mixture for maintenance–pavement preservation applications, as well as a superior leveling course when extended staging time is expected. When small quantities are needed (<100 mix tons), the HPTO has also been used for overlays on top of bridge decks. The required aggregate blend gradation, minimum asphalt content, and design–production volumetric requirements are shown in Tables 1 and 2. The HPTO requires the use of a polymer-modified PG 76-22 asphalt binder and the addition of natural sand or RAP is not allowed.

Rutting performance testing, using the APA, is required during mixture design, test strip production, and mainline production for the HPTO. For acceptance, the HPTO must achieve a maximum of 4.0 mm of rutting at 8,000 loading cycles in the APA at testing conditions of 64°C, 100-psi hose pressure, and 100-lb wheel loads.

HPTO Field Implementation: Interstate 287 Southbound

An example of the application and performance of New Jersey DOT's HPTO can be found on I-287 Southbound between mileposts 30.2 and 35.5. The full-depth asphalt pavement in that area carries

TABLE 1 Aggregate Blend Gradation of New Jersey DOT's HPTO

Sieve Size	Percent Passing by Mass
3/8 in.	100
#4	65–85
#8	33–55
#16	20–35
#30	15–30
#50	10–20
#100	5–15
#200	5.0–8.0
Minimum percent asphalt by mass of total mix	7.0

TABLE 2 Volumetric Requirements for New Jersey DOT's HPTO

	Required Density (% of Gmm)		Voids in Mineral Aggregate (VMA)	Dust-to-Binder Ratio	Draindown AASHTO T 305
	N_{des} (50 gyr)	N_{max} (100 gyr)			
Design requirements	96.5	≤99.0	≥18.0 %	0.6–1.2	≤0.1 %
Control requirements	95.5–97.5	≤99.0	≥18.0 %	0.6–1.3	≤0.1 %

approximately 44 million equivalent single axle loads (ESALs). In 2008, the pavement distress survey conducted within the New Jersey DOT's pavement management program identified milepost section 30.2 to 35.5 southbound as having a structural distress index (SDI) of 1.7 (with 0 being worst and 5 being the best condition), triggering a rehabilitation requirement (Figure 1). The primary distress associated was top-down, longitudinal fatigue cracking. It should be noted that the distressed overlay (from a mill 2 in./pave 2 in. application) had lasted 8 years.

A field forensic program identified that a 1-in. mill could be utilized to limit the amount of RAP produced on the job while eliminating the top-down cracking and crack sealer previously used to seal the exposed cracking. After milling, a 1-in. HPTO overlay was applied to help improve the cracking resistance along this section of I-287. The HPTO was placed after a hot PG 64-22 tack coat was applied to ensure sufficient bonding to the milled surface was achieved.

Additional SDI testing and analysis was conducted in 2010 and 2012 and shown in Figure 1. The SDI results, 1.5 and 3.5 years after the HPTO was placed, show that the current HPTO application is performing exceptionally well with an SDI = 3.9 and has not changed since construction.

Binder-Rich Intermediate Course

The main use of New Jersey DOT's BRIC is for placement over existing PCC and at the bottom of an HMA overlay to aid in minimizing reflective cracking of the HMA overlay due to horizontal and vertical movements at the PCC joint–crack due to environmental and traffic loading. The BRIC is a 4.75 NMAS mixture consisting of the aggregate gradation shown in Table 3 and a minimum asphalt content of 7.0%. The grade of asphalt binder is required to be at least a PG 70-28. Additional volumetric requirements for design and during production are shown in Table 4. New Jersey DOT's BRIC mixture was adapted from the crack attenuating mixture (CAM) developed and used by the Texas DOT.

In the past, the New Jersey DOT has never specified the use of a PG 70-28 asphalt binder. However, during initial research studies to evaluate its possible use, it was found that the PG 70-28 asphalt binder performed better than PG 64-22 and PG 76-22, two commonly used asphalt binder grades in New Jersey, in both the flexural beam fatigue (AASHTO T321), which simulates vertical deflection at the PCC joint–crack due to traffic loading, and the overlay tester (Texas DOT TEX 248F), which simulates horizontal movement at the PCC joint–crack due to environmental–temperature cycling (*1*). Examples of test results generated during these studies are shown in Figures 2 and 3. The test results also confirm the results reported by Bennert and Maher (*2*) regarding better fatigue resistance through the use of asphalt binders with lower low-temperature PG grades.

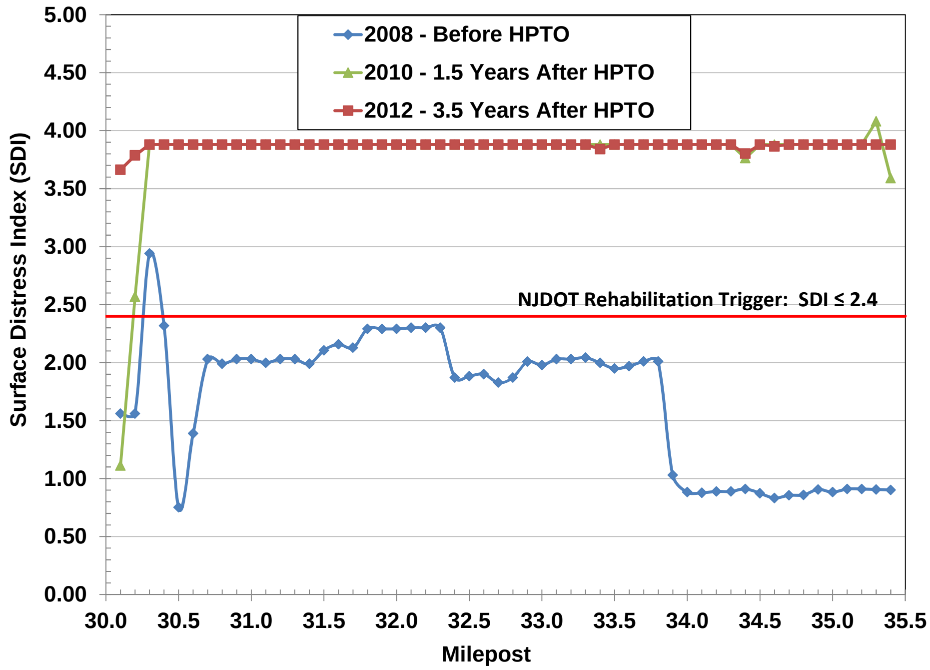


FIGURE 1 SDI for before and after HPTO application on I-287 in New Jersey.

TABLE 3 Aggregate Blend Gradation of New Jersey DOT's BRIC

Sieve Size	Percent Passing by Mass
3/8 in.	100
#4	90–100
#8	55–90
#30	20–55
#200	4.0–10.0
Minimum percent asphalt by mass of total mix	7.0

TABLE 4 Volumetric Requirements for New Jersey DOT's BRIC

	Required Density (% of Gmm)		Voids in Mineral Aggregate (VMA)	Dust-to-Binder Ratio	Draindown AASHTO T 305
	N_{des} (50 gyr)	N_{max} (100 gyr)			
Design requirements	97.5	≤99.0	≥18.0%	0.6–1.2	≤0.1%
Control requirements	96.5–98.5	≤99.0	≥18.0%	0.6–1.3	≤0.1%

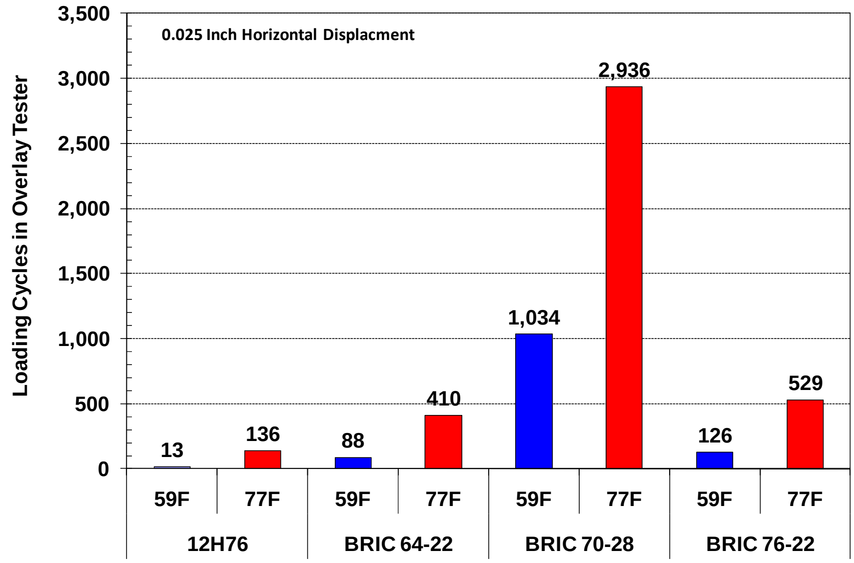


FIGURE 2 Overlay tester results for New Jersey DOT BRIC mixture with different PG-graded asphalt binders.

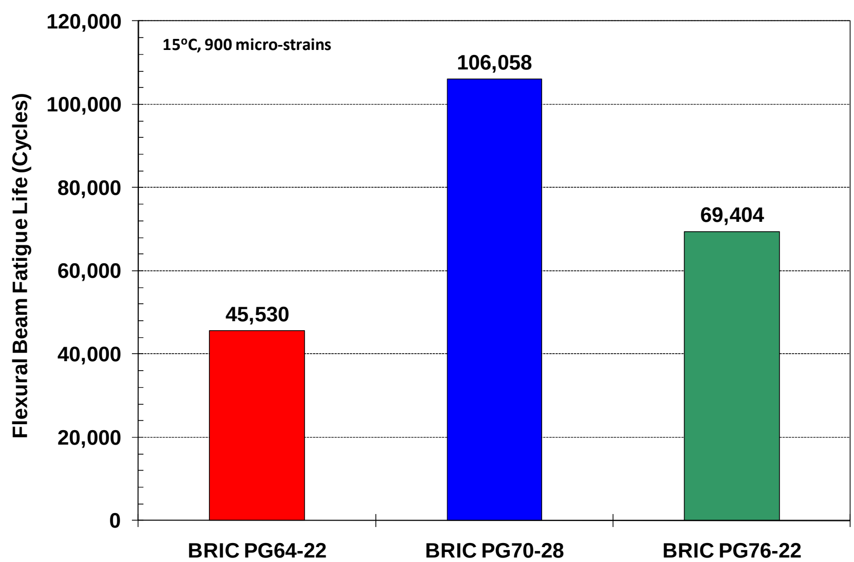


FIGURE 3 Flexural beam fatigue results of New Jersey DOT's BRIC mixture with different PG graded asphalt binders.

To verify the performance of the BRIC, the mixture is required to be evaluated for rutting performance using the APA (AASHTO T 340) and cracking resistance using the Overlay Tester (Texas DOT TEX 248F). The performance requirements for the mixture design, test strip, and production material are as follows:

- APA (AASHTO T 340):

- 64°C, 100-lb wheel load, 100-psi hose pressure, and
- Maximum rut depth of 6.0 mm @ 8,000 loading cycles;
- Overlay tester (Texas DOT TEX 248F):
  - 25°C test temperature, 0.025-in. horizontal displacement, 10-s loading frequency and
  - Minimum of 700 cycles.

It should also be noted that the New Jersey DOT is implementing the use of the BRIC mixture with a SMA being placed over it. This is to ensure that a fatigue resistant asphalt mixture can withstand residual vertical and horizontal movement not "absorbed" by the BRIC mixture. The placement of stiff asphalt mixtures above or below a highly crack resistant mixture often results in a "crack jumping" phenomenon, where a crack forms above, and sometimes below, the more flexible mixture (Figure 4).

Bridge Deck Waterproofing Surface Course

The main purpose of New Jersey DOT's BDWSC is to provide a rut and fatigue resistant and impermeable bridge deck overlay that can be placed using static compaction techniques. With an aging infrastructure, the New Jersey DOT does not allow the use of vibratory compaction techniques when placing asphalt overlays on bridge decks. This has resulted in numerous bridge deck overlays compacted to low densities, creating a highly porous bridge deck overlay. Past

FIGURE 4 Cracking above and below a highly fatigue resistant mixture.

attempts using an asphalt-treated membrane has not improved the general performance of the overlay, as infiltrated water has usually found a pathway to the bridge deck.

Since 2008, the New Jersey DOT has implemented the use of a BDWSC asphalt mixture to overlay and preserve its bridge decks. The BDWSC is a 9.5-mm NMAS, highly modified asphalt mixture purposely designed for low permeability. Tables 5 and 6 shows the aggregate blend gradation and minimum asphalt content of the BDWSC and design and production volumetrics of the BDWSC, respectively.

According to the specifications, the mixtures are recommended to be modified using either a polymer-modified asphalt binder or a concentrated thermoplastic–polymeric asphalt modifier. The specification does not provide a PG grade recommendation as the mixture performance dictates final acceptance of the BDWSC.

Performance verification testing of the BDWSC consists of rutting potential measured in the APA (AASHTO T 340) and fatigue cracking resistance measured in the flexural beam fatigue (AASHTO T 321). The performance requirements for the mixture design, test strip, and production material are as follows:

- APA (AASHTO T 340):
  - 64°C, 100-lb wheel load, 100-psi hose pressure and

TABLE 5 Aggregate Blend Gradation of New Jersey DOT's BDWSC

Sieve Size	Percent Passing by Mass
1/2 in.	100
3/8 in.	80–100
#4	55–85
#8	32–42
#16	20–30
#30	12–20
#50	7–16
#100	3–12
#200	2.0–6.0
Minimum percent asphalt by mass of total mix	7.0

TABLE 6 Volumetric Requirements for New Jersey DOT's BDWSC

	Required Density (% of Gmm): N_{des} (50 gyr)	Voids in Mineral Aggregate (VMA)	Dust-to-Binder Ratio	Draindown AASHTO T 305
Design requirements	99	≥18.0 %	0.3–0.9	≤0.1 %
Control requirements	98–100	≥18.0 %	0.3–0.9	≤0.1 %

  - Maximum rut depth of 3.0 mm @ 8,000 loading cycles;
- Flexural beam fatigue (AASHTO T 321):
  - 15°C test temperature, 10-Hz frequency, sinusoidal waveform, 1,500 micro-strains and
  - Minimum of 100,000 cycles.

During construction, the BDWSC specification states to ensure that the paving surface is clean and apply the tack coat using the same tack coat material as required for the adjacent roadway paving on the Project. However, for steel deck applications, the tack coat application of a hot, PG 76-22 with a sand "grit" to help reduce the potential of the BDWSC from sliding and shoving is recommended.

BDWSC Implementation: Rt. 80 ACROW Bridge

In November 2009, the New Jersey DOT constructed and overlaid a temporary overpass–bridge on Rt. 80 (Figure 5). The steel paneled bridge deck was originally overlaid with 2.5 to 3.5 in. of a 12.5-mm Superpave mixture with a PG 76-22 asphalt binder. The bridge was open to westbound traffic on March 26, 2010. Within 2 weeks after the bridge was open to traffic, the New Jersey DOT's contractor began patching the HMA due to excessive and rapid deterioration from cracking and shoving (Figure 6).

Approximately 1 1/2 months after the asphalt overlay was opened to traffic, it was removed due to excessive failures and repeated patching. It was determined that the BDWSC would be placed on the ACROW bridge deck using a PG 76-22 asphalt binder as a tack coat and sand broadcasted onto the tacked steel panels to help mitigate potential sliding. The asphalt supplier had a preapproved BDWSC mixture design, and therefore, only needed to have material supplied during construction. Test results indicated average flexural beam fatigue and APA to be 163,000 cycles and 1.8 mm of APA rutting, respectively. It should be noted that at the time of this project, the New Jersey DOT was utilizing a flexural beam fatigue strain level of 2,000 microstrains, instead of the current 1,500 microstrains.

After construction, the westbound side was immediately opened to traffic. After approximately 7.5 months of traffic and zero distress, the lanes were shifted and the eastbound side of Rt. 80 was open to traffic. An additional 6 months of trafficking resulted in again no distresses on the temporary bridge overlay. After approximately 1.5 years of service, the temporary bridge was removed with the bridge deck mixture looking as it had been originally placed (Figure 7).

Bottom-Rich Base Course

The main purpose of New Jersey DOT's BRBC is to provide a fatigue-resistant base course mixture that would allow for the design and performance of a perpetual pavement. In the classical perpetual pavement design (Figure 8), a flexible fatigue resistant base course mixture is constructed at the bottom of the asphalt layer to provide adequate resistance from bottom-up cracking. The aggregate gradation, shown in Table 7, is consistent with New Jersey DOT's 19-mm Superpave specification. However, the target volumetrics and design gyration level are modified in order to produce a mixture with a higher asphalt content than normally contained

FIGURE 5 Steel deck ACROW bridge on Rt. 80 in New Jersey.

FIGURE 6 Patching of rapid deterioration on Rt. 80 ACROW bridge in New Jersey.

FIGURE 7 Rt. 80 ACROW bridge with New Jersey DOT's BDWSC asphalt overlay.

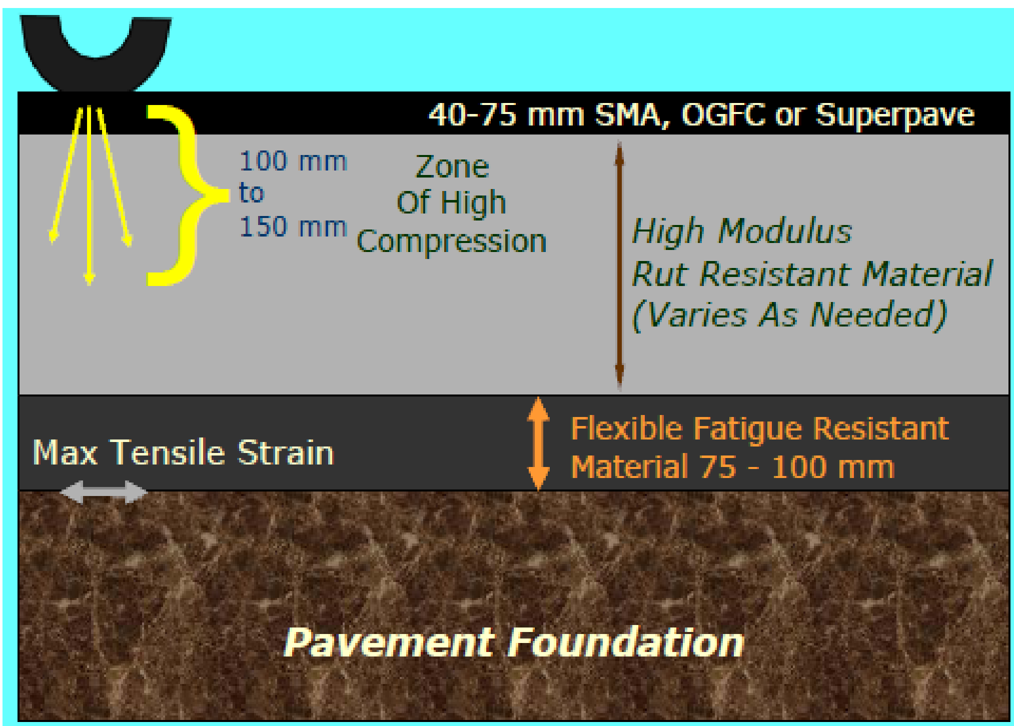


FIGURE 8 General schematic of a perpetual asphalt pavement (*3*).

in New Jersey DOT's 19-mm Superpave mixtures (Table 8). The specification recommends an asphalt binder PG grade of a PG 76-28, although similar to the BDWSC, it is the final mixture performance of the BRBC that dictates its acceptance or not. Other asphalt binder grades are allowed if the required mixture performance criteria are achieved.

The performance tests and criteria for New Jersey DOT's BRBC are as follows:

- APA (AASHTO T 340):
  - 64°C, 100-lb wheel load, 100-psi hose pressure and
  - Maximum rut depth of 5.0 mm @ 8,000 loading cycles;
- Flexural beam fatigue (AASHTO T 321):
  - 15°C test temperature, 10-Hz frequency, sinusoidal waveform,
  - Minimum of six test specimens (three tested at 400 microstrains and three tested at 800 microstrains, in accordance with NCHRP Project 9-38), and
  - Minimum of 100,000,000 cycles @ 100 microstrains as determined using the method developed under NCHRP Project 9-38.

BRBC Implementation: Interstate 295

The New Jersey DOT first implemented the BRBC on I-295 during the summer of 2010. The pavement consisted of a highly deteriorated PCC pavement that was long overdue for reconstruction. To alleviate future issues with reflective cracking in a composite pavement, the New Jersey DOT decided to rubblize the PCC pavement and apply an asphalt overlay. Initial pavement designs using the 1993 DARWIN pavement design system recommended an asphalt thickness of approximately 12 in. thick. Unfortunately, an HMA layer thickness of 12 in. would

TABLE 7 Aggregate Blend Gradation of New Jersey DOT's BRBC

Sieve Size	Percent Passing by Mass
1 in.	100
3/4 in.	90–100
1/2 in.	–90
#8	23–49
#200	2.0–8.0
Minimum percent asphalt by mass of total mix	5.0

TABLE 8 Volumetric Requirements for New Jersey DOT's BRBC

	Required Density (% of Gmm) N_{des} (50 gyr)	Voids in Mineral Aggregate (VMA)	Dust-to-Binder Ratio	Draindown AASHTO T 305
Design requirements	96.5	≥13.5 %	0.6–1.2	≤0.1 %
Control requirements	95.5–97.5	≥13.5 %	0.6–1.2	≤0.1 %

require large undercut areas under the 20-something overpasses along I-295 to maintain existing clearance. Engineers at Rutgers University and the New Jersey DOT decided to utilize an elastic layer analysis program (JULEA) to evaluate the maximum tensile strains at the bottom of the HMA layer with varying asphalt layer thicknesses. It was determined through the sensitivity analysis that the HMA layer could be reduced to 8 in. while resulting in a maximum tensile strain at the bottom of the HMA layer of 82 microstrains (still below the endurance limit described earlier). The reduction in thickness would reduce the amount of HMA required for the project by one-third (170,000 tons) and eliminated 64,000 yd^2 of PCC pavement (PCCP) removal and undercutting. Therefore, the New Jersey DOT decided upon the final pavement structure as follows:

- Surface course: 2 in. of a SMA with a PG 76-22 asphalt binder;
- Intermediate course: 3 in. of a 19-mm dense-graded HMA (Superpave) with a PG 76-22 and 25% RAP; and
- Base course: 3 in. of New Jersey DOT BRBC.

Three HMA suppliers submitted mixture designs for the BRBC with varying success. One supplier was able to achieve the performance requirement with their first design while another supplier had to make three revisions in order to pass the mixture design performance testing phase. In all cases, it was found that the rutting criteria was easy to meet with the flexural fatigue requirement of 100,000,000 cycles at 100 microstrains [as determined using the methodology established by NCHRP Project 9-38 (*4*)] being the harder of the two to pass. An example of the graphical output of the NCHRP 9-38 analysis is shown in Figure 9. The graph shows the test results for production data of the BRBC and also the intermediate course, New Jersey DOT 19M76. The comparison of the results in Figure 9 indicates that the BRBC can achieve the 100,000,000 cycles at strain levels twice the magnitude of the New Jersey DOT 19M76. It should be noted that in most pavement structures in New Jersey, the "M" compaction level (75 gyrations) is commonly used for surface, intermediate and base course mixtures.

Unlike the other performance-based mixes that the New Jersey DOT uses, the performance testing required for the BRBC takes approximately 1 week to complete, as opposed to 2 days. This is due to the time required to complete the beam fatigue testing. Therefore, for production purposes, it was decided only to conduct flexural beam fatigue tests at the 800 microstrain level for all lots, except for Lot #1, where the full set of beam fatigue tests would be conducted. The assumption made was that the general slope of the fatigue life line shown in Figure 9 should not change dramatically due to slight changes with the asphalt mixture, only shift up or down based on the magnitude of the fatigue life measured at 400 and 800 microstrains. Therefore, if it is assumed that the slope will not deviate drastically, it can be concluded that as long as the fatigue life at 800 microstrains was equal to or greater than that achieved in Lot #1, the 400 microstrain level would not be required as the final extrapolated endurance limit would always be greater than the Lot #1 material. Only if the fatigue results at 800 microstrains were lower than those determined from Lot #1 would it require that the 400 microstrain testing be necessary.

Figure 10 shows the beam fatigue test results at 800 microstrains for the sampling intervals determined by the New Jersey DOT. The test results indicate that all lots produced after Lot #1 achieved the required level of fatigue performance. The figure also shows the superior fatigue resistance of the BRBC when compared to what is commonly utilized by the New Jersey DOT in their base course applications (19M76). Additionally, it should also be known that while achieving the required level of fatigue performance, the BRBC also maintained the required rutting resistance (Figure 11).

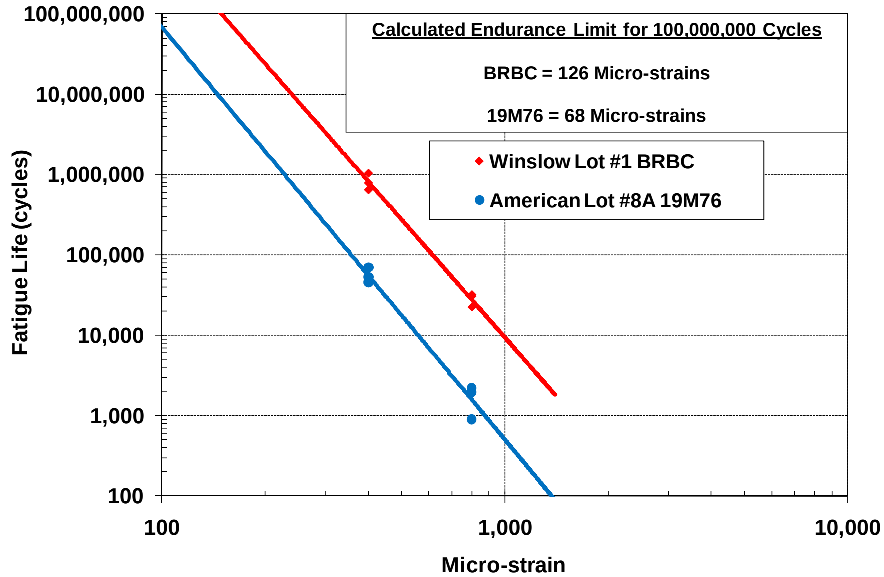


FIGURE 9 NCHRP 9-38 endurance limit graphical output.

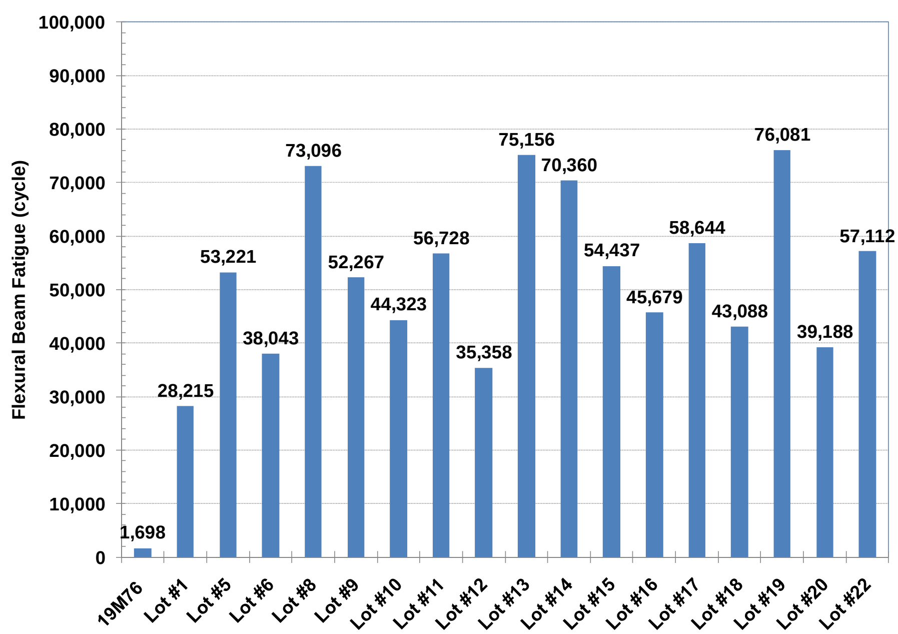


FIGURE 10 Flexural fatigue performance at 800 microstrains for New Jersey I-295 BRBC mixture.

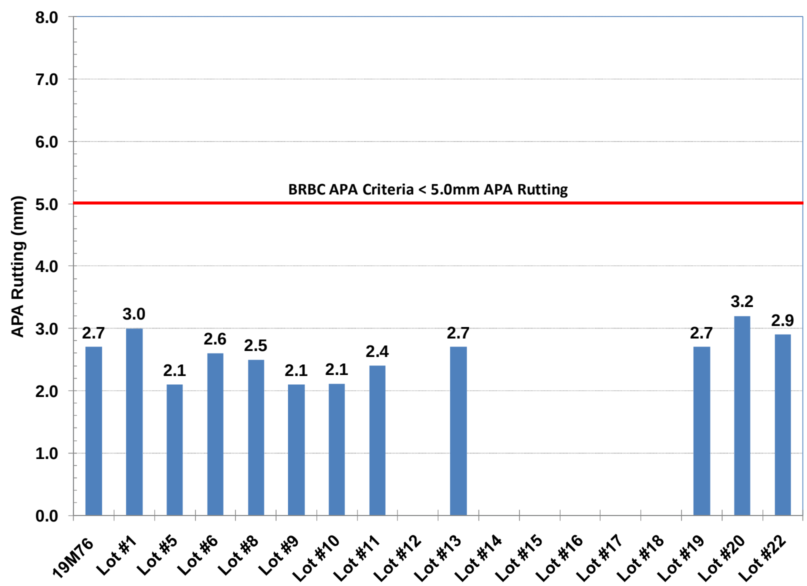


FIGURE 11 APA performance for New Jersey I-295 BRBC mixture.

High RAP

The benefit of utilizing a performance-based concept is that it puts the responsibility on the asphalt supplier to design and produce an asphalt product that meets the minimum requirements established by the state agency (*5*). In doing so, the asphalt supplier is also provided more flexibility on how to produce the asphalt mixture; in this case, high RAP mixes. Warm mix asphalt, rejuvenators, softer asphalt binders, and/or increasing asphalt content would be some of the possible "solutions" an asphalt supplier could utilize to produce higher RAP mixtures.

In 2012, the New Jersey DOT implemented a performance-based specification for HRAP mixes that requires the final mixture to meet a fatigue cracking and permanent deformation test. The HRAP specification does not include a maximum RAP content, but is governed by a minimum RAP content; 20% minimum in the surface, and 30% minimum in the intermediate and base layers. The performance testing encompasses passing a minimum number of fatigue cycles in the overlay tester (New Jersey DOT B-10) and a maximum rut depth in the APA (AASHTO T340). Table 9 shows the performance requirements associated with the HRAP specification. The criteria established in Table 9 are based on a database of virgin asphalt mixtures. Essentially, the New Jersey DOT HRAP specification says that if you can produce a high RAP mixture that performs as well as a virgin mix, than the New Jersey DOT will accept it.

As mentioned, the performance requirements are based on virgin mixtures, but the magnitude of the performance is also based on the application or need. For example, a surface course mixture to be placed on a heavy volume interstate would require less than 4.0 mm of rutting in the APA while achieving a minimum of 175 cycles in the overlay tester. However, for an intermediate or base mixture to be placed in a lower trafficked pavement, the APA requirement is lowered to less than 7.0 mm while only needing to achieve 100 cycles in the overlay tester. Therefore, the need for performance in the pavement dictates the required mixture performance in the laboratory.

Along with the performance testing requirements, slight adjustments were also made to the conventional asphalt mixture design volumetric properties in New Jersey. The volumetric requirements for the HRAP mixtures are shown in Table 10. All requirements are identical to conventional hot mix asphalt except for a 1% increase in the VMA. The same criteria are used for the production control, except the supplier is allowed to have compacted air voids of 95% to 98.5% of theoretical maximum specific gravity.

The performance acceptance testing for the HRAP specification is conducted at three separate time intervals: verifying mixture design, plant produced test strip (placed off the project limits), and plant produced and placed on project. At each time interval, the HRAP mixture must meet the performance criteria shown earlier in Table 9. Otherwise, the mixture has failed and either has to be produced again or a redesign must be conducted.

HRAP Implementation: I-295

The New Jersey DOT implemented the performance-based HRAP specification on a 2012 project on I-295 Southbound, milepost 11.26 to 14.48. The project required a New Jersey DOT 9.5M76 (9.5-mm NMAS, 75 design gyrations and a PG 76-22 asphalt binder) and a New Jersey DOT 12.5M64. The project required approximately 2,900 tons of the 9.5M76 and 1,800 tons of the 12.5M64.

In preparation for the mixture design and the production, the asphalt supplier fractionated their RAP into two stockpiles: coarse RAP (+ No. 4 sieve) and fine RAP (– No. 4 sieve). The

TABLE 9 HRAP Performance Requirements

Test	Requirement			
	Surface Course		Intermediate Course	
	PG 64-22	PG 76-22	PG 64-22	PG 76-22
APA @ 8,000 loading cycles (AASHTO T 340)	< 7 mm	< 4 mm	< 7 mm	< 4 mm
Overlay Tester (New Jersey DOT B-10)	> 150 cycles	> 175 cycles	> 100 cycles	> 125 cycles

TABLE 10 Design and Volumetric Requirements for New Jersey DOT's HRAP Mixtures

Compaction Levels	Required Density (% of theoretical max. specific gravity)		VMA[a] (% min.) NMAS (mm)					VFA (%)	Dust-to-Binder Ration
	@ N_{des}[b]	@ N_{max}	25.0	19.0	12.5	9.5	4.75		
L	96.0	≤98.0	13.0	14.0	15.0	16.0	17.0	70–85	0.6–1.2
M	96.0	≤98.0	13.0	14.0	15.0	16.0	17.0	65–85	0.6–1.2

NOTE: max. = maximum; VFA = voids filled with asphalt.

[a] For calculation of VMA, use bulk specific gravity of the combined aggregate including aggregate extracted from the RAP.

[b] As determined from the values for the maximum specific gravity of the mix and the bulk specific gravity of the compacted mixture. Maximum specific gravity of the mix is determined according to AASHTO T 209. Bulk specific gravity of the compacted mixture is determined according to AASHTO T 166. For verification, specimens must be between 95.0% and 97.0% of the maximum specific gravity at N_{des}.

fractionated stockpiles allowed for better control of the RAP and more precise use of the RAP binder. The fine RAP stockpile had an average asphalt content of 7.0%, while the coarse RAP stockpile had an average asphalt content of 3.7%. PG of extracted and recovered RAP binder indicated that the RAP binder had a continuous PG grade of PG 83.8–18.8 (29.1).

The asphalt mixture supplier submitted five different designs for each mixture before the mixtures were able to meet both the volumetric and performance requirements (*5*, *6*). In the end, the asphalt mixtures produced for the project are shown in Table 11. The asphalt supplier utilized 25% RAP in the surface and 35% RAP in the intermediate layer, both 10% higher than what is currently allowed by the New Jersey DOT. Also, since the specification does not specify a particular asphalt binder grade, an appropriate asphalt binder was selected that would allow for each of the final mixtures to meet the required rutting and fatigue cracking performance.

In accordance with the HRAP specification, the loose mix is required to be collected and tested for rutting and fatigue cracking using the APA (AASHTO T 340) and overlay tester (NJDOT B-10), respectively. Test results for the mixtures are shown in Figure 12. As Figures 12*a* and 12*b* indicate, the HRAP surface and intermediate course mixtures far exceeded the minimum cracking requirements of the New Jersey DOT HRAP specification, while still meeting the maximum allowable rutting in the APA (AASHTO T 340). As can be visually seen in Figure 12*c*, the HRAP lane looks identical to the WMA pavement immediately adjacent to the HRAP lane, where the WMA pavement was produced and placed with only 15% RAP.

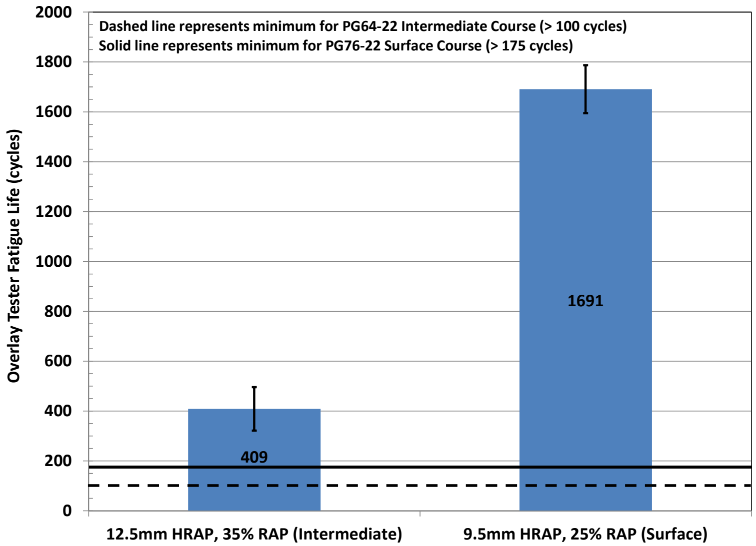
Construction data regarding compacted, in-place density and roughness [international roughness index (IRI)] indicated that the HRAP mixtures did not create an issue with respect to achieving density and ride quality requirements. The average results were

- 9.5M76 HRAP (surface):
  – Average core density = 6.6% (1.73% standard deviation) and
  – IRI (inches/mile) = 54.2 in./mi; and
- 12.5M64 HRAP (intermediate)
  – Average core density = 5.6% (1.06% standard deviation)

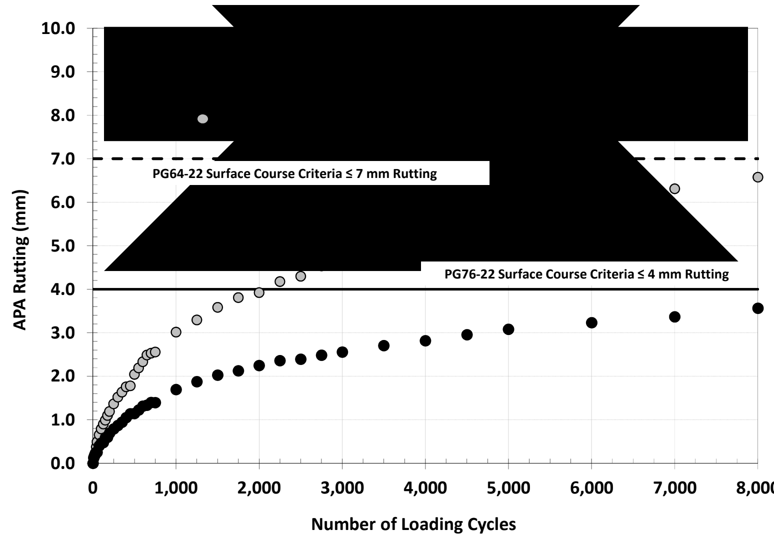
The contractor received full bonus for compacted density on two of the five lots produced on the project, with both of these lots being the one with 35% RAP (12.5M64). These sections are planned to be evaluated over the next few years to evaluate their long-term performance.

TABLE 11 Final Mixture Properties for the Surface and Intermediate Course Mixes

Property	I-295 Final HRAP Mixtures: 9.5M76 (Surface Course)	12.5M64 (Intermediate Course)
RAP used (%)	25	35
JMF asphalt content (%)	6.0	5.8
Binder replacement (%)	27.4	29.7
PG of virgin binder (continuous grade)	PG 70-22 (74.6–26.99)	PG 64-28 (64.8–28.9)
Fractionated RAP portion used (%)	100 fine RAP fraction	50 fine RAP fraction 50 coarse RAP fraction



(a)



(b)

(c)

FIGURE 12 (*a*) Overlay tester cracking results; (*b*) APA rutting results; and (*c*) final HRAP pavement on I-295.

SUMMARY AND CONCLUSIONS

With a deteriorating transportation infrastructure, decreasing transportation funding, and an increasing traffic conditions, the New Jersey Department of Transportation (NJDOT) has begun to implement a performance-based asphalt mixture design system for their asphalt mixtures. These mixtures, comprising of approximately 10% of the total asphalt tonnage placed in the state, are selected based on the extreme needs of the pavement structure in question (i.e. – composite pavement, bridge deck overlay, etc.). Each of these performance-based mixtures is required to undergo performance testing during the mixture design, test strip, and project construction phase to ensure the final mixture achieves the desired performance to the specific pavement structure.

Although the NJDOT has only begun to implement the performance-based asphalt mixtures since 2008, monitored field performance of these mixtures has indicated that these materials are all performing exceptionally well, and in some cases (i.e. – ACROW bridge in Rt 80), performing far beyond what conventional NJDOT asphalt mixtures are capable of. While New Jersey's HMA suppliers/contractors were skeptical and somewhat reluctant to begin this new age of performance-based asphalt mixtures, they understand New Jersey's need for these mixtures and have embraced their use. As the performance-based mixtures have become more widely accepted and the methodology of design and production becomes more efficient, it is hopeful that New Jersey will be able to implement some form of performance-based for all asphalt mixtures.

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Implementation of a Performance-Based Mix Design System in Texas

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Since the completion of the original SHRP program in the mid-1990s most departments of transportation (DOTs) have been searching for practical performance-related tests that can be run at the mix design stage. To address rutting issues, many states have implemented wheel tracking tests and the use of stiffer binders which have mostly eliminated the rutting problem. In recent years, with the ever-increasing use of recycled materials, the current major concern from most field engineers is premature cracking. However, at this moment no states have adopted a repeated load cracking test for use in routine mix design.

This paper describes the development and implementation of the Texas Overlay Tester (OT) as one such possible cracking test. The history of the test is described as well as recent studies to evaluate test parameters, evaluate sensitivity and reduce variability. Cases studies are also presented where the test is shown to be performance related, in that mixes that do well in the test also do well in the field at retarding reflection cracking. Other studies are also described which indicate that mixes classified as good in the OT will also have superior resistance to both fatigue and cold weather cracking.

The OT along with the Hamburg wheel tracking test are now part of the balance mix design procedure which has been implemented by Texas DOT to design its performance mixes. However field studies conducted in the past 5 years have highlighted the needed for a project-specific mix design requirements. This has led to the development of simple mechanistic-based overlay design procedure where project specific OT requirements can be determined.

INTRODUCTION

The placement of an asphalt overlay is the most common method used by the Texas DOT to rehabilitate existing asphalt or concrete pavements. Selecting the appropriate combination of aggregates and binder types are important decisions that pavement engineers make on a daily basis. This selection is a difficult balancing process, because for a hot-mix asphalt (HMA) mix to perform well in the field, it must have a balance of both adequate rutting and cracking resistance. However, improving mix rutting resistance often has a negative impact on cracking resistance.

The goal of implementing a balanced asphalt mix design process has been pursued for a long time by various researchers and practitioners (*1–4*), but without much success. In the 1980s, shear failure rutting was widely observed on high-volume asphalt pavements. To reduce asphalt rutting and the associated safety issues, stiffer polymer-modified binders, coarse aggregate gradations, lower asphalt contents, or a combination thereof were used. As a result, the rutting problem has largely been significantly reduced. However, these measures have resulted in increases in early cracking (*5–9*). The cracking problem has become the more serious concern for many pavement engineers, especially in the past few years due to the ever increasing use of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS).

The use of RAP–RAS can significantly reduce the cost of HMA paving, conserve energy, protect the environment, and improves rutting resistance of asphalt mixes. However, RAP–RAS binders are often much stiffer than virgin binders. Blending these very stiff materials with virgin materials can make the designed mixes prone to cracking and consequently, leading to durability problems. It is critical to address the premature cracking problem in the mix design process. In the past, the cracking problem has been considered through setting a minimum volume of effective asphalt (VBE). This minimum VBE approach is applicable for virgin mixes, but its application to asphalt mixes containing RAP–RAS is questionable, because it is unknown how much the binder from RAP–RAS is melted down and blended with the virgin binder. Therefore, it is imperative to have a performance-related cracking test to ensure the proposed asphalt mixes will have both adequate cracking and rutting resistance.

This paper will first discuss the development of the Texas OT as a simple performance test. This discussion will include current test conditions, sensitivity to asphalt mix factors, repeatability, and laboratory-to-field correlations. Then the importance of determining the project-specific cracking requirement will be discussed. Next the balanced mix design approach and several case studies will be described. Finally, a summary and conclusions are presented.

TEXAS OVERLAY TEST

The key part of the Texas A&M Transportation Institute's (TTI) OT is shown in Figure 1, it consists of two steel plates, one fixed and the other movable horizontally to simulate the opening and closing of joints or cracks in the old pavements beneath an overlay. The first OT was designed by Germann and Lytton in the late 1970s (*10*). Since then, the OT has been widely used by many researchers to evaluate the effectiveness of different geosynthetic materials to retard reflective cracking (*11–13*). The early results also indicated that the OT has the potential to be used as a tool to screen good from poor crack-resistant mixes. However, one limitation of the early work was that a long beam specimen was required. The long beam specimen is difficult to fabricate in the lab and more difficult to obtain from the field. To solve this and other related problems, an upgraded TTI OT was developed with the goal of being able to test 6-in. diameter specimens which could be easily fabricated in the lab or cut from field cores (*14*).

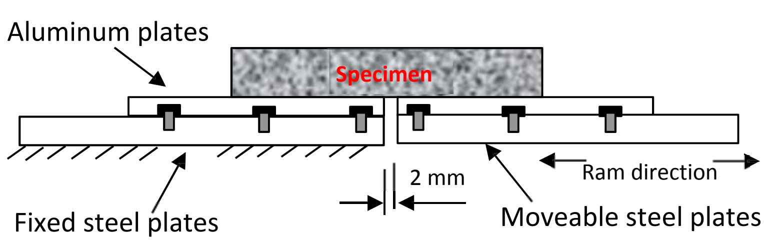


FIGURE 1 Texas OT: concept and upgrade equipment.

OT Test Procedure: Tex-248-F

Several revisions have been made to the original OT test procedure proposed by Zhou and Scullion (*15*). But the key components of the test are still the same, as listed below:

- Specimen size: 6 in. long by 3 in. wide by 1.5 in. high. This size of specimen can be prepared either from Superpave Gyratory Compactor (SGC) or from field cores. For lab design work the samples are molded to 7% air voids.
- Test temperature: 77°F.
- Loading time and wave form: a cyclic load with a 10-s period is applied in a cyclic triangular waveform with a constant maximum opening displacement.
- Maximum opening displacement: 0.025 in.
- Failure definition: 93% load drop from the maximum load measured at the first cycle.
- Cracking life: number of cycles to reach specimen failure.

To date, a wide variety of asphalt mixes have been tested. Some of them failed in less than five cycles whereas others exceeded 1,000 cycles at which time the test is terminated.

In the past 10 years, substantial work has been done to address concerns raised about using the proposed OT procedure for mix design purposes. Detailed information is presented in the following sections on justifying the selected crack opening, on sensitivity of results to mix variables and efforts to reduce repeatability.

Justification for the Maximum Opening Displacement: 0.025 in.

The maximum displacement of 0.025 in. was originally proposed based on the calculation of concrete slab movement with the following assumptions: (*a*) 15-ft-long slab, (*b*) daily temperature variation of 30°F, and (*c*) coefficient of thermal expansion of concrete slab of 4.75 in./in./°F. Concerns were raised that this opening was too severe for flexible pavement applications. To address this field crack movements due to temperature variations were measured at two different environmental regions in Texas, as detailed below.

Crack movement can be monitored by installing two reference points on either side of a crack and measuring the point spacing at different pavement temperatures (*16*). MAG nails were hammered into the pavement (Figure 2), crack spacing was measured with digital calipers in the afternoon and at sun up, and the pavement temperature was measured with an infrared gun. Each warm–cool temperature value is the average of three or four measurements.

At the Texas A&M Riverside Campus, eight unique pavements (see Table 1) identified for the measurement include thin or thick asphalt layers; cement-treated, lime-treated, or untreated bases; and clayey or gravely subgrades. Some of these cracks were 2 in. wide, while others were less than 1/8 in. wide. An additional section monitored was an asphalt overlay on jointed concrete (Figure 2). In addition to measurements over cracks, control measurements were made on the pavements in Table 1 away from any cracks.

Another set of measurement was made at the Pecos Research and Testing Center (RTC) where the movement of 19 well-developed transverse cracks was monitored. The pavement structure was 3 in. of HMA over a thick limestone base. Figure 3 presents the crack movements observed at the Riverside Campus. Each value is the observed movement of one crack from 44°F to 108°F (Δ64°F). Two of the cracks moved much more than 0.025 in. (>0.035); four cracks

TABLE 1 Riverside Campus Pavement Structures (*16*)

Pavement Structure	Surface		Base		Subbase		Subgrade	
	in.		in.		in.		in.	
A	4.6	Asphalt	3.4	Limestone + cement	4.0	Crushed limestone	41.0	Plastic clay
B	1.5	Asphalt	12.0	Limestone + cement	4.0	Crushed limestone	36.0	Plastic clay
C	3.2	Asphalt	7.8	Limestone + lime	7.0	Limestone + cement	37.0	Sandy clay
D	0.8	Asphalt	16.2	Crushed limestone		—	36.0	Gravel
E	5.5	Asphalt	22.5	Crushed limestone		—	25.0	Gravel
F	3.0	Asphalt	8.0	Limestone + lime	7.5	Crushed limestone	35.5	Sandy clay
G	1.0	Asphalt	16.0	Limestone + lime		—	38.0	Sandy clay
H	2.0	Asphalt	—	Jointed concrete		—		—

FIGURE 2 Measurement of crack movement at the Texas A&M Riverside campus (*16*).

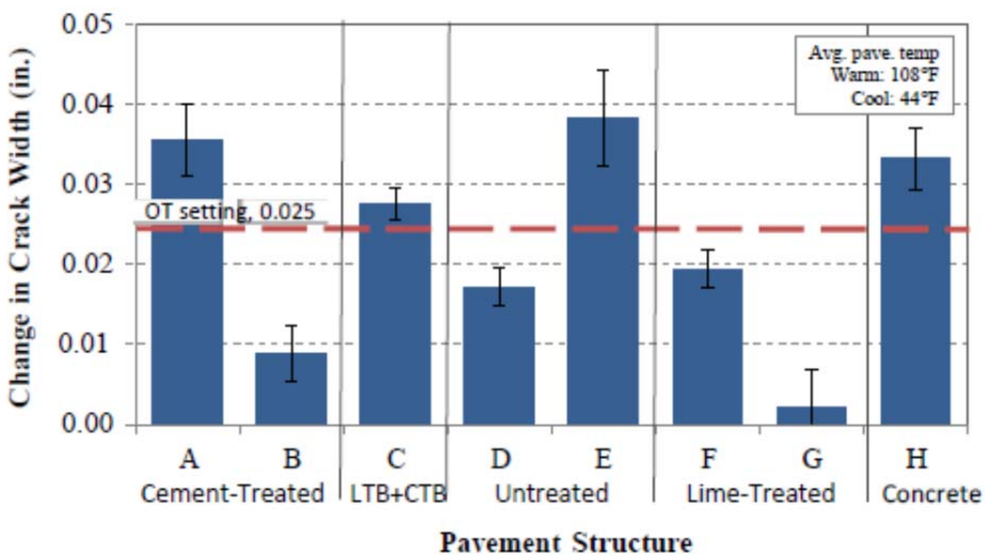


FIGURE 3 Crack movement of various pavements at Texas A&M Riverside campus (*16*).

moved within the range of 0.025 in. (>0.015, <0.035); and two measurements were much less than 0.025 in. (<0.015). These results suggest the OT opening of 0.025 in. is reasonable, if not too small, for over half the cracks measured. The control measurements (not shown in the graph) moved less than 0.005 in. Due to the limited number of readings, it is not possible to draw definitive conclusions about the crack movement associated with different pavement structures.

Similarly, Figure 4 presents the crack movements at the Pecos RTC as the pavement temperature changed from 88°F to 33°F (Δ55°F). The average crack movement of both of these pavements is about 0.06 in. and well above the OT setting of 0.025 in. In this case, actual field conditions are more severe than what is replicated in the laboratory.

Based on these preliminary measurements, the current maximum opening displacement of OT is not too severe.

OT Sensitivity Analysis

To gain confidence with any proposed cracking test one key requirement is that it must be sensitive to variations in mix parameters (such as changes in asphalt content) and that the results make sense. The test must also have adequate discrimination between good and marginal mixes. To evaluate the "reasonableness" of the Texas OT a sensitivity analysis was completed with a Texas DOT dense-graded Type D mix. The optimum asphalt content was 5.1% (by total weight of the mix). The parameters investigated included (*a*) test temperature, (*b*) opening displacement, (*c*) asphalt content, and (*d*) asphalt performance grade. Only one parameter was varied in this sequence and the others were kept constant. The detailed OT results are presented in Figure 5. It can be seen that the OT is sensitive to test temperature, opening displacement, asphalt binder content, and asphalt binder performance grade (PG) level. As expected increasing the asphalt content can significantly improve the cracking resistance of an asphalt mix.

Another aspect of the cracking test sensitivity was evaluated recently by Walubita (*26*). That study focused on comparing the reasonableness of single shot test against repeated load tests such as the OT. Details are presented elsewhere (*26*) but the single shot test did not do well in sensitivity analysis such as those shown in Figure 5, and they also were much less able to discriminate mixes with known good and poor cracking resistance

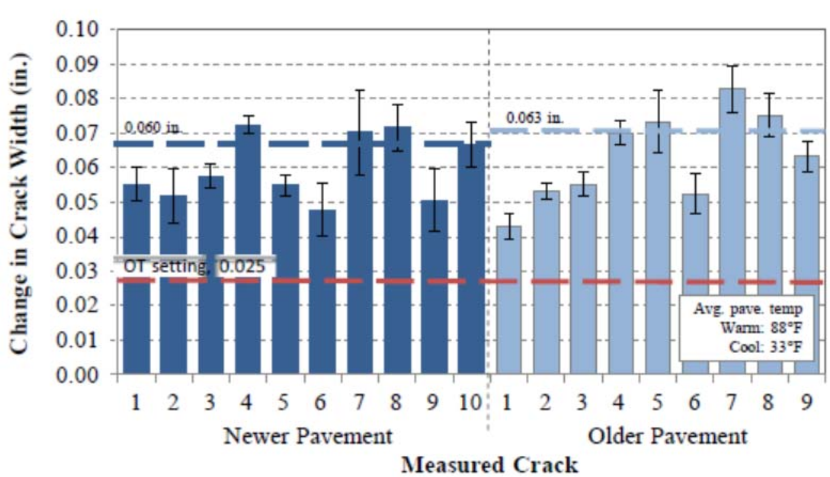


FIGURE 4 Crack movement measured at Pecos RTC (*16*).

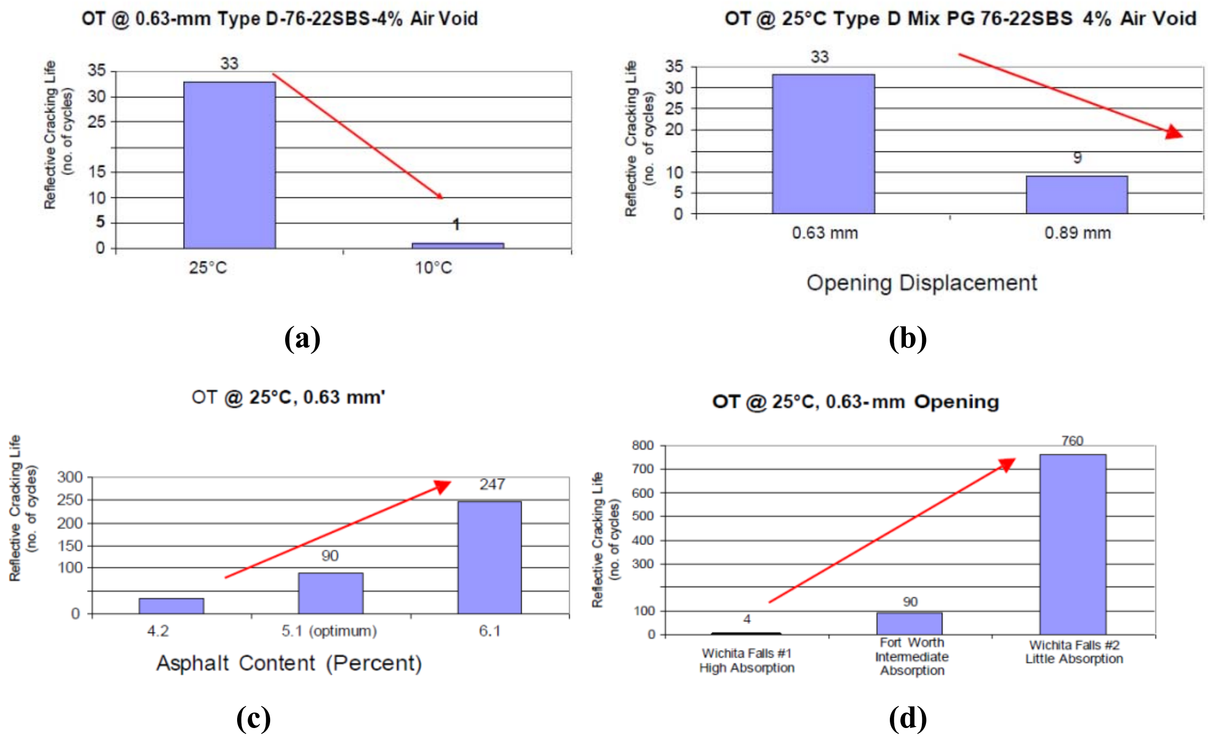


FIGURE 5 OT sensitivity analysis: (*a*) sensitivity to test temperature; (*b*) sensitivity to open displacement; (*c*) sensitivity to asphalt content; and (*d*) sensitivity to asphalt absorption.

OT Repeatability

It is a well-known fact that compared to monotonic tests [such as indirect tension (IDT) strength, disk-shaped compact tension (DCT) test], the repeated loading tests (e.g., 4-point bending beam fatigue test) often have higher coefficient of variation. For example, Table 2 documents the research results from Monismith and his associates during the first SHRP (*17*). The 4-point bending beam fatigue test commonly used for developing fatigue cracking models has a COV of 98.7%.

As noted previously, the Texas OT is a repeated loading test so that it is anticipated that the OT results are highly variable. Recently, Walubita et al. (*18*) conducted a comprehensive study on OT repeatability and improvement of the OT test procedure. It was found that many factors (e.g. amount of glue, sample drying method) had effect on the OT repeatability. Five types of asphalt mixes were used in this study. One of the major findings is that the most practical way to improve OT repeatability is to test more samples. In order to reduce the COV to less than 30% (as requested by Texas DOT) it was recommended to test 5 samples and choose the best choose the best 3 (the largest and smallest OT results are discarded.), as shown in Figure 6. Walubita et al. (*18*) also reported that the average of the bests three OT cycles was very close to the average of five OT cycles.

TABLE 2 Variability of Three Fatigue Tests Under SHRP (*17*)

	Flexural Beam Fatigue	Flexural Trapezoidal Fatigue	Diametral Fatigue
Stiffness			
COV (%)	12.3	11.4	19.7
Sample variance (in psi)	0.010	0.014	0.015
Cycles to failure			
COV (%)	98.7	171.8	65.5
Sample variance (in cycles to failure)	0.282	1.696	0.213

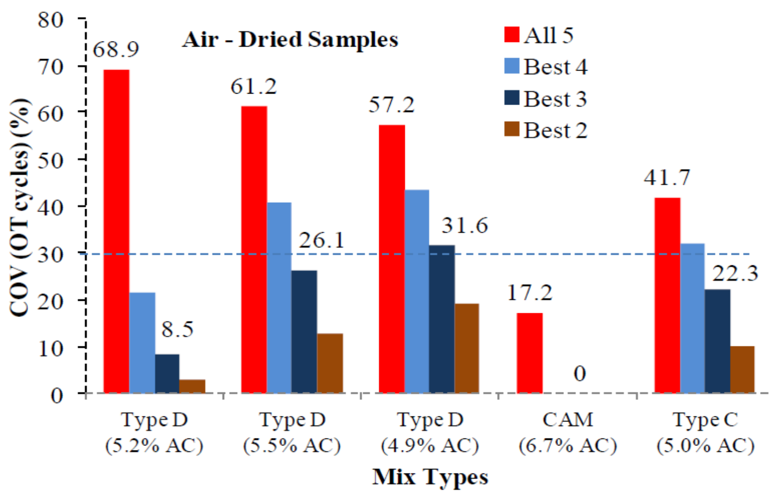


FIGURE 6 Effect of number of specimens on COV (*18*).

VALIDATION OF THE OT FOR REFLECTION CRACKING, FATIGUE CRACKING, AND LOW-TEMPERATURE CRACKING

The section below presents case studies in which the OT results were compared to field performance of sections which exhibited different type of cracking, namely; reflection cracking, fatigue cracking and low-temperature cracking.

OT for Reflection Cracking

Several studies have been completed in Texas to correlate the OT results to field performance in terms of reflection cracking. Following is a discussion of the performance of Special Pavement Study 5 (SPS) sections built in 1991 and an adjacent hot in-place recycling (HIPR) project. The SPS 5 sections were built to compare the effectiveness of rehabilitation treatments for thin and thick overlays, constructed with virgin and recycled hot mixes. This was a mill and overlay option in the main lanes only where the existing pavement had a cracked cement treated base. After 10 years of service, no significant distress was found in the SPS 5 sections. Although many transverse cracks were observed on the shoulder, they did not appear in the travel lanes. The performance for all SPS5 sections was excellent. It is important to note that the asphalt binder used was AC 5 plus 3% SBR Latex. Several 150-mm diameter cores were taken in 2000 from two sections: (*a*) 125-mm virgin asphalt overlay and (*b*) 30% recycled asphalt overlay. Three cores were cut and trimmed into OT size specimens. Figure 7 shows the test results with averaged value from three cores. It can be seen that the virgin mix has much better reflective cracking resistance than the recycled mix.

In the hot in-place recycling process the top 38 mm of asphalt pavement was initially heated. The surface is then milled and then about 25% of the new HMA mix was added and mixed with the recycled material. A 48-mm thick recycled pavement was then compacted with a vibrating steel-wheel and pneumatic rollers. This HIPR section was a few miles away from the SPS 5 section on US-175 so that both traffic and environmental conditions were the same. The reflection cracks shown in Figure 8 appeared at the surface less than 1 month after the HIPR overlay. The same HIPR process was also used on the US-84 asphalt overlay project in the Abilene District, Texas, where severe transverse cracks reflected through the overlay after only a few weeks. This premature reflective cracking clearly indicates that the thermal stress induced by the opening and closing of joints or cracks was the main contributor to the reflection cracking, because the cracks were full width and only a low amount of traffic was applied to these sections. Cores from both HIPR sections on US-175 and US-84 were taken in 2000. Similarly, three cores were tested and the test results are also presented in Figure 7. After two cycles, the mixes from both US-175 and US-84 failed. Compared to the SPS 5 recycled and virgin mixes the reflective cracking resistance of US-175 and US-84 recycled mixes are very poor. The OT results are consistent with the reflective cracking performance of those materials in the field. This demonstrated that the OT can effectively differentiate between poor from good reflective cracking resistant mixes.

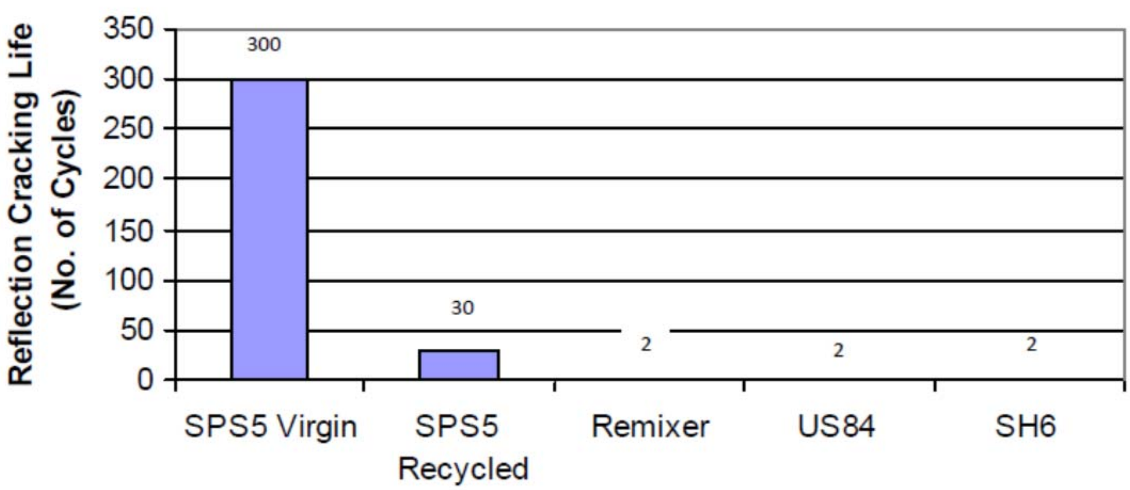


FIGURE 7 OT results on field cores from SPS 5, US-84, and SH-6.

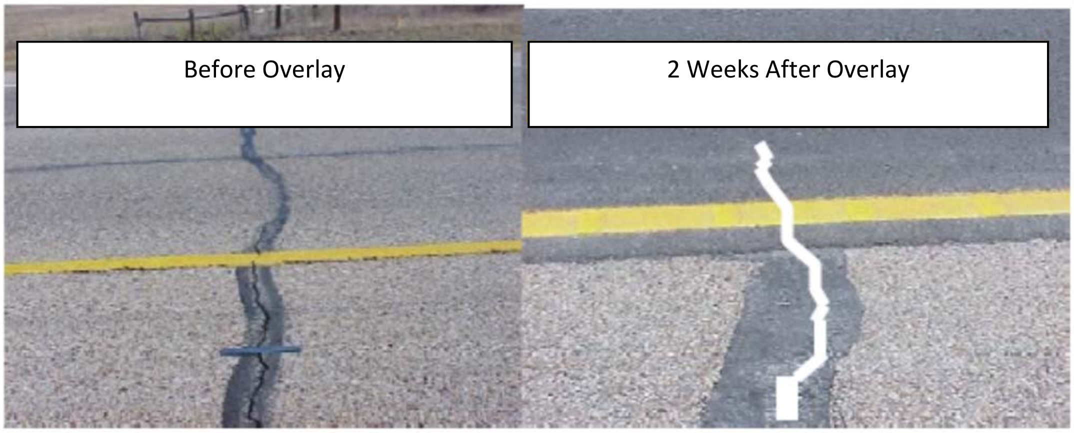


FIGURE 8 Reflective cracking on US-175 remixer section.

OT for Fatigue Cracking

In the summer of 2002, under a pooled fund study TPF-5(019), 12 full-scale lanes of pavements with various modified asphalts were constructed at the FHWA ALF facility at Turner Fairbanks in Virginia (*21*). The current layout of the 12 as-built pavement lanes is presented in Figure 9. Each pavement lane is 4 m (13 ft) wide and 50 m (165 ft) long, and is divided into four test sites. All pavement lanes consist of an HMA layer and a dense-graded, crushed aggregate base (CAB) course over a uniformly prepared, AASHTO A-4 subgrade soil. Lanes 1 through 7 were constructed with a 100-mm (4-in.) thick layer of HMA, while lanes 8 through 12 were constructed with 150 mm (6 in.) of HMA. The binders used in each lane are also listed in Figure 9. Note that the control binder (PG 70-22) and three modified binders (air-blown, SBS- LG, and Terpolymer) were used in both 100-mm (4-in.) and 150-mm (6-in.) thick lanes. The fatigue testing on 100-mm AC pavements were loaded with Super single tire [74 kN (16.6 kip) and 827.4 kPa (120 psi)] at temperature 19ºC (66ºF). Figure 9 also shows the available fatigue cracking data (*22*). The ranking of fatigue performance on Lanes 1 to 6 from best to the worst: Lane 1>Lane 4> Lane 6> Lane 5> Lane 2 ≈ Lane 3.

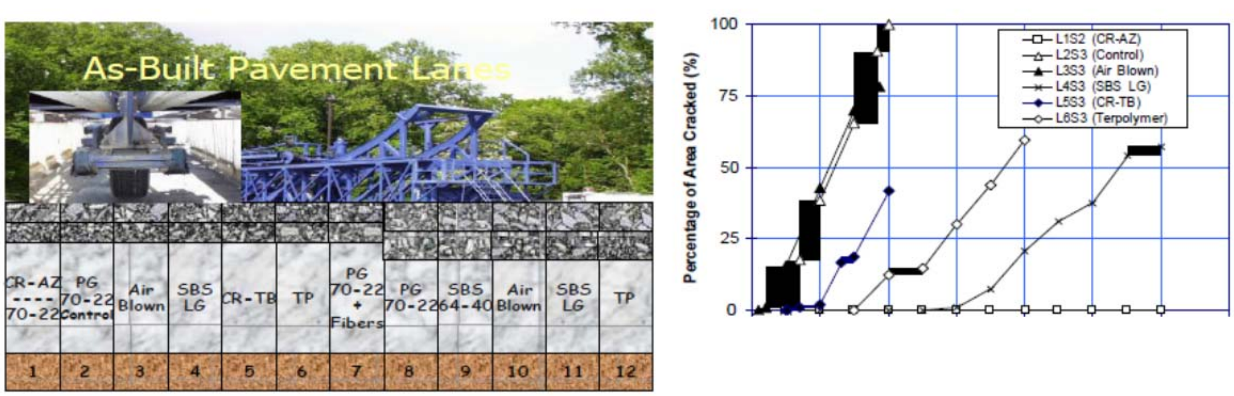


FIGURE 9 FHWA ALF test lanes and observed fatigue cracking on Lanes 2 through 6 (*22*).

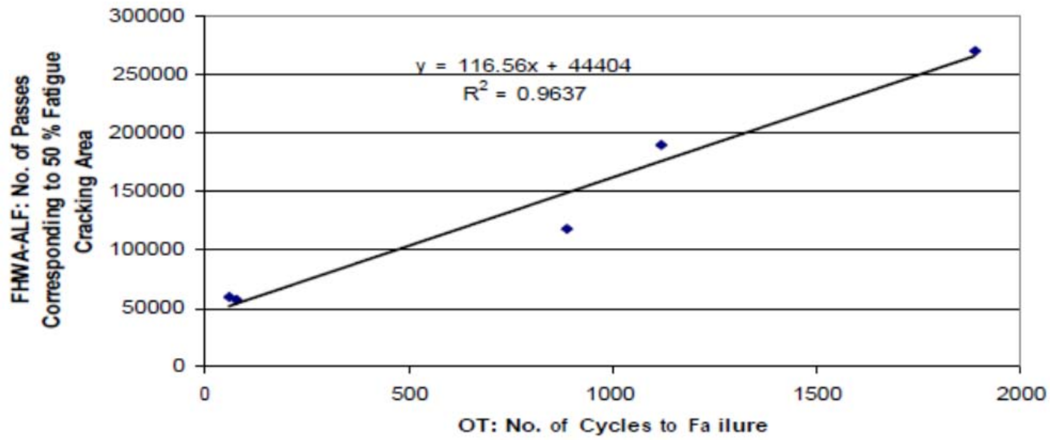


FIGURE 10 Correlation between OT and FHWA ALF fatigue test.

Field cores from the ALF sites were taken and shipped to TTI for testing. The OT was conducted with a maximum opening displacement of 0.48 mm (0.019 in.) at the same temperature (19ºC or 66ºF) as the FHWA ALF fatigue test. Note that Lane 1 was excluded from the following comparison, because Lane 1, as shown in Figure 9, is composed of two mixtures (top layer with Arizona crumb-rubber mixture and bottom layer with PG 70-22 mixture). The correlation between the OT results and the FHWAL ALF results is shown in Figure 10. It can be found that the HMA mixtures having larger number of cycles to failure under the OT performed well in the field.

OT for Low-Temperature Cracking

The OT was also utilized to evaluate the low-temperature cracking resistance of HMA mixes from cores taken from the MnRoad field test sections. Three representative test cells (15, 18, and 20) at the MnRoad 2003 were selected for OT evaluation. Table 3 presents the HMA mixes information and field performance of these three cells. Two 150-mm diameter cores from each cell were taken from the mid-lane of the driving lane (6 ft offset), then shipped to TTI for overlay testing. The OT was conducted under testing conditions: 15°C and 0.025 in. opening. The test results are presented in Table 3. It can be seen that the OT results are consistent with the observed field cracking performance of these three HMA mixes. The results also indicated that both asphalt binder content (cells 15 and 18) and asphalt binder PG (cells 15, 18, and 20) had influence on crack resistance, which is consistent with the results of the sensitivity study conducted previously.

TABLE 3 Three Test Cells of MnRoad: Asphalt Mixture and Lab and Field Cracking Performance

Test Cell	Asphalt Type	Mix Design (Marshall)	Linear Feet of Cracking in Field	OT Cycles
15	PG 64-22	75 blow	475	91
18	PG 64-22	50 blow	315	153
20	PG 58-28	35 blow	100	500

A PROPOSED ASPHALT MIX DESIGN PROCEDURE BALANCING RUTTING AND CRACKING REQUIREMENTS

Based on the success from the case studies previously described the OT was proposed as the cracking test in a balanced design procedure proposed for Texas DOT. The proposed procedure is based on the following principles and constraints:

1. Keeping the changes to the current Texas DOT design procedure as minimal as possible.
2. Directly evaluating both rutting and cracking resistances of the HMA mixes.
3. Balancing both rutting and cracking requirements.

The Hamburg Wheel Tracking Test (HWTT) is currently being used to evaluate rutting resistance and moisture susceptibility in Texas. Based on the above principles and constraints the HWTT is recommended in the balanced mix design procedure for evaluating rut resistance. The field validated OT is recommended for cracking evaluation. The balanced mix design procedure is proposed and is shown in Figures 11 and 12.

Note that for a smooth transition, Steps 1, 2, and 3 in the proposed balanced mix design procedure are the same as those in the current Texas DOT asphalt mix design method. The enhancements, as described in Steps 4 and 5, include (*a*) evaluating the impact of varying binder content on mix properties (such as rutting resistance), (*b*) adding the OT to evaluate cracking resistance, and (*c*) selecting the balanced asphalt content within a range of binder contents where both the rutting and cracking requirements are met (Figure 12). The key to this procedure is that for most mixes there is a zone where both cracking and rutting requirements are met. (However not every binder aggregate combination has this acceptable zone, in that case the complete design should be reconsidered including the quality of the aggregates and the grade of the binder.)

PROJECT-SPECIFIC OT CRACKING REQUIREMENT

One major research focus in the past 5 years in Texas has been the use of the OT to evaluate the design and performance of mixes containing various levels of recycled materials. A series of field test sections, with and without RAP–RAS, have been constructed around Texas. Table 4 lists the detailed information of these field test sections. These field test sections cover different applications of RAP–RAS mixes, as listed below:

- Asphalt overlays versus new construction pavements;
- Cold weather versus hot weather;
- Heavy traffic versus low traffic;
- Thicker versus thin asphalt layer(s); and
- Virgin mix versus RAP only or RAP–RAS.

Table 4 also lists the OT test results of asphalt mixes from each test section and the observed field performance in terms of reflection cracking.

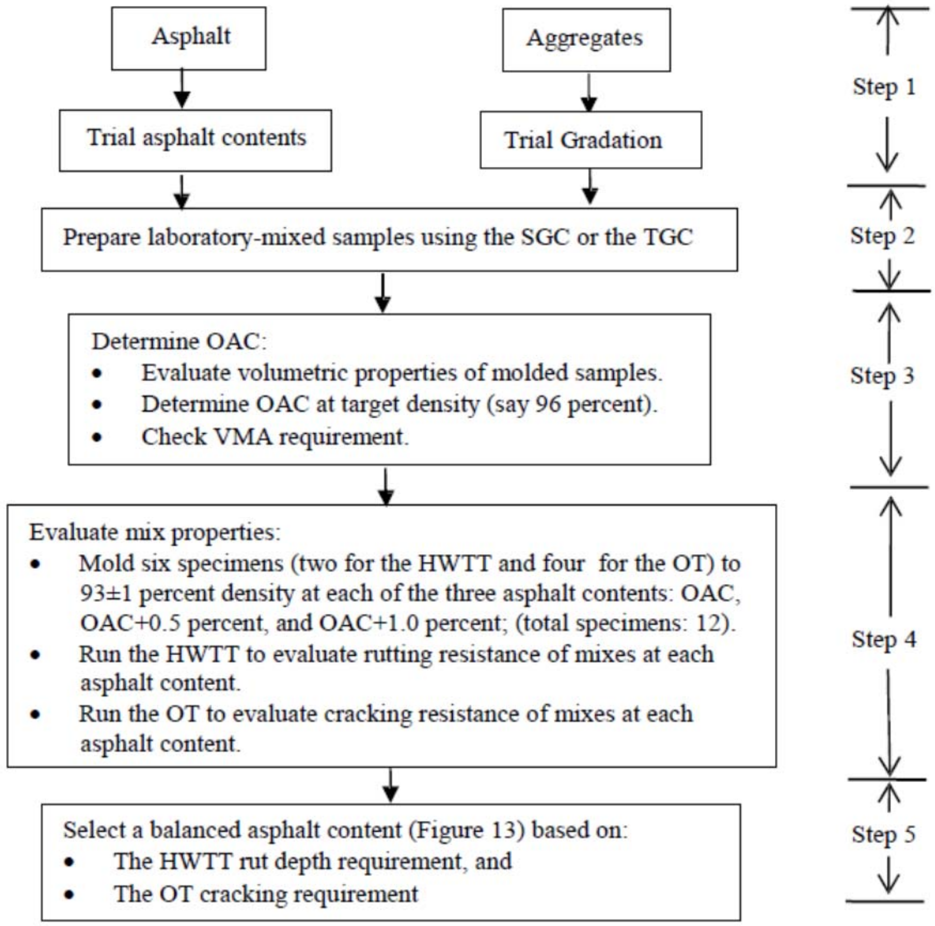


FIGURE 11 Balanced HMA mix design procedure.

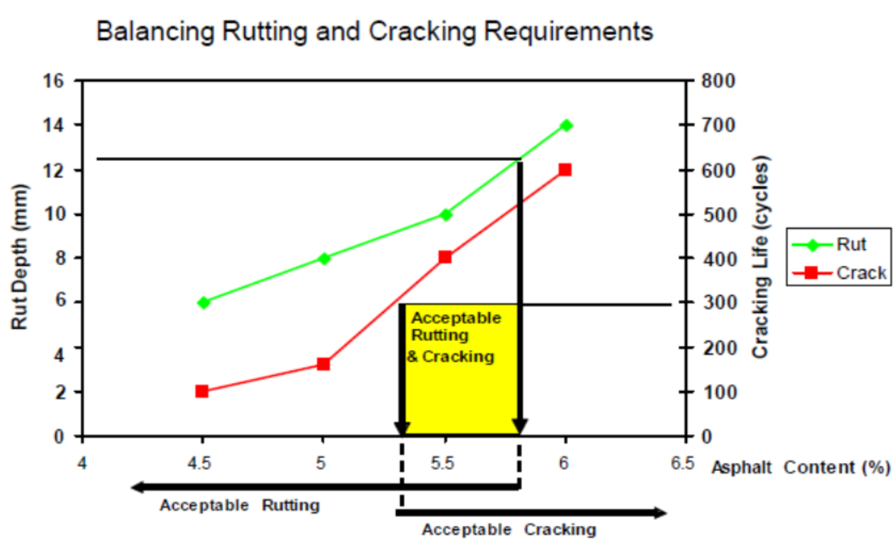


FIGURE 12 Balance mix design concept.

TABLE 4 Field RAP–RAS Experimental Test Sections and Observed Performance

Test Section			District	Weather	Traffic (mESAL/ 20 Years)	Overlay/ New Construction	Existing Condition if Overlay	OT Cycles	Field Performance
Highway	RAP–RAS	Virgin Binder							
I-40	20% RAP	PG 64-28	Amarillo	Hot summer, cold winter	30	4-in. overlay	Severe transverse cracking	10	100% reflective cracking after 3 years
	0% RAP	PG 64-28						90	
	20% RAP	PG 64-28						103	
	35% RAP	PG 58-28						200	80% reflective cracking after 3.5 years
FM-1017	0% RAP	PG 76-22	Pharr	Very hot summer, mild winter	0.8	New construction, 1.5-in. surface layer	NA	28	Limited, fine cracking after 3 years
	20% RAP	PG 70-22						6	
	35% RAP	PG 70-22						7	
SH-359	20% RAP	PG 70-22	Laredo	Hot summer, mild winter	1.0	3-in. overlay	Severe transverse cracking	3	No cracking after 3 years
SH-146	15% RAP–5% RAS	PG 64-22	Houston	Hot summer, mild winter	1.5	New construction, 2-in. surface layer	NA	3	No cracking after 2.5 years
US-87	5% RAS	PG 64-28 (control)	Amarillo	Hot summer, very cold winter	3.5	3-in. overlay	Severe transverse cracking	48	50% reflective cracking after 2.5 years
		PG 64-28 with 0.4% more virgin binder						96	20% reflective cracking after 2.5 years

NOTE: mESAL = million equivalent single-axle load; OT = overlay tester; RAP = recycled asphalt pavement; RAS= recycled asphalt shingles; PG = performance grade; NA = not available.

When comparing the observed performance data of all the field test sections (Table 4), one may get confused. RAP–RAS mixes with low OT cycles performed well on SH-359, SH-146, and FM-1017. However, those RAP–RAS mixes on I-40 and US-87 performed poorly, although these mixes had higher OT cycles. It seems that these observed performance data do not make sense. After carefully considering all the information presented in Table 4, several important observations can be made:

- Cracking performance of asphalt mixes, in contrast to rutting performance, is strongly related to the existing pavement structure (degree of cracking etc.). It is extremely difficult to propose a single cracking requirement for all projects.
- Cracking performance is also influenced by many factors, such as traffic, climate, and pavement structure and layer thickness.
- There is an urgent need to develop mix designs for project-specific conditions, including all of the above conditions.

Development of Project-Specific OT Requirement System

Based on Table 4 it impossible to establish a single cracking requirement for all scenarios, because cracking performance of asphalt mixes depends on many project specific factors. Therefore, a project-specific OT requirement system, rather than a single cracking requirement, should be developed to ensure the mixes are designed with acceptable field performance. It is envisioned that it is a two-step process:

Step 1. The existing project conditions will be determined and a performance model will be run to predict pavement performance for a range of different materials properties (mixes with different OT cycles to failure), and the designer then selects the OT requirement to meet the design performance goal (for example less than 50% reflective cracking after 5 years).

Step 2. A lab mix design is run to design a mix with the required OT cycles. If a proposed mix does not meet these requirements then it must be redesigned or the thickness changed.

In the last several years, the researchers at TTI have made significant progresses toward this goal: the balanced RAP–RAS mix design system for project-specific conditions. This work is described in detail in the following reports:

- Balanced mix design for overlay mixes developed under Project 0-5123 and documented in Report FHWA/TX-06/0-5123-1 (*23*);
- Mechanistic–empirical asphalt overlay thickness design and analysis system (TxACOL) developed under Project 0-5123 and documented in Report FHWA/TX-09/0-5123-3 (*24*); and
- High RAP mixes design methodology with balanced performance developed under Project 0-6092 and documented in Report FHWA/TX-11/0-6092-2 (*25*).

TxACOL shown in Figure 13 is an overlay design program used to predict both rutting and reflective cracking of asphalt overlays. The inputs required for running this program include both rutting parameters and fracture parameters (A and n). Both repeated load triaxial test and the OT test are needed to generate these material inputs, which is often beyond the capability of routine mix designers. In order to make TxACOL into a practical mix design tool for Texas DOT and to accelerate implementation, a simpler methodology for determining the fracture parameters (A and n) needed to be developed. This work led to the development of a project-specific OT requirement system—S-TxACOL. The rutting prediction is removed from S-TxACOL as rutting appears to be controlled by Texas DOT's current HWTT requirement. For reflective cracking, a relationship between the fracture parameters (A and n) and the routine OT test results (the number of OT cycles) was established, as shown in Figure 14.

Demonstration of Various Cracking Requirements for Project-Specific Conditions

Two series of case studies were performed using the simplified S-TxACOL to demonstrate the importance of varying cracking requirements for different applications. Detailed information is described below.

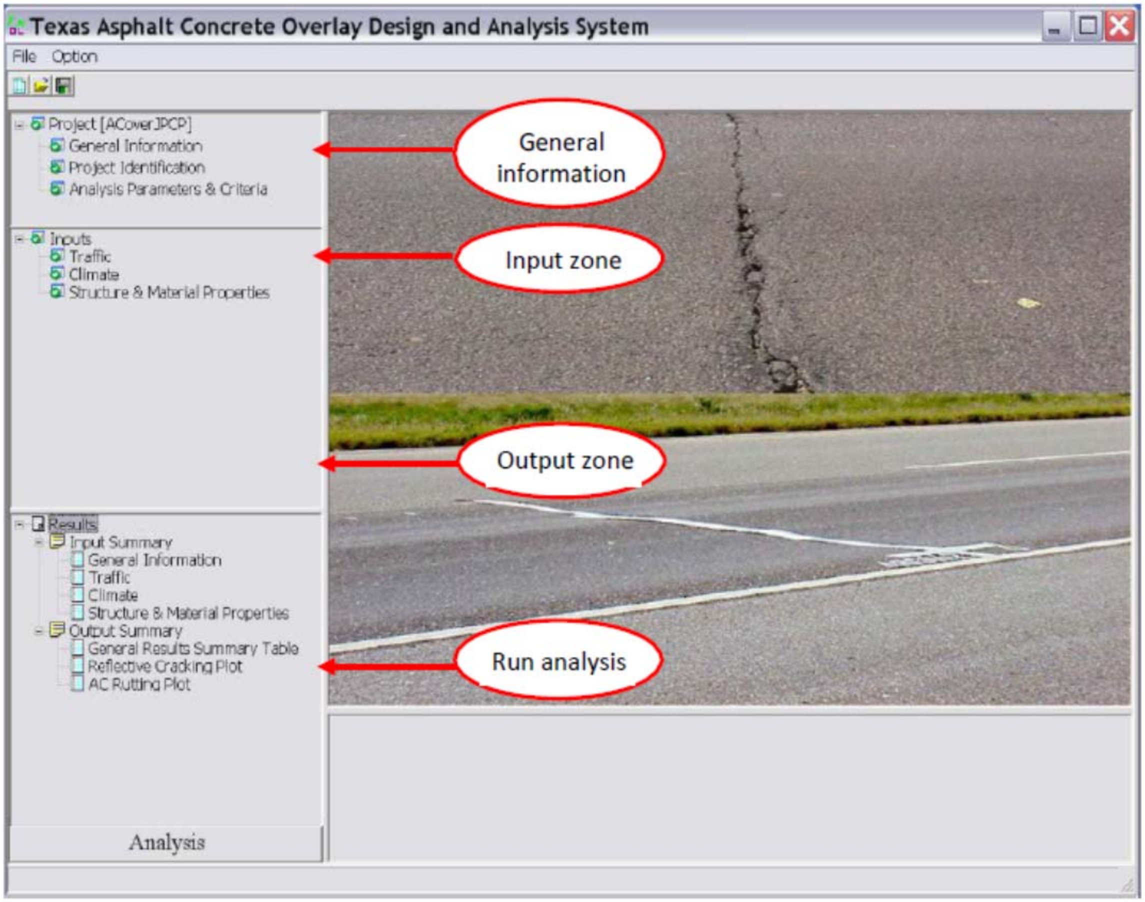


FIGURE 13 Main screen of the TxACOL program (*26*).

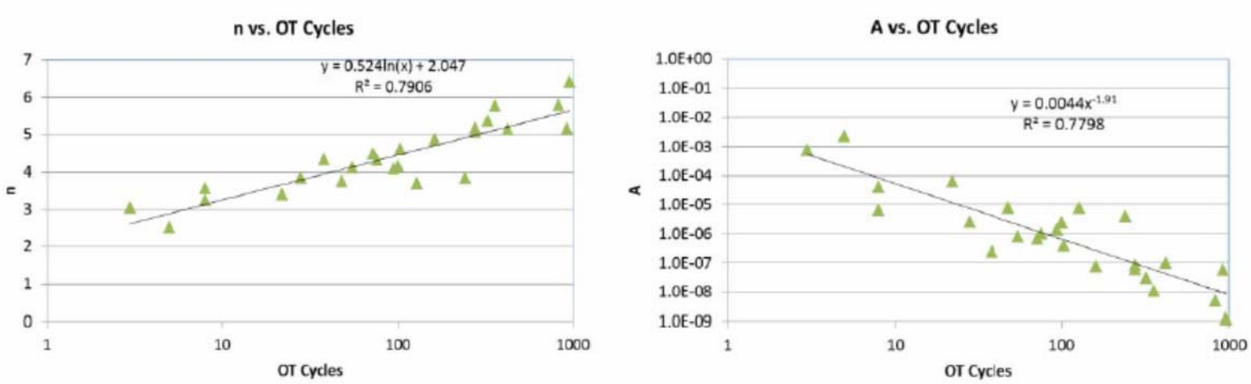


FIGURE 14 Relationship between OT Cycles and *A* and *n*.

Case 1. Impact of Different Existing Pavement Conditions on Cracking Requirements

A 2-in. asphalt overlay with PG 70-22 binder is applied to the following existing pavements with different load transfer efficiency (LTE) in Bastrop County, Austin District. The 20-year design loads are set at 3 million equivalent single-axle loads (ESALs). The relationship between OT cycles and cracking development for each application predicted from S-TxACOL is shown in Figure 15:

- 10-in. (250-mm) jointed portland concrete pavement (JPCP) over 6-in. (150-mm) base with LTE = 70%.
- 3-in. (75-mm) asphalt pavement over 10 in. (250 mm) cement-stabilized base (CTB) with LTE = 70%.
- 5-in. (125-mm) asphalt layer over 12 in. (300 mm) granular base with medium severity cracking (LTE = 70%).

The results shown in Figure 15 clearly indicate that varying OT cycles are necessary to achieve the same performance life for the different pavement types, with the JCP requiring a mix which last a minimum of 300 cycles in the OT.

Case 2. Impact of Climate on Cracking Requirements

Again, the same 2-in. (50-mm) asphalt overlay with PG 70-22 binder is assumed to be used on the following existing pavements in three different climatic zones: Amarillo, Austin, and McAllen. Where Amarillo has severe winter conditions with freeze–thaw cycling and McAllen has a very mild winter with no freeze–thaw cycle. The same traffic level of 3 million ESALs within 20 years is assumed. The relationship between OT cycles and cracking development for each application as predicted in S-TxACOL is shown in Figure 16. The overlay life is defined as time until 50% reflection cracking. It is clear that climate has significant influence on cracking development and consequently on cracking requirement:

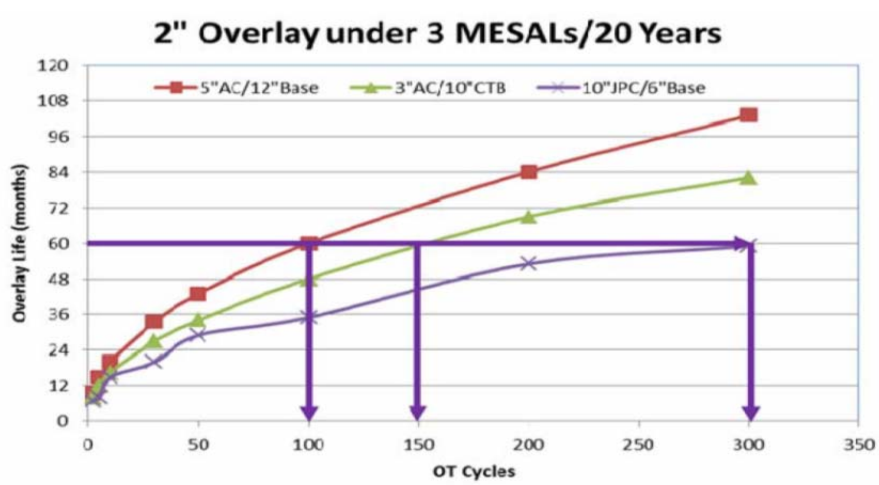
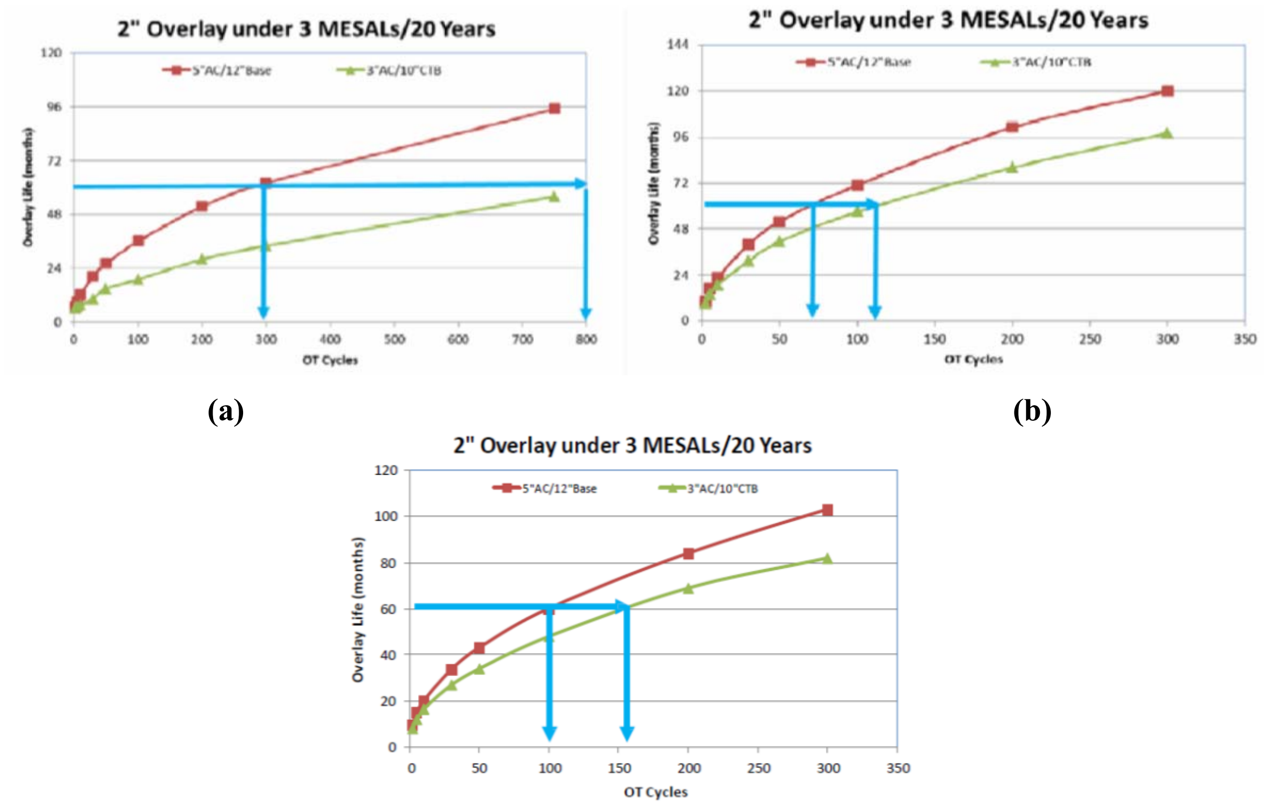


FIGURE 15 Relationships between OT cycles and cracking development for three applications with medium cracking severity.



(c)

FIGURE 16 Relationships between OT cycles and cracking development: (*a*) Amarillo; (*b*) McAllen; and (*c*) Austin.

- 10-in. (250-mm) JPCP over 6-in. (150-mm) base with LTE = 7%.
- 3-in. (75-mm) asphalt pavement over 10-in. (250-mm) CTB with LTE = 70%.

In summary, all things else being equal to get equivalent life until reflective cracking returns different OT requirements are needed for these three zones. For the flexible pavement design, the OT requirement would changes from 65 to 300 cycles with a change from mild to cold climates. This section further demonstrates that a single cracking requirement does not apply to all asphalt overlay applications and the necessity of performing S-TxACOL analysis for project-specific conditions.

CONCLUSIONS AND RECOMMENDATIONS

This paper presents the development of the Texas balanced mix design procedure and how this can be used to determine project specific mix design requirements. Based on the research presented in this paper, the following conclusions and recommendations are offered:

- The Texas OT is a simple performance test for reflection cracking; studies presented in this paper have found that mixes that do well in the OT also have superior resistance to fatigue cracking and low-temperature cracking.

- The OT is sensitive to asphalt mix composition and volumetric properties. To address the OT variability, using the best three out of five replicates is recommended.
- A balanced HMA mix design procedure incorporating both rutting and cracking requirements is proposed in this paper. The HWTT is used for evaluating the potential rutting and moisture sensitivity and the OT for cracking resistance. This balanced mix design procedure has minimal changes to the current Texas DOT HMA mix design procedure. The proposed changes include
  - Addition of the OT for evaluating cracking resistance and
  - Running the performance tests at different asphalt contents around the OAC determined based on volumetric design.
- Field cracking performance of asphalt mixes is influenced by many factors including traffic, climate, existing pavement conditions for asphalt overlays, and pavement structure and layer thickness. This paper clearly demonstrates that a single cracking requirement does not apply to all asphalt overlay applications. Instead, a project-specific service conditions based mix design system should be developed.
- A project-specific OT requirement system was developed and demonstrated in this paper. When all things else being equal to get equivalent life until reflection cracking returns, different OT requirements are needed for different zones. For the flexible pavement design, the OT requirement would changes from 65 to 300 cycles with a change from mild to cold climates. This section further demonstrates that a single cracking requirement does not apply to all asphalt overlay applications and the necessity of performing analysis based on a project-specific basis.

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Balanced Asphalt Mixture Design Through Specification Modification
Louisiana's Experience

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Traditional asphalt mixture design practices recognize the need for laboratory parameters that relate to field performance throughout the life of the pavement. However, many of the design methodologies consider volumetric proportions and strength characteristics of the mixtures, which may not provide adequate insight into mixture performance. Laboratory testing, capable of ascertaining an asphalt mixture's ability to resist common distresses, is needed to complement current design methodologies. Distresses commonly identified with flexible pavement failure are fatigue cracking and permanent deformation (rutting). The Louisiana Department of Transportation and Development has proposed specification modifications for 2013 to address the need for balanced mixtures (i.e., mechanistic laboratory evaluation to compliment volumetric criteria). This research presents Louisiana's experience with specification modification to develop a balanced mixture as evaluated by the use of the Hamburg loaded wheel tester (HLWT) and semicircular bend (SCB) tests. The laboratory performance of 11 mixtures produced using the 2013 proposed specification modifications was compared to that of 40 mixtures produced under the 2006 specifications. Laboratory tests included HLWT and SCB to evaluate rutting and intermediate temperature cracking, respectively. The research shows that specification modifications did not adversely affect rutting or fatigue cracking resistance of the mixtures.

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Development and Validation of Performance-Based Specifications for High-Performance Thin Overlay Mix

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A pilot specification for high-performance thin overlay (HiPO) mixtures utilizing a highly modified asphalt binder (HiMA) was developed by state departments of transportation (DOT) agencies in the Northeast Pavement Preservation Partnership (NEPPP), the Pennsylvania Asphalt Pavement Association (PAPA), academia, and industry. The pilot specification allows the incorporation of reclaimed asphalt pavement (RAP) in the mixture. Also, it addresses surface preparation, material properties, tack coat, mixture design requirements, RAP testing requirements, and mixture performance criteria in terms of reflective cracking, thermal cracking, fatigue cracking, and rutting. The National Center for Pavement Preservation (NCPP) published and posted the pilot specification on the AASHTO Transportation System Preservation Technical Services Program (TSP2) website. In 2011, the state transportation agencies of Minnesota, New Hampshire, and Vermont placed demonstration projects of the HiPO mixture incorporating up to 25% RAP. This paper presents the evaluation of the laboratory performance of plant produced mixtures from field project of three state DOTs (Minnesota, New Hampshire, and Vermont). Based on the evaluation of the mixtures and field observations, recommendations were provided to refine the pilot specification. It was recommended to put more emphasis on the testing of the RAP materials, as it showed a significant impact on the performance of the mixtures. Furthermore, surface preparation of the existing pavement impacted the performance of the HiPO mixture. Finally, to make the specifications universal, alternative tests were proposed.

BACKGROUND

A pilot regional specification for HiPO mixtures using a HiMA binder, Superpave 9.5-mm Highly Polymer-Modified Thin Overlay Specifications, was developed in response to changes in the asphalt paving industry. Specifically, because of budget constraints, state DOT agencies are now focusing their resources and efforts on preserving the existing roadway infrastructure as opposed to new construction or rehabilitation (*1–3*). This approach allows for maximization of already limited funds and maintains existing roadways in good condition. This type of asset management approach is highly supported by the FHWA, AASHTO, and national and regional pavement preservation organizations like the NCPP. For this study, member agencies from the NEPPP including New Hampshire, Vermont, Massachusetts, Rhode Island, New Jersey, and

Maryland, as well as PAPA were involved in the development of the pilot specification. The goal of the specification was to provide a guide that could be utilized to develop overlay HiPO mixtures that address the reflective cracking, thermal cracking, fatigue cracking, and rutting issues encountered with conventional overlays that shorten their service life.

The NCPP published and posted the pilot specification on the AASHTO TSP2 website (*4*). The pilot specification addressed surface preparation, material properties (binder, aggregate, tack coat), mixture design requirements, RAP testing requirements, and mixture performance criteria in terms of reflective cracking, thermal cracking, fatigue cracking, and rutting. From the posting of the pilot specification, multiple state agencies (Maryland, Massachusetts, Minnesota, New Hampshire, Oregon, Pennsylvania, Rhode Island, Vermont, Virginia, and Washington, D.C.) expressed interest in utilizing the pilot specification for demonstration paving projects. In 2011, three state DOTs (Minnesota, New Hampshire, and Vermont) placed demonstration projects of the HiPO mixtures incorporating up to 25% RAP. The data available from the testing of the plant produced mixtures for these projects were used to revisit the specifications in order to verify and suggest refinements to the performance requirements.

Per the specification, for the projects that were placed, a HiMA binder was used. This binder contained 7.5% of a styrene-butadiene-styrene (SBS) polymer designed not to increase the binder viscosity at larger dosage rates. Normally, large dosages of polymer increase the binder viscosity which can lead to construction issues such as poor mixture workability. As outlined in the specification, the HiMA binder had a performance grade (PG) of PG 76-34 or PG 82-28.

The plant-produced mixture for each of the projects was sampled during placement and then evaluated in the laboratory in terms of reflective cracking using the Texas overlay tester (OT), thermal cracking using the thermal stress restrained specimens test (TSRST), fatigue using the four-point flexural beam fatigue, and rutting using the Asphalt Pavement Analyzer (APA). In attempt to make the specifications more universally applicable for all state agencies, additional tests that were not in the pilot specifications were performed to determine if they can a serve as a substitute for tests listed in the specifications. These tests were the Hamburg wheel tracking device (HWTD) for rutting and the semicircular bending (SCB) test for cracking.

Results of laboratory test and field observations resulted in suggested refinements to the pilot specification in areas of mixture design, RAP testing, surface preparation, binder requirements, and mixture performance testing (reflective cracking, fatigue cracking, and rutting).

OBJECTIVES

To develop the specifications, several objectives were outlined, including the following:

1. Develop a pilot specification for a 9.5-mm Superpave HiPO mixture incorporating a HiMA and up to 25% RAP based on inputs from state DOTs, industry, and academia;
2. Assist three state DOTs (Minnesota, New Hampshire, and Vermont) in verifying HiPO mixture designs developed by contractors using the pilot specification;
3. Evaluate the performance of the plant produced mixtures from the field projects in the laboratory based on performance tests and criterion listed in the pilot specification;

4. Perform additional tests not in the pilot specification in attempt to make a more universal specification applicable for all state agencies;
5. Document any special surface preparations and exiting distress prior to placement of the HiPO mixtures;
6. Evaluate the field performance of the mixtures; and
7. Provide recommendations to refine the pilot specification based on the performance of the mixtures measured in the laboratory and the field.

DESCRIPTION AND REQUIREMENTS OF PILOT SPECIFICATION

The specification requirements for the HiPO mixture performance are shown in Table 1. The developed pilot specification, contrary to some available thin lift specifications, was tailored to address the condition of the existing pavement. The specification provided provisions to alter the HiMA modification based on the level of severity of the distresses of the existing pavement. Additionally, the pilot specification was designed to allow for the use of up to 25% RAP in the mixture or the amount of RAP corresponding to 1% binder replaced, whichever is less. The percent binder replaced was calculated by Equation 1:

$$\text{Binder Replacement (\%)}= \frac{(\text{\% Binder in RAP})\times(\text{\% RAP in Mixture})}{\text{Total \% Binder in Mixture}} \tag{1}$$

The specification outlined how mixtures incorporating RAP must perform within a defined range relative to the same mixture with all virgin materials. The final version of the pilot specification addressed surface preparation, material properties (binder, aggregate, tack coat), mixture design requirements, RAP testing requirements, and mixture performance measures.

Several material property requirements were outlined in the pilot specification. The HiMA binder was required to have a performance grade of PG 76-34 or PG 82-28. The PG 76-34 was recommended for roadways exhibiting only low severity cracking. The PG 82-28 was recommended for roadways with little or no distress. If milling of the existing pavements was conducted, either binder could be utilized. Tack coat material type was required to be either polymer modified emulsion or the performance grade asphalt binder specified by the corresponding state DOT in which the HiPO mixture would be placed.

Extensive testing of the RAP material was required to be completed prior to the mixture design (binder content, extraction–recovery of binder and subsequent binder grading, recovered RAP aggregate gradation, specific gravity of recovered RAP aggregates, and maximum theoretical specific gravity of RAP). Additionally, no material was allowed to be added to the RAP stockpiles after the required testing samples were taken. The HiPO mixture was required to meet all the 9.5-mm Superpave requirements listed in AASHTO R35: Standard Practice for Superpave Volumetric Design for Hot-Mix Asphalt and AASHTO M323: Standard Specification for Superpave Volumetric Mix Design (*5*). These requirements are further outlined in Table 2. Additionally, all volumetric properties for mixtures incorporating RAP were required to be the same for the mixture without RAP.

The pilot specification outlined laboratory mixture performance criteria, Table 1, in terms of reflective cracking, thermal cracking, and fatigue cracking.

TABLE 1 Overview of Pilot Specification Binder and Mixture Performance Requirements

HiPO Mixtures without RAP		
Property	**Device/Test**	**Criteria**
Thermal cracking temperature of mixture	TSRST: AASHTO TP 10-93	± 6°C from the low-temperature PG of the binder (minimum of 3 test specimens per mixture)
Cracking	OT: Texas DOT Test Designation Tex-248-F	Mixtures shall exhibit average OT cycles to failure (93% load reduction) ≥ 300
Fatigue life[a]	Flexural beam : AASHTO T 321	≥100,000 cycles[a]
Rutting	APA: AASHTO TP 63 at the standard PG high temperature for the project location	Average rut depth for 6 specimens is ≤ 4 mm at 8,000 loading cycles
Added Requirement for HiPO Mixtures with RAP		
Property	**Device/Test**	**Criteria**
Cracking	OT: Texas DOT Test Designation Tex-248-F	Mixtures containing RAP shall exhibit average OT cycles to failure (93% load reduction) within ± 10% of the OT cycles to failure of control specimens without RAP (minimum of 3 test specimens per mixture)

[a] The specification outlines that it is preferred that the strain level should be equal to the strain in the existing hot-mix asphalt layer or alternatively use a strain level of 750 microstrain when PG 76-34 is used and use a strain level of 500 microstrain when a PG 82-28 is used.

EXPERIMENTAL PLAN

An experimental plan was developed as shown in Figure 1. A majority of the plan consisted of laboratory testing of plant produced mixture from the three field trial projects to determine each mixture's conformance to the pilot specification.

DEMONSTRATION PROJECT INFORMATION

Three demonstration projects involving the placement of a HiPO mixture were attempted in 2011. Only two of the three projects placed met the gradation requirements for the HiPO mixture (New Hampshire and Vermont). The Minnesota mixture did not meet the gradation requirements and was excluded from further evaluation as will be discussed later.

The New Hampshire DOT had 1,500 tons of the HiPO mixture incorporating 25% RAP on Route 202 in Rochester. This roadway segment has an annual average daily traffic (AADT) of 4,600 vehicles. The existing pavement was in poor condition and no milling was done prior to the placement of the HiPO. The HiPO mixture was placed at a one inch thickness on a 1 3/4-mi section of the road. A conventional New Hampshire DOT mixture was placed on an adjacent section as well for comparison purposes.

TABLE 2 Mixture Gradation and Design Details

Sieve Size	New Hampshire HiPO	Vermont HiPO No RAP	Vermont HiPO with RAP	Minnesota Mixture[a]	Pilot Spec.	Pilot Spec. Production Tolerance
25.0 mm	—	—	—	—	—	—
19.0 mm	—	—	—	100	—	—
12.5 mm	100	100	100	95.0	100	±6
9.5 mm	98.8	99.0	98.0	83.0	90–100	±6
4.75 mm	68.4	83.0	81.0	62.0	≤90	±6
2.36 mm	49.9	55.0	55.0	50.0	32–67	±4
1.18 mm	36.8	34.0	35.0	35.0	—	—
0.600 mm	26.2	21.0	21.0	24.0	—	—
0.300 mm	15.2	11.0	11.0	13.0	—	—
0.150 mm	8.0	6.0	6.0	6.0	—	—
0.075 mm	4.8	3.7	3.7	3.3	2–10	±1
RAP (%)	25	0	24	25	25 max.	—
Total binder content (%)	6.3	6.8	6.5	5.3	6.5 min.	± 0.3
Virgin binder content (%)	5.3	6.8	5.5	4.9	—	—
Mixing temperature	171°C (340°F)	155–177°C (311–351°F)	155–177°C (311–351°F)	153–161°C (307–321°F)	—	—
Compaction temperature	149°C (300°F)	144–154°C (291–310°F)	144–154°C (291–310°F)	129–133°C (265–272°F)	—	—
N_{Design}	75	65	65	90	—	—
Binder Grade Information and Rheological Properties						
Base binder PG grade	200 PEN	200 PEN	200 PEN	PG 52-34	—	—
HiMA PG grade	PG 76-28[(2)]	PG 76-34	PG 76-34	PG 76-34	PG 76-34 or PG 82-28	—
HiMA cross-over frequency (ω_c)	215.1259	295.2267	295.2267	362.6039	—	—
HiMA rheological index (R)	2.736479	2.629055	2.629055	2.758131	—	—
HiMA defining temperature (T_d)	–15.3293	–15.9699	–15.9699	–17.8842	—	—

NOTE: — = not applicable; max. = maximum; min. = minimum.

[a] Minnesota mixtures did not meet the NMAS for a HiPO mixture as it was 12.5-mm mixture, not a 9.5-mm mixture.

[b] Binder low-temperature continuous grade was –33°C.

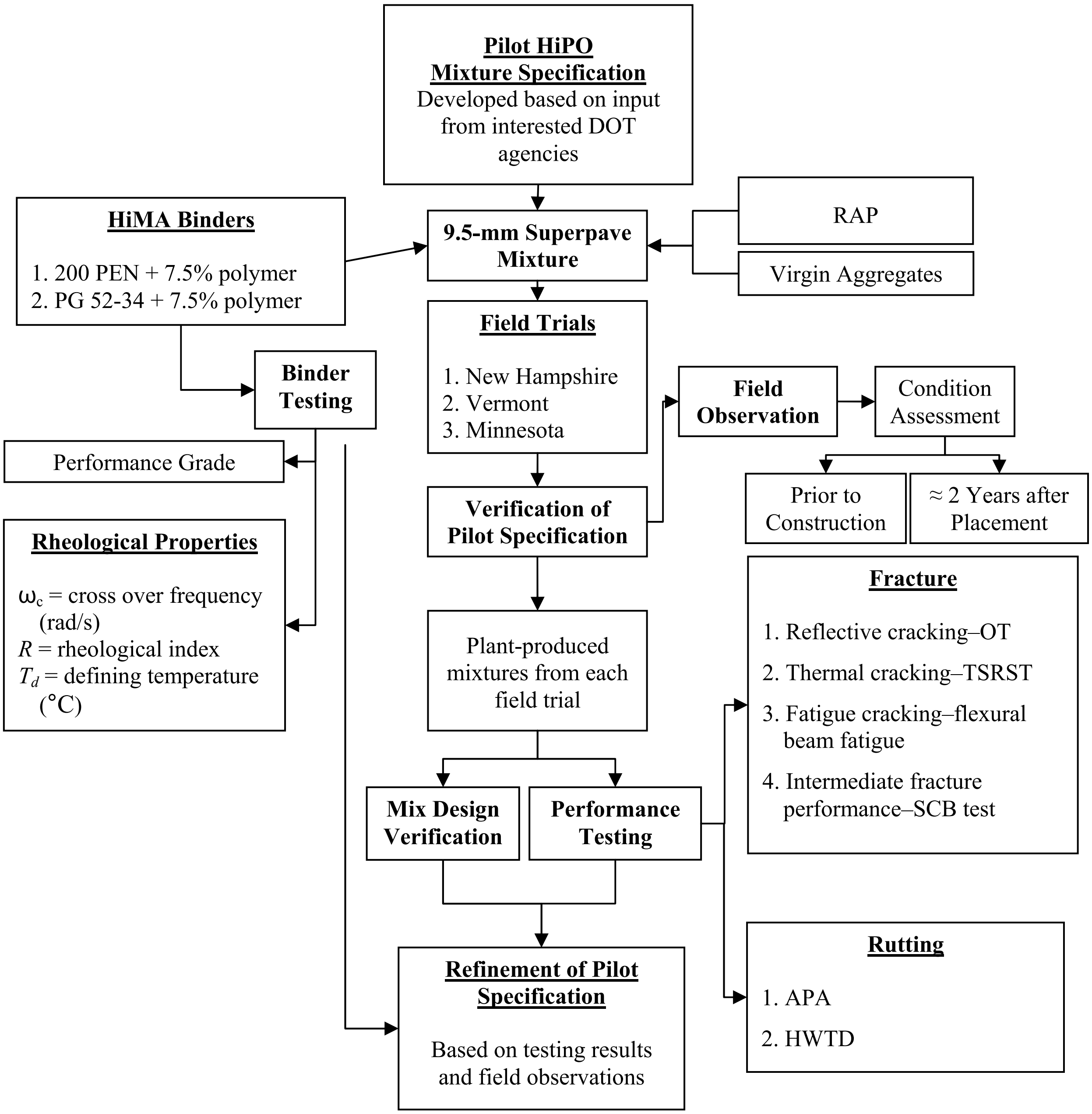

FIGURE 1 Experimental plan.

The Vermont Agency of Transportation (VTrans) had two 1-mi sections of HiPO mixture placed in the summer of 2011. One HiPO mixture contained no RAP and the other HiPO mixture contained 25% RAP for comparison purposes. The mixtures were placed on US-7 in Danby, Vermont. This roadway has an AADT of 4,500 vehicles. Per the VTrans representative, the existing pavement surface was in its 14th year of service and in “fair to good” condition. The representative noted that there were isolated areas of permanent deformation, some transverse cracking and some shrinkage cracking. Prior to overlay placement, surface preparations included spot shimming of permanent deformation areas, crack sealing along the length of the project, patching of cracks wider than 25.4 mm (1 in.), and patching of all potholes. Milling was only completed at transition areas and across bridges.

MATERIALS AND MIXTURE DESIGN

Binders

The HiMA binder utilized in the HiPO mixtures was designed to increase the viscosity of the virgin asphalt binders without adversely affecting the workability of the mixtures. For each field project, the base binder (200 PEN or PG 52-34) was heavily modified with 7.5% of a SBS polymer to create the HiMA binder. As outlined in the pilot specification, the target final performance grade of the HiMA binder was a PG 76-34 or a PG 82-28. For the field demonstration projects, the PG 76-34 HiMA was used since each field projects had some existing distress. The mixing and compaction temperatures utilized during production are shown in Table 2.

Reclaimed Asphalt Pavement

Per the pilot specification, the RAP utilized in the mixture designs was required to be extensively tested prior to the mixture design approval. The demonstration projects were placed without the entire required RAP testing being completed. Typically only RAP gradation and binder content were determined.

Mixture Design Verification

Mixture design information is shown in Table 2. This information was submitted to and approved by each respective state DOT prior to production. The pilot specification gradation targets, production tolerances, binder content target, and RAP content limitations are also shown in Table 2.

The Minnesota mixture did not meet the gradation and binder content criteria of the pilot specification. The Minnesota mixture was a 12.5-mm mixture based on an existing specification and not the 9.5-mm mixture required by the pilot specification. The state elected to use this mixture as opposed to changing the gradation to meet the proposed specification. Therefore this mixture was not included in the remainder of the evaluations in this study.

For the remaining field demonstration projects, loose plant produced HiPO mixture was sampled during production. To verify the mixture properties, the plant produced mixtures were re-heated in the laboratory to the compaction temperatures noted in Table 2 and compacted in the Superpave gyratory compactor (SGC) to the design gyration level specified in for each project. The volumetric properties of these specimens were then verified for conformance with the requirements of AASHTO M323: Superpave Volumetric Mix Design, Table 6 as outlined in the pilot specification.

Mixture design verification in the laboratory indicated that the New Hampshire HiPO mixture had lower (2.0%) air voids than the design of 4.0%. The corresponding voids in mineral aggregate (VMA) for the mixture was 16.3% (15.0% minimum design) and the voids filled with asphalt (VFA) was 87.9% (65% to 75% design). During production, these issues with the mixture volumetrics were noted by the state DOT and brought to the attention of the research team. Although the mixture volumetric properties could be corrected by altering the binder content, the research team and the state DOT agreed that maintaining the binder content was more critical in evaluation of the HiPO mixture. Binder content is more vital for the performance of thin lift mixtures as they are functional and not structural layers. Thus no adjustments to the mixture were made. Similar trends in the mixture volumetric properties were noted for the Vermont HiPO mixtures. For Vermont, the HiPO mixture without RAP had an average air void content of 3.2% and the HiPO mixture with RAP was 2.7%. This data along with the fact that since these mixtures did not exhibit early rutting or shoving in the field, indicated that the specification should be revised to expand the acceptable range of air voids to 3±1%.

BINDER TESTING

Performance Grade

As outlined in the pilot specification, the addition of the 7.5% SBS polymer to the base binder should result in a HiMA binder with a performance grade of PG 76-34 or PG 82-28 (desired grade based on existing pavement condition). Thus, the binders were tested by each respective state DOT agency to verify their performance grade in accordance with AASHTO R29: Grading or Verifying the Performance Grade of an Asphalt Binder and AASHTO M320: Standard Specification for Performance-Graded Asphalt Binder (*5*). The results of the PG grading verification are shown in Table 2.

Rheological Properties

The Christensen-Anderson model (CAM), Equation 2, was used to determine the rheological properties (ω_c, R, and T_d) associated with constructing a master curve for the HiMA binder used in New Hampshire and Vermont. The parameters ω_c, R, and T_d have specific physical significance (*6*). The cross-over frequency, ω_c, is a measure of the overall hardness of the binder. As the cross-over frequency increases, the hardness decreases at the reference temperature, which is generally more desirable for binders used in thin lift mixtures. The rheological index, R, is an indicator of the rheological type. It is defined as the difference between the log of the glassy modulus and the log of the dynamic modulus at the cross-over frequency. As the value of R increases, the master curve becomes flatter indicating a more gradual transition from elastic behaviour to steady-state flow, which is a desirable trend for thin lift mixtures. Normally, R is higher for oxidized asphalt (*6*). The defining temperature, T_d, is related to the glass transition temperature of the binder, and is an indicator of the temperature dependency. The temperature dependency increases as T_d increases.

$$G^*(\omega) = G_g\left[1+\left(\frac{\omega_c}{\omega_r}\right)^{\frac{\log 2}{R}}\right]^{\frac{-R}{\log 2}} \tag{2}$$

where

$G^*(\omega)$ = complex shear modulus;
G_g = glass modulus assumed equal to 1 GPa;
ω_r = reduced frequency at the defining temperature, rad/s;
ω_c = cross over frequency at the defining temperature, rad/s;
ω = frequency, rad/s; and
R = rheological index.

It was deemed worthy to determine if the rheological properties of these binders were different and if the difference had any significant effect on the performance of the HiPO mixtures. The binder data in Table 2 illustrated that the rheological properties ω_c, R, and T_d were similar, which suggests that the HiMA binders should have similar effects on the performance of the HiPO mixtures.

MIXTURE PERFORMANCE TESTING

In general, all mixture specimens for performance testing were fabricated by reheating loose plant produced mixture to the compaction temperatures and subsequently compacting in the SGC.

Reflective Cracking Testing: OT

The OT was used to evaluate the reflective cracking potential of each HiPO mixtures in accordance with Texas DOT specification Tex-248-F (*7*).

Trimmed gyratory specimens for this test had an air void level of 7.0±1.0%. Specimens were tested at a temperature of 15°C (59°F) which is a typical intermediate temperature corresponding to the field project locations. Mixtures were tested with a joint opening (displacement) of 0.06 cm (0.025 in.) and a failure criteria of 93% reduction in the initial load or 2,000 cycles (whichever occurred first). The results of the testing are shown in Table 3. Generally, mixtures with more cycles to failure exhibit more resistance to cracking (*7–9*).

The pilot specification required that all HiPO mixtures exhibit average overlay test cycles to failure (93% load reduction) greater than or equal to 300 cycles. In addition, if the HiPO mixture incorporated RAP, it should exhibit cycles to failure within ±10% of OT results for specimens without RAP. Note that the RAP versus no RAP comparison could only be completed for the Vermont mixtures as the remaining mixture contained RAP but did not have a counterpart without RAP.

The OT testing results shown in Table 3 suggested that the current pilot specification limit of greater than or equal to 300 cycles in the OT is acceptable as all mixtures met the criteria. This suggests the current pilot specifications limit of greater than or equal to 300 cycles in the OT appears to be a reasonable threshold.

TABLE 3 Mixture Performance Test Results

Mixture Cracking					
Type	**Reflective**	**Thermal**	**Fatigue**	**Fracture**	
Test information	Average OT cycles to failure (Tex-248-F)	AASHTO TP 10-93 TSRST average low-cracking temperature	AASHTO T 321 beam fatigue N_f to 50% reduction in stiffness	SCB test (*12*)	
Pilot specification criteria	Mixtures shall exhibit average OT cycles to failure (93% load reduction) ≥ 300 Added requirement for mixture incorporating RAP: Exhibit cycles to failure within ± 10% of specimens without RAP	± 6ºC from the low-temperature PG of binder	$N_f \geq$ 100,000 cycles at 750 μ strain for PG 76-34 binders (500 μ strain for PG 82-28 binders)	Not in spec. Critical value of strain energy, J_c, kJ/m^2	Mixture meets all cracking criteria in pilot spec.?
NH HiPO with RAP	2,000	–33.1ºC	348,266	NT	Yes
VT HiPO no RAP	2,000	–30.1ºC	794,790	0.45	Yes
VT HiPO with RAP	1,144	–27.8ºC	383,065	0.36	No, reflective and thermal

Mixture Rutting				
Test	**APA**	**HWTD**		
Test information	AASHTO TP 63 conducted at the standard PG high temperature for the project location	AASHTO T 324 Conducted at 50ºC		
Pilot specification criteria	Average rut depth for six specimens ≤ 4 mm at 8,000 cycles	Not in spec.—average rut at 10,000 cycles (mm)	Not in spec.—average rut at 20,000 cycles (mm)	Mixtures meets rutting criteria in pilot spec.?
NH HiPO with RAP	5.16	4.20	12.91	No
VT HiPO no RAP	2.03	2.55	8.98	Yes
VT HiPO with RAP	2.87	1.26	2.70	Yes

NOTE: NH = New Hampshire; VT = Vermont; NT = not tested due to lack of materials; spec. = specification.

The data from the Vermont mixtures indicated that the HiPO mixture containing RAP (1,114 cycles) was unable to meet the pilot specification criteria of ± 10% of OT results for HiPO specimens without RAP (> 2,000 cycles). This data may suggest that the reflective cracking resistance could be decreased when RAP is incorporated into the mixture. This highlights the need for testing the RAP stockpile before incorporating RAP in HiPO mixture to better understand its influence on the mixture performance. The only refinement to the specification that can be made based on this data is that complete RAP stockpile characterization should be mandatory before the mixture design process. No refinements can be made to the OT criterion for HiPO mixtures with and without RAP as only one set of comparative mixtures had been tested.

In terms of field observations of the HiPO mixture reflective cracking performance, only the HiPO mixture incorporating RAP placed in New Hampshire has had minimal cracking. The comparative conventional mixture placed on an adjacent section estimated to have 25% of cracking that has returned. Since the existing pavement was in poor condition and no milling was performed prior to the placement of the HiPO mixture, the lack of proper surface preparation may have been a contributing factor to the cracks reflecting through the mixtures. There have been no reports of reflective cracking on either HiPO mixture placed in Vermont where surface preparation were undertaken prior to placement of the HiPO mixture.

Thermal Cracking Testing: TRSST

Each HiPO mixture was tested in the TSRST device in accordance with AASHTO TP 10-93 (*10*). In the TSRST test, the asphalt specimen is cooled at a constant rate (–10°C/h) while its original length is held constant by the TSRST device. As the specimen cools it tries to contract but cannot which results in the accumulation of thermal stresses. Eventually the thermal stresses exceed the tensile capacity of the specimen resulting in specimen fracture (crack). The temperature at which this fracture occurs is recorded and noted as the thermal cracking temperature of the mixture.

A minimum of three replicate SGC specimens 185 mm (7.3 in.) tall by 150 mm (5.9 in.) in diameter were fabricated for each mixture. TSRST specimens were them cored and cut to a final height of 160 mm (6.3 in.) tall by 54 mm (2.1 in.) in diameter. The air voids of the final cut specimens were 7 ± 1%.

The pilot specification required that the mixture thermal cracking temperature be within ± 6°C from the low-temperature PG of HiMA binder which was approximately –34°C (shown in Table 2). All HiPO mixtures tested met the mixture thermal cracking requirement with the exception of the Vermont HiPO mixture with RAP which was only marginally outside the specification criteria at –6.2°C. This suggested that the current specification criterion is attainable. Furthermore, field observations of the HiPO performance have not indicated any signs of environmental related cracking after 2 years in service. As previously mentioned, the specification should be refined to require complete RAP characterization testing which was not completed. This RAP data would help clarify the cause of the larger decrease in the thermal cracking temperature for the Vermont mixture.

Fatigue Cracking Testing: Flexural Beam Fatigue

Each HiPO mixture was evaluated for fatigue resistance using the four point flexural fatigue apparatus following the procedure outlined in AASHTO T 321 (*5*). Slabs were fabricated in the

IPC Global Pressbox slab compactor. From each slab, beams with dimensions of 63 mm (2.5 in.) wide, 50 mm (2.0 in) tall, and 380 mm (15.0 in.) long were cut such that the sides had smooth faces. The air voids of the final cut specimens were 7±1%. Beam specimens were conditioned at the test temperature of 15°C (59°F) for at least two hours prior to testing. The 15°C (59°F) temperature was selected as it represents the intermediate temperature for the locations of the field projects.

The pilot specification required the testing of the HiPO mixtures in strain control mode. For the HiPO utilizing the HiMA binder with a target grade of 76-34, the pilot specification suggested the target strain level of 750 microstrains. Since a PG 76-34 binder was used for all demonstration projects, the HiPO mixtures were tested using a strain level of 750 microstrains.

Each fatigue test continued until the specimen reached 50% of its initial stiffness calculated at cycle 50. The number of cycles to failure was determined by fitting an exponential function to the flexural stiffness versus number of cycles and then evaluating the number cycles that it took to decrease the initial stiffness by 50%. The results of the testing are shown in Table 3.

The pilot specification required a number of cycles to 50% reduction in stiffness of ≥100,000 cycles at 750 microstrains. The data indicated that all the HiPO mixtures easily met the specification requirement regardless of whether or not RAP was incorporated into the mixture. This suggests further refinement to the specification may be needed to select the appropriate strain level used for this testing as it may not accurately reflect experienced field conditions. It is suggested to refine the specification so that the strain level is determined for the actual field location and utilized for this fatigue testing.

The Vermont HiPO mixture without RAP exhibited the highest number of cycles to failure, which may be attributed to the fact it contained more fine material (83% passing No. 4 sieve versus 68.4% passing No. 4 sieve for the New Hampshire mixture), higher binder content (0.5% more than the New Hampshire mixture) and did not contain any RAP (25% for the New Hampshire mixture). Similarly, comparing HiPO mixtures with and without RAP from Vermont, the data suggested that the HiPO mixture without RAP exhibit more fatigue resistance than similar mixtures incorporating RAP. No definitive conclusion on the impact of RAP on the fatigue resistance of the mixture can be made due to the lack of RAP characterization data; however the data suggested that the fatigue resistance of the mixture is reduced when RAP is incorporated. Because fatigue cracking generally does not appear early in the service life of a pavement, no other refinement to the pilot specifications can be made at this time based on field observations.

Fracture Testing at Intermediate: Semicircular Bending Test

In order to expand the testing options in the pilot specification, fracture resistance potential was assessed using the SCB approach proposed by Wu et al. (*11*). This test characterizes the fracture resistance of HMA mixtures based on fracture mechanics principles, the critical strain energy release rate, also called the critical value of *J*-integral, or J_c. To determine the critical value of *J*-integral (J_c), semicircular specimens with at least two different notch depths need to be tested for each mixture. In this study, three notch depths of 25.4, 31.8, and 38 mm were selected based on an a/r_d ratio (the notch depth to the radius of the specimen) between 0.5 and 0.75. Test temperature was selected to be 25°C which is a typical test temperature utilized previously for this type of testing. The semicircular specimen is loaded monotonically until fracture failure under a constant crosshead deformation rate of 0.5 mm/min in a three-point bending load configuration. The load and deformation are continuously recorded and the critical value of *J*-integral (J_c) is determined using Equation 3 (*11*). Specimens were compacted to an air void level of 7 ± 0.5%. Triplicate specimens were utilized for this test. In general, the coefficient of variation was 15% for the samples tested.

$$J_c = \left(\frac{U_1}{b_1} - \frac{U_2}{b_2} \right) \frac{1}{a_2 - a_1} \tag{3}$$

where

b = sample thickness;
a = the notch depth; and
U = the strain energy to failure.

Table 3 shows a comparison of the critical strain energy (J_c) data for the HiPO mixtures evaluated in this study. The New Hampshire HiPO mixture was not evaluated due to lack of materials. High J_c values are desirable for fracture-resistant mixtures. A threshold of a minimum J_c of 0.50 to 0.65 kJ/m^2 is typically used as a failure criterion for this test. It was noted that none of the mixtures evaluated met the minimum criteria of J_c of 0.50 kJ/m^2. The Vermont HiPO mixture that contained no RAP showed an improved critical strain energy value as compared to mixture with RAP. Ultimately, more lab testing and field data is needed to determine which fatigue cracking test (beam fatigue and SCB) more accurately represents the field condition. Accordingly, the demonstration projects will be monitored for the next 3 years to confirm the field performance of the mixtures and determine which test most accurately reflects the realized performance.

Rutting: Asphalt Pavement Analyzer

The rutting resistance for the mixtures of each field project was measured using the APA in accordance with AASHTO TP 63 (now AASHTO T 340) as outlined in the pilot specification (*5*).

Six replicate APA specimens were fabricated to a height of 75 mm (3.0 in.) and air voids of 7 ± 1%. The APA rut test was conducted at 60°C (140°F) which corresponded to a realistic estimate of the maximum high pavement temperature that each mixture would experience in the field. The results of the testing are shown in Table 3.

The pilot specification required that each HiPO mixtures exhibit an average rut depth less than or equal to 4 mm at 8,000 cycles. Both Vermont HiPO mixtures were able to meet this requirement of the specification, but not the New Hampshire HiPO mixture. As previously discussed, the New Hampshire HiPO mix design had lower air voids than the target in order to maintain the minimum binder content required by the specification. This might be the reason for the mixture not meeting the requirement for the APA. However, Field observations after 2 years in service have not indicated any rutting in any mixture. This suggested the APA requirements may be too stringent and need refinement.

Rutting: Hamburg Wheel Tracking Device

Since not every state agency has access to an APA for rut susceptibility testing, another popular device known as the HWTD was utilized. In this test mixture specimens are placed in a heated water bath at a specified temperature and subjected to continuous loading from a steel wheel. The HWTD data is typically utilized to assess the moisture susceptibility of mixtures in terms of a stripping inflection point (SIP). The SIP is determined by plotting the rut depth versus numbers of passes of the steel wheel. For this project, the average rut depth at specific intervals was determined. All HWTD testing for this study was conducted in accordance with AASHTO T 324 (*5*).

HWTD specimens were fabricated to a height of 60 mm (2.36 in.)and an air voids of 7 ± 1%.The water bath temperature during testing was 50°C (122°F) and specimens were allowed to soak for 30 min prior to loading as outlined in AASHTO T 324. The results of the testing are shown in Table 3. A comparison of the APA and HWTD results showed similar trends with the Vermont HiPO mixtures exhibiting better rut resistance. Accordingly, a rutting criterion could be added in the pilot specification for using the HWTD. Again, field observations have not show any evidence of rutting in any mixture after 2 years in service.

FIELD PERFORMANCE OBSERVATION INFORMATION

New Hampshire Route 202

After 2 years in service, the HiPO mixture is performing well. The HiPO mixture has minimal cracking returned. The conventional mixture is estimated to have 25% of cracking that has returned. Currently, the HiPO mixture is showing significantly less cracking, transverse, and fatigue, in comparison to New Hampshire's conventional mixture

Vermont US-7

In summer 2012 the VTrans representative noted that there is "no apparent distress in either test section as of mid to late spring 2012." Similarly, in spring 2013 there is still no apparent distress in either section, HiPO with and without RAP. The VTrans reiterated that VTrans is "very pleased with the mixture."

PROPOSED REFINEMENTS TO THE SPECIFICATION BASED ON FIELD AND LABORATORY DATA AND OBSERVATIONS

Based on the field observations and laboratory testing, areas for refinement of the pilot specification were noted. The following outlines the proposed refinements:

- Using plant produced mixtures, the laboratory compacted specimens did not meet the target 4.0% air voids at N_{design}. Samples were compacted at the compaction temperature. It is suggested to maintain the minimum required design binder content (6.5% by weight of mixture) even if the mixture exhibits low air voids. The binder content is considered more critical to the performance of the mixtures. The specification should be revised to expand the acceptable range of air voids to 3±1% since these mixtures did not exhibit early rutting or shoving in the field.

- Because of the influence of RAP on the resultant mixture performance results for all cracking tests, all RAP characterization tests in the specification should be completed prior to the mixture design verification. This should be done in an effort to better understand the impact of the amount and properties of the RAP on the resultant mixture. The specification should be revised to make this RAP testing mandatory.
- No definitive refinements could be made to the OT criterion for HiPO mixtures with and without RAP as only one set of comparative mixtures had been tested. The available data suggest that the pilot specification criteria of ±10% agreement between the two mixtures results may be too stringent, but further testing and field observation data will be collected before any changes are proposed.
- The flexural beam fatigue data suggested refinement to the specification may be needed to determine the appropriate strain level used for fatigue testing as it may not accurately reflect experienced field conditions. All mixtures passed the fatigue testing at the 750 microstrain level utilized. It is suggested to refine the specification so that the strain level is determined for the actual field location and utilized for this fatigue testing.
- Both Vermont HiPO mixtures were able to meet the APA rutting requirement of the specification, but not the New Hampshire HiPO mixture. Field observations after 2 years in service have not indicated any rutting in any mixture. This suggested the APA requirements may be too stringent and may need refinement. This will be confirmed through testing of future demonstration projects and field observations of existing demonstration projects.
- In order to make the specifications more universal to all end users, it is suggested to expand the specification to include another rut testing device like the HWTD and corresponding rutting limits should be set and included in the specification. Existing state agencies' specifications that utilize the HWTD could be used as a starting point in establishing criteria for the HiPO specification. The use of another intermediate fracture test, like the SCB, should also be considered and added to the specification.
- The specification should be revised to highlight the need for proper surface preparation (milling, crack sealing, etc.) prior to placement of these mixtures. In New Hampshire the existing pavement was in poor condition and no milling was done prior to the placement of the HiPO mixture, the lack of proper surface preparation may have been a contributing factor to the cracks reflecting through the mixture. In Vermont, surface preparations were undertaken prior to placement of the HiPO mixture and there have been no reports of reflective cracking for either HiPO mixture.
- The requirements for the HiMA binder selection in the pilot specification were based on severity of existing distress of the pavement, either low to no distress. HiPO mixtures developed following this specification should not be placed on roadways with moderate or greater distresses or structural deficiencies. In order to make the specification more universal, it is proposed to revise the specification to completely clarify this issue so that HiPO mixtures are not utilized incorrectly.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results and analyses of the data, the following conclusions were made:

- Results of laboratory testing and field observations suggested refinements to the pilot specification in areas of mixture design, RAP testing, surface preparation, binder requirements, and mixture performance testing (reflective cracking, fatigue cracking, and rutting).
- The rheological properties derived from construction of the binder master curves (ω_c, R, and T_d) were similar, suggesting that the HiMA binders should have similar effects on the performance of the HiPO mixtures.
- The reflective and fatigue cracking data indicated that the HiPO mixtures are resistant to cracking, but this resistance could be decreased when RAP is incorporated into the mixture.
- APA and HWTD rut testing indicated similar rankings of rut resistance of the HiPO mixtures. One HiPO mixture did not meet the specification criteria for rutting, but no mixtures have exhibited rutting in the field.
- The impact of RAP on the mixtures performance could not be properly evaluated as the required RAP testing was not completed prior to mixture design. Therefore the influence of the RAP on overall binder grade and degree of binder blending could not be ascertained.

AUTHOR'S NOTE

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