Guidebook for Application of Polymer-Modified Asphalt Overlays: From Decision-Making to Implementation

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16. Abstract

After the successful experiences of multiple transportation agencies in adopting the usage of polymer-modified asphalt (PMA) cement overlays, now is the time to advocate for the implementation of this pavement preservation technique. Despite the affirmative endorsements from numerous departments of transportation (DOT), a structured process for systematically selecting PMA overlays under specific pavement and service conditions remains conspicuously absent. Incorporating the application of PMA overlays, or any analogous treatment, into agencies' decision-making frameworks hinges upon comprehensive insights into the treatment's performance and cost-effectiveness across diverse pavement types and varying service conditions. Regrettably, quantitative data to substantiate objective decision-making remain limited.

This research endeavors to lay the groundwork for the integration of PMA overlays into agencies' overall pavement preservation strategies. This goal is accomplished through the development of the guidebook presented herein, which offers insights into the implementation and efficacy of PMA overlays. The objective of this guidebook is to expedite the assessment of potential benefits conferred by PMA overlays under diverse conditions. In turn, this facilitates informed decisions by pavement engineers on whether they represent a viable and efficient pavement preservation strategy.

To meet the objectives, the research team agglomerated the collective experiences of US transportation agencies in utilizing PMA overlays and reviewed pertinent literature to foster a framework for selecting the optimal timing and techniques for PMA overlay treatments. The researchers conducted in-depth scrutiny of prior PMA overlay endeavors, particularly the experiences of state DOTs, and direct engagements with DOT engineers. This comprehensive approach primarily sought to accrue pavement performance data before and after the placement of overlays. Secondly, it aimed to uncover insights into success stories, design methodologies, material choices, and construction practices. The amassed data set and analytical findings serve as the foundation for quantifying treatment effectiveness, measured in terms of extended service life and benefit-cost ratios.

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LIST OF ABBREVIATIONS

Abbreviation	Definition
AADT	Annual average daily traffic
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt concrete
ADT	Average daily traffic
ADTT	Average daily truck traffic
APA	Asphalt pavement analyzer
APT	Accelerated pavement testing
BCA	Benefit-cost analysis
BCR	Benefit-cost ratio
CAM	Crack attenuating mixture
DOT	Department of transportation
DSR	Dynamic shear rheometer
EMA	Ethylene methacrylate
ESAL	Equivalent single axle load
EUAC	Equivalent uniform annual cost
EVA	Ethylene-vinyl acetate
FDOT	Florida DOT
FHWA	Federal Highway Administration
HiMA	Highly modified asphalt
HMA	Hot-mix asphalt
HPTO	High-performance thin overlays
IDT	Indirect tensile
IRI	International Roughness Index
MSCR	Multiple stress creep recovery
MTV	Materials transfer vehicle
NCAT	National Center for Asphalt Technology
NHS	National Highway System
NJDOT	New Jersey DOT
PCI	Pavement condition index
PG	Performance grade
PMA	Polymer-modified asphalt
PMIS	Pavement Management Information System
RAP	Reclaimed asphalt pavement
RAS	Reclaimed asphalt shingles
SBR	Styrene-butadiene-rubber
SBS	Styrene-butadiene-styrene
SHS	State highway system
SMA	Stone-matrix asphalt
TOPS	Targeted Overlay Pavement Solutions

EXECUTIVE SUMMARY

After successful experiences of multiple transportation agencies in adopting the usage of polymer-modified asphalt (PMA) cement overlays, now is the time to advocate for the implementation of this pavement preservation technique. Despite the affirmative endorsements from numerous departments of transportation (DOT), particularly the state DOTs, a structured process for systematically selecting PMA overlays under specific pavement and service conditions remains conspicuously absent. Incorporating the application of PMA overlays, or any analogous treatment, into agencies' decision-making frameworks hinges upon comprehensive insights into the treatment's performance and cost-effectiveness across diverse pavement types and varying service conditions. Within the context of PMA overlays, intermittent anecdotal accounts of successful implementations by select transportation agencies can be found. Regrettably, quantitative data to substantiate objective decision-making remain limited.

This research endeavors to lay the groundwork for the integration of PMA overlays into agencies' overall pavement preservation strategies. This goal is accomplished through the development of the guidebook presented herein, which offers insights into the implementation and efficacy of PMA overlays. The objective of this guidebook is to expedite the assessment of potential benefits conferred by PMA overlays under diverse conditions. In turn, this facilitates informed decisions by pavement engineers on whether they represent a viable and efficient pavement preservation strategy.

To meet the objectives, the research team agglomerated the collective experiences of US transportation agencies in utilizing PMA overlays and reviewed pertinent literature to foster a framework for selecting the optimal timing and techniques for PMA overlay treatments. The researchers conducted in-depth scrutiny of prior PMA overlay endeavors, particularly the experiences of state DOTs, and direct engagements with DOT engineers. This comprehensive approach primarily sought to accrue pavement performance data before and after the placement of overlays. Secondly, it aimed to uncover insights into success stories, design methodologies, material choices, and construction practices. The amassed data set and analytical findings serve as the foundation for quantifying treatment effectiveness, measured in terms of extended service life and benefit-cost ratios. Simultaneously, the project team's analysis of anecdotal information pertaining to project success and design/implementation strategies culminated in the identification of recommended materials and methodologies, ensuring a successful application of PMA overlays.

INTRODUCTION

Motivation

Polymer-modified asphalt (PMA) cements have been extensively used as high-performance pavement materials. Polymer modification of asphalt binder allows altering the material’s properties to suit specific climatic and service conditions. Controlling the binder viscosity, improving temperature stability, improving mechanical strength, reducing rutting susceptibility, improving fatigue behavior, improving abrasion resistance and binder-aggregate bond, and increasing service life are among the main advantages of polymer modification of asphalt binder (Yildirim 2007, Habbouche et al. 2020). The exceptional attributes of PMA enable a reduction in pavement layer thickness, establishing it as a highly advantageous material for both conventional and thin asphalt overlays. Nevertheless, the effectiveness of PMA in overlays is considerably contingent on several factors including the inherent properties of the asphalt and polymers, the harmonious interaction of materials, the precision of mixing procedures, the execution of construction practices, and the underlying layer’s properties. Conversely, akin to various pavement preservation techniques, the optimal efficacy of PMA overlays is realized when applied strategically, at the appropriate timing and in the suitable context.

PMA overlays made with different types of polymers, such as styrene-butadiene-styrene (SBS), reclaimed rubber, ethylene-vinyl acetate (EVA), and ethylene methacrylate (EMA), have shown promising performance and considerable economic benefits. However, these materials’ application is yet to be systematized and embedded within transportation agencies’ pavement management systems. The Iowa Department of Transportation (DOT) has reported an incredibly successful experience with using PMA overlays. Notably, the high-performance thin overlay (HPTO) application has been a tremendous success, making the Iowa DOT one of the pioneering states in harvesting the benefits of PMA overlays for preventive maintenance of pavements. The Iowa DOT has used HPTO, which it refers to as HIPRO, since 2015 as a novel, cost-effective, and highly durable pavement preservation technique, and thus the agency has created a valuable source for obtaining performance data and evaluating the effectiveness of PMA overlays in practice.

The objective of this project was to survey the experiences of state agencies using PMA overlays and consolidate the existing knowledge on the implementation and effectiveness of this pavement preservation technique in the guidebook presented herein to provide a decision-support source for future applications.

Background

The United States infrastructure system, of which the state highway system (SHS) and National Highway System (NHS) form a major part, holds an important key to the country’s national and global economic competitiveness. However, 4 in every 10 public roadways in the nation are in poor or mediocre condition (ASCE 2020). The NHS also contends with problems of underfunding, further necessitating the need for more proactive, innovative, and cost-effective solutions to address the pavement condition problem. Additionally, there has been a major and continuous increase in overall traffic volume and truck traffic, leading to more permanent deformation, cracking, and moisture damage.

Amongst the different pavement management alternatives, pavement preservation presents a planned, proactive, and economically viable alternative for extending the life of pavement structures. These preservation techniques include slurry seal, crack sealing, microsurfacing, chip seal, thin overlays, and scrub seal, among others, and they provide different ranges of service-life extension to the pavement sections (Chan et al. 2021). Overlays typically offer solutions for both asphalt and concrete pavements, allowing agencies to achieve long-lasting performance across various traffic, environmental, and pavement conditions. Thin overlays, on the other hand, have benefited from advancements such as performance-engineered mixtures, ensuring thinner bonded overlays through the use of stone-matrix asphalt (SMA), PMA, and other materials and agents that reduce rutting, increase resistance to cracking, and prolong pavement life (Newcomb 2009).

PMA cements have been widely adopted for improved performance in pavement material (Von Quintus et al. 2007). Through the altering of certain specific material properties of asphalt, polymer modification offers specific advantages such as enhanced mechanical strength, reduced rutting, improved fatigue behavior, and increased service life, among others (Von Quintus et al. 2007, Montanelli 2013, Mashaan et al. 2014). Appropriate utilization of PMA binders allows the designers to reduce the nominal maximum aggregate size, add higher asphalt content, and increase flexibility of a mixture without compromising mixture stability or rutting resistance (Habbouche et al. 2019, 2020). These superior characteristics of PMA allow for thickness reduction of the friction course layer, making it an excellent choice for regular and thin asphalt overlays. However, the performance of PMA in overlays depends significantly on the asphalt and polymer characteristics, material compatibility, traffic levels, mixing conditions, construction practice, and the underlying layer properties. On the other hand, like other pavement preservation techniques, PMA overlays show the highest efficiency when used appropriately as the right treatment, and at the right time and place. Given that a substantial portion of infrastructure investment is allocated to pavements, with overlays comprising a significant proportion of that investment, enhancing overlay performance becomes essential for maximizing returns and ensuring the longevity and safety of roadways (Small et al. 1991).

Polymers typically include a wide variety of performance properties modifiers, with elastomers (rubber) and plastomers (plastic) being the most dominant categories. Elastomers mostly enhance strength at high temperatures and elasticity at low temperatures, while plastomers are only suitable for strength enhancement. Polymer types from which PMA overlays are produced include SBS, EVA, reclaimed rubber, and EMA, with all of them showing significant economic and performance promise.

A number of DOTs have reported successful experiences with their applications of the preservation treatment—notably the Iowa DOT through its HPTO projects that date back to 2015—and have recorded tremendous effectiveness and durability with PMA overlays. Florida DOT (FDOT) has also reported significant success in its applications of highly modified asphalt (HiMA) overlays to address problems of severe rutting, fatigue, raveling, and reflective cracking under different traffic conditions, representing over 500,000 tons of placed HiMA across the state. While many applications of PMA overlays as a preservation treatment have been recorded by several transportation agencies, an aggregated decision-making framework for selecting it as the right treatment under a given set of conditions or constraints does not yet to exist,.

The selection and use of appropriate PMA overlays play a crucial role in pavement preservation. As a result, the Federal Highway Administration (FHWA) initiated a Targeted Overlay Pavement Solutions (TOPS) program aimed at integrating innovative overlay procedures into highway agency practices to achieve significant benefits, including improved performance, reduced traffic impacts, and lower costs associated with pavement preservation. The TOPS initiative focused on different asphalt overlay products including HPTO, crack attenuating mixture (CAM), HiMA, enhanced friction overlay (EFO), SMA, asphalt rubber gap-graded (ARGG), open-graded friction course (OGFC), and ultra-thin bonded wearing course (UTBWC). The adaptability of the different asphalt overlay products based on the number of states using them is as shown in Figure 1.

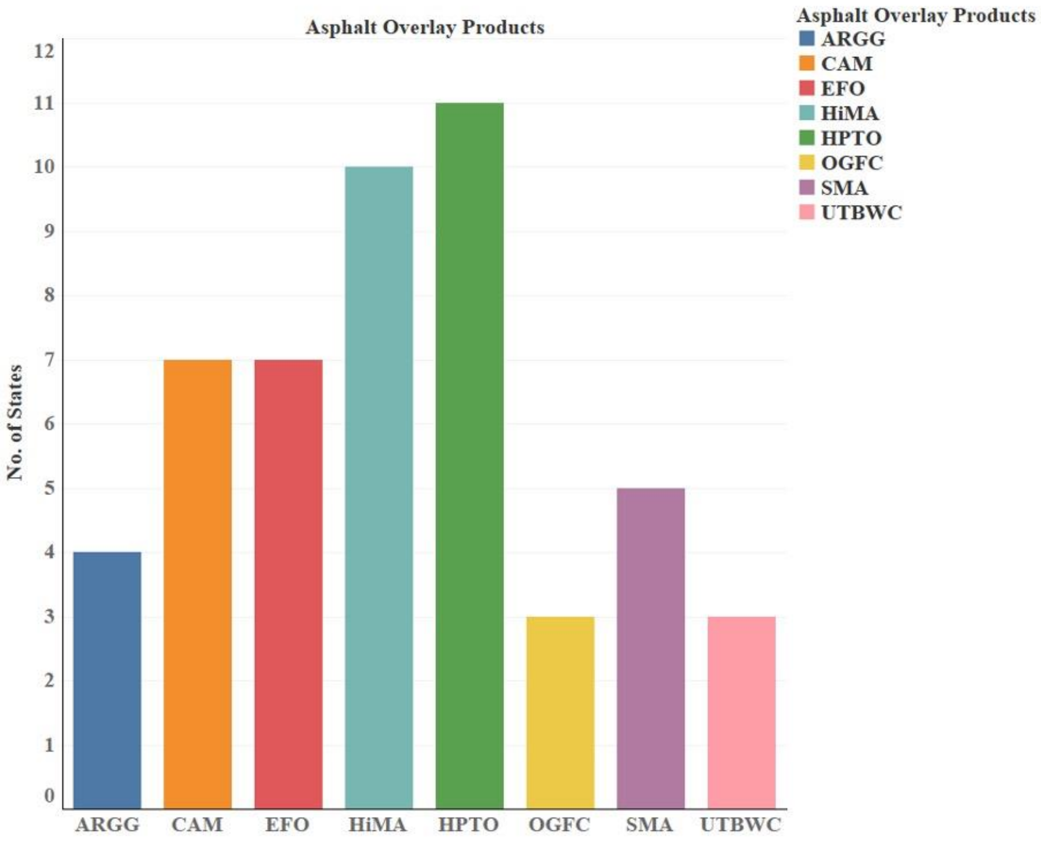


Figure 1. Asphalt overlay products distribution by number of states

Report Organization

This report can be divided into three parts.

Part one is based on the information drawn from the literature. This part includes the following chapters:

- Introduction, which provides the background on PMA overlay applications and describes the objectives of the research project.
- Literature Review, which provides a summary of application history, concepts, materials, and methods. Additionally, a literature guide is provided in the Appendix that lists pertinent issues related to PMA overlays, which frequently necessitate consulting the existing literature, and recommends some go-to publications.
- Case Studies and Implementation Examples that covers published information from previous implementations of PMA overlays by state DOTs, discussing the methods and specifications used therein and the resulting benefits, challenges, points of success, and lessons.

The second part of the report includes the chapter Decision-Making Process and builds on the information gained from previous chapters and the research team’s correspondence with state DOTs to develop the basic decision-making framework for the application of PMA overlays as a pavement preservation method.

The third part of the report includes evaluating the effectiveness of PMA overlays as a pavement preservation technique based on the data from the Iowa DOT and FDOT. The data analysis results are discussed in the chapter Data-Driven Evaluation of PMA Overlay as a Pavement Preservation Treatment.

The Conclusion and Recommendations chapter summarizes the findings, lessons learned, and recommendations for the implementation of PMA overlays as described in previous chapters and provides recommendations for future research.

LITERATURE REVIEW

PMA overlays have emerged as a promising solution to enhancing the durability and extending the service life of pavement structure in recent years, making research in this realm important. The primary intention of this literature review is to aggregate experiences and findings from the related research performed on PMA overlays. It also intends to summarize the background and specific applications of PMA and its adoption by transportation agencies. Through the literature survey, highlights of the different types of polymer modifiers, including variations in polymer concentration as well as classification of HiMA, are presented. Finally, the pavement performance benefits of PMA overlays are synthesized and discussed.

Overview of PMA Adoption, Types, And Effects

The adoption of PMA dates back to the 1970s, even though it was not until the 1980s that its implementation became commonplace in the United States (Yildirim 2007). Over the years, the practice of enhancing the physical and rheological properties of asphalt by introducing binders has become a well-established tradition within the asphalt industry. Major distresses related to the rheological properties of asphalt such as thermal cracking, fatigue cracking, and rutting are found to significantly affect the performance of pavement (Behnood and Gharehveran 2019). As a result of this, attempts were made by material scientists and engineers to alter the properties of asphalt using different types of modifiers including but not limited to polymers (Coplantz et al. 1993). The viscoelastic properties of PMA are substantially enhanced through the process of high-temperature and high-shear mixing with asphalt, creating a solid cohesive network (Polacco et al. 2015).

PMA involves the incorporation of polymers into traditional asphalt binders aiming to beneficially impart a range of properties that could improve the pavement’s resistance to distresses (Zhu et al. 2014). PMA overlays come in different types, with each best suited to specific underlying conditions and requirements, while also offering distinct advantages (Plati 2019). While there are several polymeric additives available for use in the global market, two major types (based on chemical composition) are utilized in the asphalt industry: elastomers and plastomers (Cuciniello et al. 2018). The most commonly used polymers for the purpose of asphalt binder modification include SBS, styrene-butadiene rubber (SBR), and EVA, which are all grouped as plastomers, as well as other forms of elastomers (Topal et al. 2011). The presence of these polymers serves to alter the asphalt binder’s characteristics, resulting in key benefits such as improved resistance to rutting, enhanced crack resistance, and increased durability and longevity, as well as enhanced flexibility and elasticity (Von Quintus et al. 2007).

At the network level, the application of PMA overlays presents great benefits to asset managers and agencies. Although, the initial construction cost of PMA overlays may be higher compared to other preservation alternatives, they come with the advantages of reduced maintenance requirements and longer service life extension, leading to significant life-cycle cost savings (Plati 2019). PMA overlays also offer superior performance characteristics compared to certain other preservation alternatives, enabling a more robust and resilient pavement network. Through the reduction in maintenance cycles, the durability and longevity of the roadway, as well as reduced disruption to traffic, is assured. PMA overlays find their application in a wide range of pavement preservation scenarios and across different traffic volumes. The typical performance grade (PG) of PMA includes, but is not limited to, PG 76-22, PG 64-28, PG 70-22, and PG 82-22, and is defined based on the project climate (Bukowski et al. 2012).

The utilization of PMA binders, notably with SBS, has garnered considerable attention since the initiation of the Strategic Highway Research Program. Polymers can be classified into elastomers, which amplify strength and elasticity across a wide thermal range, and plastomers, which augment overall strength. SBS serves as a typical example of an elastomer. PMA, particularly when incorporating SBS, is extensively employed in pavements subjected to high traffic loads, with the intention of bolstering resistance against deformations, elevating durability, and expanding the permissible temperature spectrum. The integration of polymers into asphalt increases viscosity, effectively addressing concerns about rutting and concurrently bolstering fatigue resistance. Beyond these mechanical advantages, PMA’s benefits encompass attributes such as improved aging resilience and enhanced adhesive bonding. These characteristics collectively contribute to mitigating challenges during construction and minimizing the likelihood of mix raveling (Rodenzo et al. 2018). Diagrams of the major categories of polymer modifiers and the most commonly used types are shown in Figure 2 (Illinois DOT 2005).

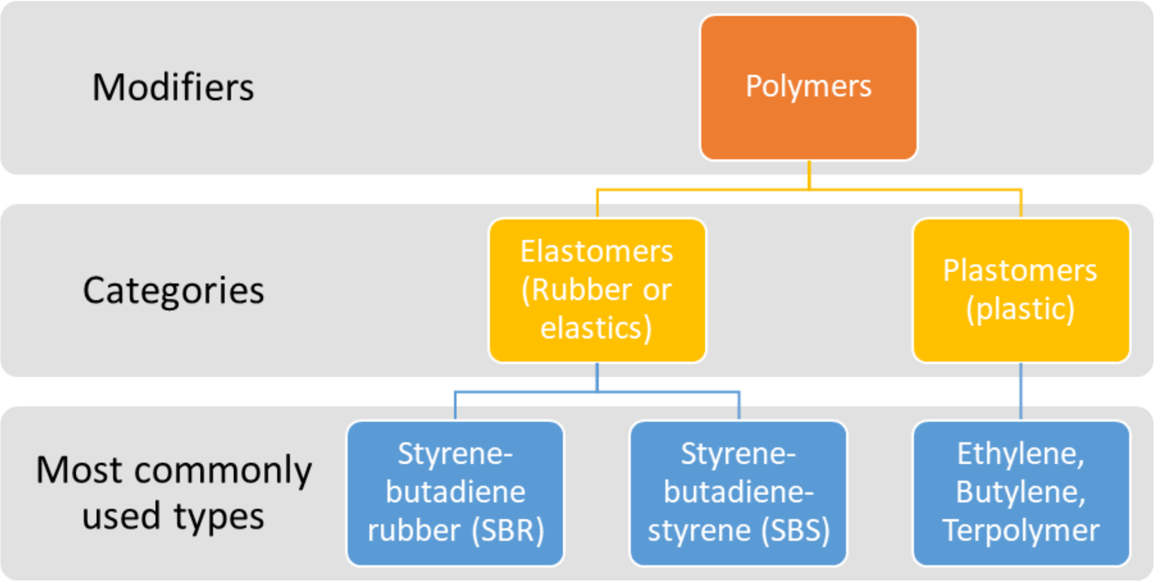


Figure 2. Polymer modifications and their most used types

Amongst the different commonly used types, SBS is the most recognized due its excellent elastic properties and recycling capabilities (Habbouche et al. 2021a).

The different polymer types and their distinct effects were examined in Habbouche et al. (2021b), presented under the classifications of natural rubber and tire rubber, SBR, and high polymer asphalt binders. The effects are as follows:

- Natural Rubber and Tire Rubber:
  - Improved rutting resistance
  - Issues with compatibility, storage stability, and decomposition
- SBR:
  - Improved low-temperature ductility, elasticity, and adhesive properties
  - Offers frost-resistance, anti-penetrability good mechanical properties
- High Polymer Asphalt Binders:
  - High polymer content leads to improved elasticity and resistance to rutting, shoving, and cracking
  - Phase reversal with increased polymer content transforms asphalt into an asphalt-modified polymer
  - Enhances resistance to oxidative age hardening for more durable pavements
  - Can be used to create asphalt-modified rubber, improving cracking resistance

The anticipated performance desired from altering the physical and rheological properties of asphalt using polymer modifiers varies significantly with the polymer concentration. Thus, it is necessary to consider and understand the potential effect and interaction of the asphalt source, polymer type, and polymer concentration through an understanding of each of the three factors (Al-Dubabe et al. 1998). In Chen et al. (2002), the effect of SBS modification on asphalt binder properties was investigated, with results reflecting optimal modified asphalt performance at greater than 5% SBS content. Cuciniello et al. (2018) also explored the effect of SBS-modified asphalt degradation with aging as a function of three different polymer concentrations. Results from this study emphasizes the strong correlation between higher polymer concentrations and increased elasticity of asphalt. Another study (Panda and Mazumdar 1999) considered EVA, a different type of polymer, in evaluating the effect of its concentration variation on binder properties. The study evaluated penetration, softening point temperature, and ductility across two EVA grades. Overall, increased polymer concentration led to decreased penetration and ductility and an increase in softening point temperature.

With past work reflecting the effect of polymer concentration variation on asphalt binder properties, it is then necessary to examine what constitutes high polymer modification of asphalt binders. In Chen et al. (2018), asphalt cement containing 6% of SBS was compared with 3% SBS and unmodified asphalt. The research classified the asphalt with 6% polymer content as highly modified and the 3% modified version as conventional. Rivera et al. (2021) in their study comparing the aging effects of conventionally modified and HiMA binders maintained a higher SBS dose range of 7%–8% for the latter. In a similar study evaluating the state of practice for high PMA binders, the authors prescribed an approximate rate of 3% and 7.5% polymer content as PMA and high PMA, respectively, with the latter showing higher elasticity range, which could be helpful in addressing related pavement failures (Habbouche et al. 2021a). Greene et al. (2014) showed through their study for FDOT that high polymer modification of asphalt offers increased rutting resistance, effectively making it a better candidate for heavy rutting problems compared to regular PMA and unmodified options. This was achieved at 6% SBS content, using PG 82-22. In all of the considered works, the range of SBS content sufficient for consideration as high polymer modification is 6%–8%. In conclusion, it is crucial to recognize that the classification of polymer modification as high or low/conventional is contingent upon the type of asphalt binder used and the design specifications or standards. This variability contributes to discrepancies observed among studies when designating polymer-modified asphalt binders with different polymer loading rates.

Performance Benefits of PMA Overlays

Pavement preservation offers transportation agencies an economically viable method of ensuring the longevity and sustainability of their highway network (Galehouse et al. 2003). While transportation agencies have little to no control over external factors that affect roads and highways, such as ever-increasing traffic demands and environmental challenges, they have a need for adept innovation in enhancing the effectiveness of available preservation techniques (Beatty et al. 2002). One such technique is PMA overlays, which have emerged as a promising solution to enhancing the durability and extending the service life of pavement structures in recent years (Habbouche et al. 2021a, 2022a). Von Quintus et al. (2007) estimated an expected increase in service life for flexible pavement of between 5 and 10 years across different site features tested, including traffic, climatic, underlying pavement condition, and foundation soils. The crack mitigation capabilities of conventional and high PMA overlays were revealed by several studies through laboratory and field testing; some notable studies include Uddin 2003, Habbouche et al. 2022a, and Habbouche et al. 2022b, with more given in the appended Table A.1.

Various DOTs have consistently reported substantial performance benefits associated with the application of PMA overlays. FDOT, through its accelerated pavement testing (APT) program, observed that the utilization of HiMA mixtures for overlay solutions effectively mitigates issues related to reflective cracking, reduces rutting, and enhances overall cracking performance, all of which contribute to an extended service life for pavements (Greene et al. 2014). Similarly, Mississippi DOT, through its field trials, confirmed that PMA overlays offer significant advantages, particularly in areas with high equivalent single axle load (ESAL), due to their enhanced resistance to rutting (Albritton et al. 1999). Oregon DOT’s findings revealed that the implementation of thin asphalt overlays incorporating polymer modification effectively prolongs the pavement structure’s life span, while maintaining a low life-cycle cost (Habbouche et al. 2021a). Virginia DOT, in its field evaluations of pavement sections with high PMA overlays, quantified the performance benefits by calculating the average extension in service life. Notably, the application of regular PMA overlays resulted in an average service life extension of 6.2 years, while the highly modified variant exhibited a remarkable 34% higher extension in service life (Habbouche et al. 2022a). These reported experiences from various DOTs collectively underscore the consistent positive impact of PMA overlays on pavement performance and longevity.

Overall, polymer modification of asphalt binders is a well-established practice that has gained increasing traction during the past several decades. While some agencies still rely on unmodified asphalt binders, a considerable number have shifted toward PMA binders. This trend is particularly prominent in regions characterized by wide temperature variations and heightened oxidation levels. Consequently, the need to comprehensively understand the multifaceted benefits conferred by polymer modification is becoming increasingly crucial. In this regard, the subsequent section encompasses a compilation of six distinct studies that rigorously examined the performance of high-performance asphalt binders and mixtures within controlled laboratory settings (Habbouche et al. 2020). These studies illuminate the profound influence of polymer modification on various critical properties, including stiffness, viscosity, temperature sensitivity, oxidation resistance, elastic modulus, and structural integrity.

Habbouche et al. (2019) explored how performance assessment encompassed diverse facets, including the evaluation of properties such as moisture susceptibility, stiffness, fatigue cracking, rutting, and thermal cracking within plant-produced mixtures. The study gauged pavement responses by examining longitudinal and transverse strains, vertical stresses within base and subgrade layers, and overall performance under traffic loads. The outcomes underscored the superior performance of high-performance asphalt concrete (AC) mixes concerning strain resistance and fatigue life. Rutting and roughness characteristics were also studied. Notably, high-performance AC mixes exhibited diminished rutting depths and secondary rutting rates when contrasted with PMA mixes. The advantages of high polymer modification over lower dosage rates was further discussed by Habbouche et al. (2021b) in their later study. The latter study used the results of various performance tests to evaluate the rutting and cracking characteristics of highly PMA mixtures, comparing them with regular (low polymer dosage) PMA when used in different mixture types. Their findings indicate that high polymer modification in asphalt mixtures offers substantial advantages compared to lower dosage rates of polymer modification.

Further research indicates that the incorporation of SBS-modified asphalt can yield notable enhancements in pavement performance. By effectively addressing challenges like rutting, thermal cracking, and fatigue resistance, PMA overlays can protract the life span of roadways, curtail maintenance requirements, and enhance overall durability. The potential for employing thinner pavement sections carries economic and sustainability benefits, rendering PMA overlays an invaluable prospect, especially in high-traffic locales. The research’s ramifications underscore the necessity for a comprehensive structural design approach that accounts for the augmented properties of PMA mixes, ultimately culminating in more robust and enduring pavement solutions (Rodenzo et al. 2018). In Habbouche et al. (2019), the rutting and cracking performance of highly polymer-modified AC mixtures, containing ~7.% (Vol.) SBS, were compared with moderately polymer-modified AC mixtures containing about 3.5% (Vol.) SBS. The rutting performance was tested through a repeated load triaxial (RLT) test under repeated loading conditions, a static confining pressure of 10 psi, and a contact stress of 3.5 psi, and conducted at temperatures of 86°F, 104°F, and 122°F. The study involved polymer modification of two classes of asphalt mixtures, stone-matrix asphalt mixtures, and dense-graded surface mixtures. For the both mixture classes, the highly modified AC exhibited lower rutting characteristics (i.e., a smaller ratio of permanent strain [εp] to resilient strain [εr] for a given number of load repetitions) compared to the moderately modified mixes. Stone-matrix mixes generally showed lower and flatter rutting curves compared to the dense-graded surface mixtures, and the highly modified stone-matrix mixtures showed the lowest and flattest rutting curves overall. Note that the laboratory rutting resistance, as investigated in the said study, doesn’t always directly correlate with field performance due to various factors like stiffness, sub-layer behavior, and mixture properties.

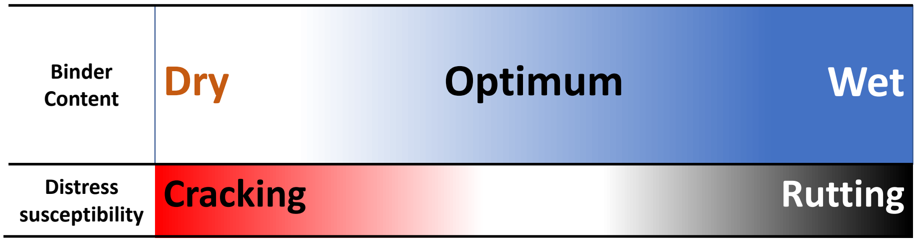
Cracking performance was assessed through the indirect tensile (IDT) test and Texas overlay test assessed cracking resistance. The IDT test didn't show significant differences between highly and moderately modified mixtures in terms of cracking resistance, especially for the dense-graded surface mixtures. The Texas overlay test showed that highly modified AC mixtures had similar or greater resistance to reflective cracking compared to the moderately modified AC mixes, regardless of mixture class. The highly modified stone-matrix AC mixtures displayed better cracking resistance overall. The test also evaluated fatigue cracking susceptibility under cyclic loading, where the modified AC mixtures exhibited relatively better fatigue performance, indicating increased flexibility. It should be noted that the IDT test in this study had limitations in evaluating cracking performance due to sensitivity issues and the influence of various factors.

Mix Design Considerations for PMA Mixtures

This section delves into the important aspect of formulating PMA mixtures, a pivotal step in optimizing the performance and longevity of pavements. The integration of polymer modifiers presents unique challenges and opportunities in achieving desired material properties. The section discusses mix design considerations and addresses factors such as binder selection, asphalt composition, job mix formula, and volumetric properties. By meticulously examining these elements, this section aims to provide a comprehensive understanding of how mix design intricacies interact with polymer modification to yield asphalt mixtures that are both resilient and sustainable over the course of their service life.

Habbouche et al. (2019) studied mix design considerations for PMA and highly PMA cement concretes, adopting the Superpave methodology. Despite variations in polymer content, the volumetric properties of the mixtures remained comparable. Asphalt binder properties were scrutinized using American Association of State Highway and Transportation Officials (AASHTO) M320-10 and multiple stress creep recovery (MSCR) methods. The analysis revealed that polymer-modified binders exhibited heightened resistance to cracking. SBS-modified asphalt, particularly in surface courses, significantly enhances pavement performance. PMA offers extensive benefits, especially in deformation resistance and durability, making it an attractive option despite higher costs. The potential for developing thinner pavement sections, promoting sustainability, and improving overall pavement design is noteworthy. The research underscores the importance of incorporating PMA into structural design systems and calls for further investigation to quantify specific PMA mixtures' increased structural value (Rodenzo et al. 2018).

Other specific considerations must be made when designing a PMA overlay mix to ensure the desired performance and durability of the overlay. The design should follow the Balanced Mix Design Concept, which emphasizes the need for an optimum binder content for a mix considering key factors as climate conditions, traffic, aging problems, and location. This concept is further illustrated in Figure 3.



Adopted from Buchanan 2016

Figure 3. Balanced AC mix design concept

In addition, some specific essential mix design considerations include the following (Podolsky et al. 2020):

- Due to the very high cost associated with the use of PMA binder, reclaimed asphalt pavement (RAP) materials can be utilized in the mix design in order to offset the polymer cost.
- When considering RAP materials in the mix design, its use should comprise mostly fine-graded mixtures with minimal coarse aggregate, given the relative thinness of PMA overlays.
- Additionally, when using RAP, it is typically recommended to maintain a very small RAP composition with the PMA binder in order to avoid blending problems that could prompt new performance deficiencies. Rejuvenators could also be included.
- Fatigue and low-temperature cracking examination might be necessary for compositions with high percentages of fine-graded RAP in order to ensure they offer sufficient resistance to fatigue cracking and are durable under low temperatures. In Iowa, these tests are the four-point beam fatigue test and disc-shaped compact tension test, respectively.

In alignment with the Standard Specification on Roads and Bridges Construction outlined by the New Jersey DOT (NJDOT), particular attention is directed toward the HPTO. Within this context, NJDOT also delineates specific mix design considerations associated with HPTO applications as follows (NJDOT 2019):

- The typical composition is coarse aggregate, fine aggregate, asphalt binder, and polymer modifier. The use of RAP, ground bituminous shingle material, remediated petroleum contaminated soil aggregate, or crushed recycled container glass are generally not recommended.
- Acceptable PMA binders are those that are specially designed to meet the set mix performance criteria.
- A job mix formula must be submitted at least 45 days prior to initial production certifying that each component meets the specified percent passing as well as production control tolerances criteria. The job mix formula essentially establishes the percentage of dry weight of aggregate passing each required sieve size and an optimum percentage of asphalt binder based on the overall mix weight.
- The job mix formula should provide a mixture with a minimum tensile strength ratio of 85%, prepared and tested in accordance with AASHTO T 312 and AASHTO T 283, respectively.

- The use of undiluted PMA of the rapid-setting, cationic rapid-setting, medium-setting, and cationic quick-setting types are allowed in conformance with AASHTO M 316. An annual quality control plan subject to AASHTO R 77 and must be provided by the PMA producer.
- For coarse aggregate, the options are gneiss, quartzite, or trap rock. Fine aggregate should contain 100% stone sand, with an uncompacted void content of not less than 45% according to AASHTO T 304.

FDOT led a comprehensive evaluation of PMA mixtures, including those with high polymer content Greene et al. (2014). The evaluation involved laboratory testing and field performance assessments, aiming to discern the impact of high polymer mixtures on rutting and cracking resistance. Tests included Cantabro mass loss, dynamic modulus, and rutting performance using the asphalt pavement analyzer (APA) rut test. Results indicated that high polymer AC mixtures exhibit improved durability and abrasion resistance, attributed to the higher polymer content. The dynamic modulus and phase angle data showed that SMA mixtures with high polymer binders exhibit higher resistance to rutting and cracking. Moreover, the APA rut test revealed that high polymer mixes generally outperform conventional PMA mixes in terms of rutting resistance, with SMA-high polymer mixes displaying the lowest rut depths. These findings highlight the potential benefits of using highly PMA overlays, particularly in terms of mitigating rutting and cracking, which are critical factors for pavement longevity and overall performance (Greene et al. 2014).

Due to the FDOT's requirement of using only virgin aggregates (non-RAP materials) for HiMA mixtures, projects usually necessitate a new mixture design rather than a straightforward binder type substitution within an existing non-HiMA job mix formula. FDOT states that the use of HiMA doesn't result in a substantial alteration of the necessary binder content compared to mixtures utilizing a conventionally modified PG 76-22 binder. Typically, the optimal binder contents, ranging from 5%–6%, as indicated by FDOT, are contingent upon the characteristics of the aggregate.

Additional investigations have been carried out, including research by the National Center for Asphalt Technology (NCAT) on HPTO, which extensively employed PMA binders containing 7.5% SBS polymer. Its study also incorporated RAP up to 25% of the dry weight of the aggregate (Mogawer et al. 2014). Moreover, the Iowa DOT, in its developmental specification for HPTO, mandates a comprehensive mix design approach that considers the following conditions (Iowa DOT 2023):

- The use of reclaimed asphalt shingles (RAS) is explicitly forbidden, and only a maximum of 15% binder replacement is allowed.
- If thin lift overlays are used on interstates, a minimum of 30% of the total aggregate shall be Type 2 or better; otherwise, a minimum of 50% of the total aggregate shall be Type 4 or better.
- Additionally, for interstate paving mixes, a Hamburg test is required; compaction should be done to 3.5% air voids, with no more than 4 mm rutting in the first 8,000 passes.
- The following additional requirements are also important:
  - The sand equivalency should be a minimum of 50.

- The fine aggregate angularity should be a minimum of 40.
- The crushed content should be a minimum of 50%.
- The aggregate quality should be A.
- The film thickness should be within the range of 8–15.
- The design voids target based on %Gmm should be less than or equal to 2.
- The design gyrations should be 50.

Selection of Aggregate Gradation and Characteristics

Generally speaking, the gradation of an aggregate represents one of the most important factors influencing the performance of a mix. The sizing of aggregates for PMA overlays can vary among different agencies and practices. For instance, the NJDOT mandates a fine-graded PMA mixture for its HPTO, utilizing 100% high-quality crushed stone with a nominal maximum aggregate size of 0.375 in. (9.5 mm). FDOT specifies 0.492 in. (12.5 mm) nominal maximum aggregate size for its HiMA mixtures friction course. The bituminous mix can be dense-graded, gap-graded, or open-graded. The Iowa DOT’s specification for HPTO earmarks a 91% minimum passing and 100% maximum passing for its 3/8 in. sieve. For a No. 8 sieve (2.36 mm), a minimum passing of 27% and a maximum passing of 63% is required. A maximum passing of 90% for a No. 4 sieve (4.75 mm) is required, and a minimum passing of 2% and maximum passing of 10% for a No. 200 sieve (0.075 mm) is required. The aggregate gradations for in-place mixes from a full-scale experiment conducted at the NCAT Test Track are presented in Habbouche et al. (2020).

Determination of Polymer Loading Rate

The percentage of polymer added relative to the residual asphalt content can be a major determinant in the overall performance of the polymer modifier. Table 1 shows the performance of different polymer types and loading on the average rut depth and average International Roughness Index (IRI) obtained for Mississippi DOT’s polymer-modified hot-mix asphalt (HMA) mix trial (Albritton et al. 1999).

Table 1. Rut and IRI performance under different polymer loading for modifiers

Trade name	Type	Polymer loading (%)	Avg. rut depth (in.)	Avg. IRI (mm/m)
Cryopolymer	Cryogenic ground rubber	10.0	-0.014	0.74
Kraton	SBS block copolymer	4.25	0.037	0.67
Multigrade	Gelled asphalt	Indeterminable	-0.065	0.66
Novophalt	Low-density polyethylene (Recycled)	5.5	-0.028	0.72
Rouse Rubber	80 mesh tire rubber	10.0	-0.044	0.78
Sealoflex	SBS	4.25	-0.025	0.75
Styrelf	Styrene-butadiene block copolymer	4.3	0.058	0.54
Ultrapave	Styrene-butadiene latex	3.0	-0.067	0.80
Vestoplast	Ethylene, butylene, terpolymer	7.0	Not tested	Not tested

Source: Albritton et al. 1999

As illustrated in Table 1, most research tends to lean toward a practicable range between 2% and 10% by weight of the residual asphalt content, and most manufacturer specifications are within the 3%–5% range. Low or conventional polymer modification is commonly employed within the range of up to 3% SBS, a prevalent choice for standard applications. Conversely, the ambit of highly polymer-modified solutions extends to approximately 6%–8% SBS content, primarily reserved for advanced applications where heightened resistance to rutting and increased performance demands are paramount (Habbouche et al. 2020).

Performance-Based Specifications and Testing Methods

Laboratory evaluations have been pivotal in understanding the behavior of high polymer-modified binders. Tests such as dynamic shear rheometer (DSR), MSCR, and IDT have been employed to evaluate parameters like stiffness, elastic response, and fracture resistance. The results consistently reveal improved properties of high polymer binders, particularly in terms of stiffness, rutting resistance, and fatigue resistance. Additionally, long-term aging effects on high polymer binders were explored, demonstrating their improved resistance to aging-related distress. Evaluation of the aging susceptibility of the highly modified and moderately modified asphalt binders with DSR test resulted in measuring lower dynamic shear modulus (G^*), lower phase angles (δ), and a steeper slope between the two parameters for the highly modified binders, which are indicators of lower susceptibility to long-term aging. An evaluation of thin overlay mixes using high polymer binders showcased their application in HPTO mixtures for pavement preservation. Mixtures incorporating RAP and high polymer binders exhibited superior resistance to rutting, fatigue, reflective cracking, and thermal cracking. The findings from performance tests underscored the advantages of high polymer binders in maintaining pavement quality (Habbouche et al. 2019).

Habbouche et al. (2021b) investigated the implications of using highly PMA overlays—focusing on their performance, resistance to rutting and cracking, and their potential to enhance pavement durability—, and they highlighted the challenges posed by increasing traffic volume, axle loads, and tire pressures, which necessitate the development of high-quality asphalt mixtures capable of resisting rutting, cracking, and other forms of distress while maintaining long-term durability. At the heart of this study lies the utilization of PMA binders and overlays as solutions to tackle these challenges. The exploration of polymer modification in asphalt binders spans decades, encompassing an array of components like polymers, ground tire rubber, and chemical additives, all aimed at enhancing mixture properties. The advantages of polymer-modified AC mixtures in withstanding various forms of distress have not gone unnoticed by state DOTs. Significantly, the emergence of high polymer binders, characterized by heightened elasticity, presents a promising avenue for addressing potential pavement failure modes (Habbouche et al. 2021a).

In terms of performance, extensive testing has been conducted on PMA mixes, particularly those incorporating SBS. A notable study investigated a section utilizing a HiMA configuration consisting of base, binder, and wearing courses with 7.5% SBS content, showcasing superior performance when compared to control sections. This HiMA mixture demonstrated enhanced endurance against bending beam fatigue cycles, exhibited improved resistance to rutting, and boasted a fatigue endurance limit three times higher than conventional sections. Notably, the Kraton base mixture displayed exceptional fatigue performance, while assessments through APA and flow number tests further underscored the Kraton mixtures' superiority in rutting resistance (Rodenzo et al. 2018).

Central to this chapter's focus is the influence of oxidative aging on the ductility of both unmodified and polymer-modified binders. Research findings illuminate that while polymer modification initially enhances ductility, oxidative aging imparts a significant degradation of this improvement over the pavement's life span. This degradation is primarily attributed to the stiffening of the base binder due to oxidation, coupled with secondary contributions stemming from the reduction of the molecular size of the polymers due to degradation. Although endeavors to mitigate the impact by softening modified binders do recover a noteworthy degree of improved ductility, the presence of polymer degradation due to oxidation remains a pivotal factor contributing to reduced performance (Woo et al. 2007).

Construction Practices

Efficient and precise construction practices play a paramount role in realizing the full potential of this rehabilitation technique. This section delves into the complexities of construction methodologies, emphasizing the significance of proper material handling, mixture placement, and compaction techniques. By scrutinizing these practices, this section aims to provide comprehensive insights into the critical aspects that underpin successful PMA overlay implementation.

Pre-Construction Planning and Coordination

Prior to mixing and placement, the following pre-construction considerations need to be put in place to ensure the desired outcomes (NJDOT 2019):

- Weather considerations should be the top concern. Adequate consideration of the predicted weather forecast should be made to ensure that work is not started when rain is expected. The ideal weather would be warm and dry in order to promote proper binder setting and curing.
- Adequate preparation should be made in advance of construction of the overlay to ensure that the underlying surface is free of potholes or cracks that could easily propagate to the new surface.
- A pre-construction meeting should be held to discuss and finalize the mix design and the proposed plan for mix production.
- Appropriate traffic control measures should be put in place until construction is completed and the roadway is duly open.
- Plans should be made for the use of a uniform tack coat to enable proper bonding between the existing surface and the new overlay.

Mix Production and Placement Techniques

The art of ensuring proper mix production and placement techniques lends to the objective of achieving enhanced structural integrity and longevity of roadways. The significance of optimal mix production and placement of PMA is underpinned by the profound impact they exert on the overall performance and durability of the overlay. Based on several implementation examples, the specifics of production and placement include the following:

- Given the relatively thinner sections of PMA overlays compared to thicker HMA overlays, PMA overlays tend to cool more quickly, leaving a short window for compaction. This needs to be considered to ensure effective compaction (Georgia DOT 2006).
- Georgia DOT typically tests the quality of its binder PGs to ensure that they meet the requirements for the PG 82-28. The mix is produced in the plant at approximately 325°F and hauled 10 mi to the job site where it is placed by the paving crew at about 315°F (Georgia DOT 2006).
- The Iowa DOT in its developmental specifications for HPTO requires the production temperature of HMA mixtures to be kept between 225°F and 335°F until placed on the grade. Compaction should be done with a static steel-wheeled roller. The road section should not be open to traffic until the entire mat has cooled below 150°F (Iowa DOT 2023).
- Given the importance of adequate mix compaction in ensuring the durability of constructed overlay sections, FDOT in its years of experience implementing both conventional PMA overlays and its highly modified variant suggests that temperature control and minimizing the use of hand work can be very helpful in this regard. FDOT generally recommends that the ideal storage temperature for HiMA binder is approximately 320°F. The agency also advises against exposing the modified binder to high temperatures in order to avoid encountering workability issues. Additional specific construction considerations are discussed in the Florida case study in the following chapter (Habbouche et al. 2019).
- Mississippi DOT stipulates a typical mixing temperature that is greater than regular HMA, with a range between 320°F and 351°F. Additionally, PMA production does not require a specially designated facility that is different from the one used for HMA production (Albritton et al. 1999).

- “Smoothseal,” a fine-graded PMA concrete described in the Ohio DOT (ODOT) specification item 424 (ODOT 2023), is produced with high-quality aggregates and polymer-modified asphalt and provides an exceptionally durable and densely graded paving mixture. This material is particularly suitable for thin preventive maintenance overlays. What sets Smoothseal apart from other paving materials in Ohio is that it adheres to ODOT specifications, mandating that the sand used must contain at least 50% silicon dioxide (SiO_2) (quartz) to ensure superior skid resistance. This requirement is unique to Smoothseal, and no other material specified by ODOT shares this criterion. Due to the fact that not all sands in southwestern Ohio meet the specified percentage of SiO_2, Flexible Pavements of Ohio has issued an advisory letter to both users and producers in this region (FPO 2013). The manufacturing process requires an elevated mix temperature adequate for effective compaction. This production temperature should not exceed 350°F, while the placement temperature should be at least 290°F (ODOT 2023).
- Virginia’s experience with production and placement of high PMA binder was also consistent with other DOTs. Specifically, they require that the temperatures of the high polymer binder must be closely monitored during production at the terminal and upon delivery at the plant. The production temperature specified is within the range of 330°F–345°F. It is recommended that the mixture should not be stored in tanks for longer than three days (Habbouche et al. 2021a).

Quality Control and Quality Assurance Measures

Ensuring the quality of PMA overlays necessitates well-structured quality assurance procedures. These procedures encompass deliberate and methodical inspections, along with sampling and testing, to instill confidence in the performance of the modified binder mix as per the anticipated standards. Additionally, quality control entails conducting sampling and testing by the contractor to further validate the mix’s integrity and performance. Focusing strongly on quality control is a recipe for success with polymer-modified mixtures. Based on several implementation examples, the specifics of quality control and quality assurance include the following:

- Virginia DOT through contractors implementing PMA/high polymer overlays recommend obtaining liquid samples of the modified mix through the sampling valve of the storage tank. The sample should be obtained after draining approximately five gallons of asphalt binder (Habbouche et al. 2021a).
- Quality assurance testing reports for asphalt binders of all high PMA mixtures must certify viscosity values of up to 135°C measured based on AASHTO T 316 (Habbouche et al. 2021b).
- The standard method for viscosity determination of asphalt binder using rotational viscometer must be evaluated and compared to the baseline value of 3 Pa, as recommended by AASHTO M 332 (Habbouche et al. 2021b).
- The uniformity and quality of the PMA must be verified through standard quality control tests (Greene et al. 2014).

Construction Troubleshooting and Common Challenges

A variety of challenges and troubleshooting scenarios can emerge, potentially impacting the efficiency and quality of the outcome. In order to forestall this from happening, the following considerations should be ensured:

- There is no reported specific health, safety, and environmental challenges abounding from the construction of PMA overlays that are not applicable to standard conventional asphalt binder's construction. Therefore, contractors should incorporate all of the transferable precautions they ordinarily would have taken into consideration for typical asphalt works (Habbouche et al. 2021b).
- PMA mixtures can exhibit heightened sensitivity to temperature changes during production and placement. Both low and high temperatures can impact workability, leading to difficulties in achieving proper compaction and uniform distribution of the mixture (Greene et al. 2014).
- Achieving the desired workability of PMA mixtures can be challenging, particularly due to the increased viscosity caused by polymer modification. Finding the right balance between viscosity and workability is essential to ensure efficient placement and compaction (Albritton et al. 1999).
- Transition zones and construction joints between existing pavement and the PMA overlay require careful attention to ensure a seamless connection. Inadequate preparation or bonding at these interfaces can lead to premature distresses (Albritton et al. 1999).

CASE STUDIES AND IMPLEMENTATION EXAMPLES

This chapter collects notable case studies and practical implementation examples drawn from various DOTs. The project team's exploration extends to those DOTs that have embraced the utilization of PMA not only for conventional applications, i.e., full-depth AC pavements, but also specifically for overlays. These case studies present a comprehensive overview of DOTs that have not only adopted PMA overlays but also analyzed and reported performance records. Through these real-world instances, the project team uncovered the tangible benefits, challenges faced, and lessons learned, painting a vivid picture of the impact and viability of PMA overlays in diverse operational contexts.

Overview of Successful Case Studies from Different States

A survey of successful DOT case studies provides valuable insights into the effective application of PMA overlays in pavement rehabilitation. These case studies showcase best practices, innovative approaches, and positive outcomes achieved by various DOTs. A brief overview of these case studies are given in the following sections.

FDOT's Implementation and Evaluation of PMA Binder through APT

Research led by FDOT (Greene et al. 2014) evaluated the implications of using PMA binders for pavement performance. The study evaluated the rutting and cracking performance of AC mixtures made with PMA binders containing high and moderate dosages of SBS polymer, using three types of binders as follows:

- Polymer-modified PG 82-22 with 6% polymer content
- Polymer-modified PG 76-22 with approximately 3% polymer content
- Unmodified PG 67-22

As the basis of this information lies in APT, FDOT has transitioned beyond studying and testing PMA overlays into the implementation phase, using the PG 82-22 binder in two of its counties, namely Hillsborough and Nassau Counties. In the Hillsborough County project, the road's underlying condition presented rut depths exceeding 1 in., and historical data from Florida Traffic Online indicated an annual average daily traffic (AADT) of 15,700 in 2012 at the resurfacing location. Similarly, in Nassau County, despite a prior resurfacing six years earlier, the project encountered average rut depths of 1 in. before implementing PMA overlays. The historical AADT for this location in 2012 was 5,900. The aggregated comparison across different performance parameters for an unmodified and the two variants of polymer-modified binders (conventional and high) are shown in Table 2.

Table 2. Comparison of unmodified, conventional modified, and high modified asphalt binders

Parameter	PG 82-22	PG 76-22	PG 67-22
Cost*	PG 76-22 + $100/liquid* metric ton, and $250/liquid* metric ton more than the unmodified binder		
Material characteristic	SBS	SBS	Unmodified
% composition	6% SBS modifier	~3% SBS modifier	Unmodified
Rutting resistance	Rutting 0.5 times less than unmodified after 100,000 passes	Rutting 0.8 times less than unmodified after 100,000 passes	
Fatigue resistance (evaluated at 20°C with a 455 mm wide-base tire loaded to 12,000 lb and inflated to 100 psi)	More than 20 times greater than unmodified section and ~7 times greater than PG 76-22	More than 20 times greater than unmodified section	

Source: Greene et al. 2014

* Need to factor in inflation in cost as this study was conducted in 2014.

FDOT has amassed a remarkable record of research and implementation projects regarding the application of HiMA. Some of the most notable findings and facts about the use of HiMA in Florida were documented in Vargas-Nordcbeck and Mussleman (2021).

- **High modification rate:** FDOT has utilized SBS at high concentrations of 7%–8%, which is more than twice the quantities typically seen in PMA binders.

- **Observed benefits:** This approach primarily addresses issues of fatigue, reflective cracking, raveling, and severe rutting common in Florida’s road conditions. Initial success has led FDOT to extend the use of HiMA to other high-stress areas like truck weigh stations, agricultural inspection stations, and high-volume intersections and interchanges. The elevated polymer content imparts a rubber-like behavior, enhancing pavement performance notably in terms of cracking resistance and rutting. Notably, in critical situations demanding rapid completion, this option has been considered as an alternative to portland cement concrete reconstruction.

- **Adoption:** FDOT has impressively incorporated more than 500,000 tons of HiMA across at least 40 projects throughout the state.

- **Construction:** FDOT undertook specific measures to ensure favorable construction outcomes, including the following:
  - *Storage Control:* Preventing overheating during storage and limiting the storage period of the binder to avoid crosslinking of the polymer that can degrade the binder’s rheological properties and adversely affect its handling. For FDOT, the two critical controlling factors in HiMA storage are duration and temperature, which should be strictly limited.

    - *Limiting High-Temperature Exposure:* Ensuring that modified binders aren't subjected to prolonged high temperatures to maintain proper mix workability. FDOT allows mixing temperatures of HiMA up to 340°F, and the mix preparation for the implementation project discussed here was performed around this temperature.
    - *Effective Planning and Communication:* Addressing storage limitations through meticulous planning and stakeholder communication.

- **Cost:** Cost evaluation was based on a comparison with regular polymer asphalt modification, specifically juxtaposing HiMA mixture costs against the PG 76-22 binder. For dense-graded mixtures, there's an added cost of \$20–\$25/ton for HiMA, and \$15–\$20/ton for open-graded mixtures. According to FDOT, for these costs to balance out, HiMA projects would need to exceed the service life of PG 76-22 by a minimum of 10 months. Early data from FDOT projects show that this gain in life span is not only met but exceeded.

- **Performance Comparison:** FDOT employs a fatigue-based structural coefficient of 0.44 for HiMA mixtures. The maiden HiMA project was executed on I-10, targeting areas with severe rutting beyond 2 in. The steps taken encompassed milling the section to a depth of 2.5 in. and replacing it with a dense-graded, 12.5 mm nominal maximum aggregate size friction course using the HiMA mixture.

Georgia DOT Asphalt Pavement Selection Guidelines

In Georgia DOT's Asphalt Pavement Selection Guidelines, the favored choice for HMA is PG 76-22, which is a PMA cement (Georgia DOT 2006). This particular cement finds widespread usage, particularly in high-traffic zones across the state. Alternatively, options include the standard grades like PG 67-22 or the polymer-modified grade PG 76-22 asphalt cements. The differentiating factor in selection is based on the traffic requirement parameter as shown in Table 3 and Table 4.

Table 3. Standard PMA grade selection for Georgia DOT based on traffic

Parameter	PG 67-22	PG 76-22
Traffic Requirement	Specified for roadways with average daily traffic (ADT) of 10,000–25,000	Required for traffic >25,000 ADT

Georgia DOT 2006

Table 4. Bituminous material type selection guide for medium- to high-volume mixes

Parameters	Regular	Regular HMA	Polymer-modified AC
ADT (% trucks should be considered)	1,000–2,000	Yes	Yes
	2,000–10,000	Yes	Yes
	10,000–25,000	Yes	Yes
	>25,000	N/A	Yes
Rutting	<¼ in.	Yes	Yes
	¼–½ in.	Yes, with leveling	Yes, with leveling
	½–¾ in.	Yes, with milling	Yes, with milling
	>¾ in.	Yes, with milling	Yes, with milling
Transverse cracking	Minor	Yes	Yes
	Major	Yes, with crack-relief interlayer	Yes, with crack-relief interlayer
Longitudinal cracking	Minor	Yes, with crack-seal or crack-relief interlayer	Yes, with crack-seal or crack-relief interlayer
	Major	Yes, with crack-relief interlayer	Yes, with crack-relief interlayer
Load related cracking	Minor	Yes, with crack-seal or crack-relief interlayer	Yes, with crack-seal or crack-relief interlayer
	Major	Yes, with deep patching	Yes, with deep patching
Raveling	Minor	Yes	Yes
	Major	Yes, with milling	Yes, with milling

Georgia DOT 2006

It is critical to note that these recommendations were before the MSCR test was widely used. After MSCR-based grading of binders was introduced and widely adopted, agencies might allow either PG or MSCR grading of asphalt cements, not specifying particular additives to meet the grading.

NJDOT's Guidelines for HPTO

The NJDOT's Standard Specifications for Road and Bridge Construction, particularly focusing on the High Performance Thin Overlay section (Section 406), offer a comprehensive framework for utilizing PMA overlays. This guideline elaborates on the entire process, encompassing material selection, equipment requirements, construction procedures, quality control, and payment considerations as outlined by NJDOT and given as follows (NJDOT 2019):

- **Material Selection:** The selection of appropriate materials is paramount for successful PMA overlays. It involves utilizing polymer-modified emulsified asphalt, specifically Grade CRS-1P, for tack coat purposes. Additionally, the use of HPTO material is recommended for the overlay itself. These materials have been carefully chosen to ensure compatibility, adhesion, and durability within the pavement structure.

- **Equipment Requirements:** The availability and utilization of the requisite equipment play a crucial role in achieving successful PMA overlays. To this end, a materials transfer vehicle

(MTV) is essential for the construction of HPTO, ensuring proper material handling and temperature maintenance. Furthermore, HMA pavers are indispensable for accurate and consistent placement of the HPTO. For bridge deck paving, the option of using an MTV is provided as an enhancement to the process.

- **Paving Plan Submission:** Prior planning and communication are vital elements of a well-executed PMA overlay. It is imperative to submit a comprehensive paving plan to the resident engineer at least 20 days before the commencement of HPTO placement. This detailed plan outlines the operational approach, ensuring alignment with the project's goals and specifications.

- **Weather Limitations:** External conditions, particularly weather, can significantly impact the quality and longevity of PMA overlays. In the case that the National Weather Service forecasts a 50% or greater chance of precipitation within three hours before paving, it is advised to postpone the HPTO placement. Precipitation during or imminent to paving should be strictly avoided. Paving operations may resume once precipitation chances drop below 50% and the pavement surface is sufficiently dry. Moreover, a minimum pavement surface temperature of 50°F is crucial for successful overlay placement.

- **Test Strip Construction:** Constructing a test strip serves as a preliminary assessment of the overlay's viability and compatibility. This step involves the careful construction of a representative section of the overlay at least 14 days before full-scale production paving. The results from this test strip are submitted to the resident engineer, who, in conjunction with HMA plant results, evaluates the feasibility and performance of the proposed overlay.

- **Transportation and Delivery of AC for PMA Overlay Construction:** NJDOT's specification provides specific guidelines for the transportation and delivery of high-modulus asphalt that is used in the construction of PMA thin overlays. Ensuring that the AC reaches the construction site in optimal condition and within specified temperature ranges is fundamental to the success of the overlay.

- **Surface Preparation:** The existing pavement surface requires meticulous preparation before overlay placement. This involves the removal of foreign and loose materials. To achieve this, a self-propelled power broom with a vacuum collection system is employed. Prior to HPTO placement, the surface must be dry and approved by the resident engineer. For areas where existing pavement is not milled, the removal of traffic stripes and markings is also addressed.

- **Tack Coat Application:** Application of a tack coat is a critical step to ensure proper adhesion between the existing pavement and the overlay. The specified tack coat, a polymer-modified tack coat, plays a crucial role in promoting bond strength and integrity. Adhering to the recommended application procedures guarantees a strong bond between the existing pavement and the overlay material.

- **Placement of HPTO:** The placement of HPTO demands precise execution to achieve the desired performance outcomes. Adhering to the recommended laydown temperature provided by the supplier of the asphalt binder or modifier is crucial. It is imperative to avoid exceeding the maximum discharge temperature of 330°F. Furthermore, proper spreading and grading techniques must be employed, in line with NJDOT specifications.

- **Compaction:** Proper compaction is essential to ensure the longevity and durability of the overlay. Adhering to NJDOT guidelines for compaction procedures is crucial. In cases where vibratory compaction may cause aggregate breakdown or asphalt surfacing, operating rollers in static mode is recommended. This ensures that the overlay retains its integrity without compromising its structural qualities.

- **Opening to Traffic:** Before allowing traffic on the newly constructed overlay, it is essential to remove loose materials from the traveled way. Traffic and construction equipment must be kept off the overlay until it cools to a temperature of less than 140°F. This precautionary step guarantees that the overlay achieves its desired properties without any detrimental effects from premature traffic loading.

- **Air Void Requirements:** The determination of air void content within the overlay is a critical quality control measure. Cores are drilled and analyzed according to NJDOT guidelines. The classification of different lots, calculation of percent defective, and subsequent pay adjustments are determined based on air void ranges. This quality control process ensures that the overlay meets specified standards.

- **Outlier Detection:** Outliers within the quality control process are detected following statistically valid procedures. The process involves careful screening and replacement of outlier cores, with the goal of maintaining the integrity and reliability of the quality control data.

- **Bridge Deck Requirements:** Bridge deck overlays require specific considerations due to their unique characteristics. The option to waive coring or conduct nuclear density gauge testing for bridge decks is provided, based on the discretion of the resident engineer. This approach ensures that the overlay effectively addresses the challenges posed by bridge decks.

- **Ride Quality Evaluation:** The NJDOT places significant emphasis on the evaluation of ride quality. This evaluation encompasses the final riding surface of all constructed pavement sections, ensuring that the overlay meets specified ride quality criteria.

- **Measurement and Payment:** The measurement and payment procedures for PMA overlays are well-defined. Payment is based on tonnage and excludes certain items like tack coat, polymer-modified tack coat, and core samples. This approach ensures transparency and accountability in the payment process.

Other Notable DOT Applications

The innovative solutions presented by other DOTs serve as noteworthy instances of strategic pavement improvement. These remarkable applications highlight the versatility and efficacy of PMA overlays in tackling distinct challenges across varied operational settings. Through an examination of these practical implementations, the project team acquired valuable insights into the decisions, methods, and outcomes that mold the successful integration of PMA overlays. The additional notable DOT applications include the following:

- **New York City DOT (HPTO):** In New York City, a successful application of HPTO coupled with HiMA took place on 1st Avenue in Manhattan and from 72nd Street to 125th Street. Remarkably, this combination has exhibited enduring performance over a span of seven years, exemplifying its resilience and effectiveness (Fee 2019, Aschenbrener 2022).

- **Virginia DOT:** Virginia DOT's strategic employment of binder grade PG 76E-28 (HiMA) in conjunction with dense-graded and SMA has yielded noteworthy results. Since 2014, HiMA has been a staple across at least 16 projects, amounting to an application of over 205,000 tons. This innovative approach has found its application primarily on terrains marred by cracked asphalt pavements and jointed concrete pavements. Its deployment on high-volume roads such as interstates (I-95, I-495) has notably curtailed reflective cracking rates, particularly on extensively deteriorated pavements. Moreover, its impressive 34% life extension in comparison to conventional binder grades underscores its enduring benefits (Aschenbrener 2022, Habbouche et al. 2022a).

- **Oklahoma DOT (CAM):** The Oklahoma DOT's adoption of CAM as an alternative to fabric interlayer encompasses a cost-efficient strategy, with CAM costing \$1.2/yd^2 less than the alternative. Employing binder grade PG 76E-28 (HiMA) with a mandated binder content of not less than 5.5%, the DOT's implementation has yielded commendable outcomes. Evaluations conducted in 2012 on candidate sections for CAM application showcased minimal cracking and rutting, with IRI levels remaining under 50 in./mi up to 2021 (Aschenbrener 2022).

- **Alabama DOT (CAM):** An impactful application of CAM occurred on I-59/20 near Tuscaloosa, Alabama. This approach was undertaken to address an underlying pavement condition characterized by longitudinal cracking extending beyond the top 4 in. of the pavement. Through the deployment of HiMA, this rehabilitation initiative was successfully executed and finalized in 2016 Aschenbrener 2022).

Lessons Learned and Best Practices from Implementation Projects

Overall, the studies and previous implementation projects underscore the positive impact of polymer modification on asphalt binder properties and performance, spotlighting the potential of high polymer AC mixes to bolster resistance against diverse distress modes. A comparative analysis of the existing literature further highlights the significance of field performance data in corroborating laboratory findings. The research findings on the effects of polymer modification on asphalt binder characteristics and performance are summarized in the following sections.

Structural Coefficient and Optimization

The research explored diverse strategies for recalibrating the structural coefficient concerning PMA mixes. The assessment covered both empirical techniques and mechanistic methodologies, with a specific emphasis on the three dimensional (3D)-Move model. The study outcomes provide valuable insights into the impact of various polymer types and their proportions on asphalt binder traits and effectiveness. This comprehension paves the way for optimizing pavement design and enhancing performance through polymer modification.

Positive Impact of SBS Polymer Modification

The positive impact of polymer modification, specifically SBS polymer, is underscored. Success stories from previous implementations of PMA overlays using SBS, documented in Greene et al. (2014), Aschenbrener (2022), Habbouche et al. (2022), Fee (2019), and Gilliland et al. (2022) highlight the significance of increased SBS content (up to approximately 7.5%) in enhancing asphalt binder and mixture performance. The modifications lead to improved resistance to various types of cracking, including rutting, fatigue, thermal, and reflective cracking. Consequently, polymer modification contributes to the development of more durable asphalt pavements with extended longevity. New York City's successful application of HPTO showcased the positive impact of SBS polymer modification. Enduring over seven years on 1st Avenue and from 72nd Street to 125th Street, this application demonstrated the resilience and effectiveness of polymer-modified overlays in high-stress urban environments. Virginia DOT's extensive use of binder grade PG 76E-28 (HiMA) emphasized the positive impact of SBS polymer modification. By significantly curtailing reflective cracking rates on high-volume roads, the agency's application illustrated how SBS-modified asphalt enhances pavement performance, particularly in addressing distress modes associated with high traffic and cracking. Alabama DOT's deployment of CAM on I-59/20 underscored the positive impact of SBS polymer modification. By employing HiMA overlays, the agency effectively addressed longitudinal cracking extending beyond the pavement's surface. This case demonstrates the efficacy of SBS-modified asphalt in mitigating distress and enhancing pavement durability.

In these cases, the strategic implementation of PMA overlays has showcased both structural optimization and the positive impact of SBS polymer modification in addressing various pavement challenges and extending pavement life. These real-world examples provide valuable insights into the tangible benefits that polymer-modified overlays can offer in the realm of pavement enhancement.

Recommendations for High Polymer Asphalt Mixes

The recommendations put forth for design and implementation focus on the incorporation of high polymer asphalt mixes with a structural coefficient of 0.54 (Habbouche et al. 2019) This integration is based on rigorous laboratory evaluations, advanced mechanistic modeling, and extensive full-scale testing. The adoption of this approach could result in a substantial 23% reduction in AC layer thickness compared to PMA mixes, all while maintaining or enhancing performance attributes.

Implications and Engineering Innovations

The implications and interpretation of research findings underscore a range of outcomes, including improved performance, optimized mix design, flexible pavement enhancement, advanced testing methods, and engineering innovation. These aspects collectively contribute to the potential transformation of pavement design and construction practices. The success stories of various DOTs' implementation of PMA overlays underscore the far-reaching implications and engineering innovations in pavement enhancement.

The applications of HPTO and HiMA in New York City, Virginia, and Alabama serve as a testament to the transformative potential of polymer-modified overlays. The significant extension of pavement life, reduction in distress modes, and enhanced durability signal the innovative strides in the field of pavement engineering. FDOT's transition to implementing PG 82-22 binder with polymer modification in Hillsborough and Nassau Counties showcases the engineering innovation in real-world scenarios. By leveraging APT data, the implementation of these overlays illustrates the fusion of research insights with practical application, resulting in substantial improvements in pavement performance. Oklahoma DOT's adoption of CAM as a cost-efficient alternative to fabric interlayers showcases engineering innovation. By using binder grade PG 76E-28 (HiMA) and strategic application techniques, the agency successfully addressed cracking and rutting challenges. This approach exemplifies how inventive solutions can lead to effective distress mitigation and pavement preservation.

In conclusion, these case studies and applications illuminate the power of recommendations, engineering innovations, and strategic decision-making in the realm of PMA overlays. These examples emphasize the impact of informed choices on pavement performance and durability, ultimately contributing to safer and more sustainable road networks.

DECISION-MAKING PROCESS

Factors to Consider in the Decision-Making Process

Many factors influence the selection decision of the right treatment for pavement. In a study conducted as part of Indiana's pavement preservation guide, these factors included pavement age, condition, traffic levels, availability of funding, and agency policy, as well as expected future plans (Ong et al. 2010). The type and severity of distresses on the underlying pavement are also considered major factors in selecting a treatment (Lee and Shields 2010). Based on available guidance documents from state DOTs, the basic steps involved in the application matrix development are described in the following sections.

Identify Key Factors

In broad terms, many factors play a part in the selection process of PMA overlay as the right treatment option for pavement preservation. These factors include making due consideration for the underlying pavement type and condition, traffic volume as well as truck traffic, climate and environmental conditions, project budget and time frame, and expected treatment performance as well as the structural coefficient of the pavement. A PMA overlay would be considered the right treatment under different sets of constraints when the combination of the conditions gives the best cost/benefit. The key factors for consideration are as follows:

- **Underlying Pavement Type:** Certain roadway types, such as gravel roads, are automatically rejected as PMA overlay candidates. Thus, it's worth considering, the underlying type of the pavement considered for rehabilitation, whether asphalt, concrete, or composite.

- **Underlying Pavement Condition:** This could include assessing the condition of the existing pavement for functional capacity impairment including examining the different distresses, surface defects, as well as the pavement's structural integrity. The following should be considered prior to placing a PMA overlay on an existing pavement surface:
    - Cracks wider than 1 in. should be repaired.
    - If existing surface bears patches, they must be in good condition.
    - Potholes must be repaired full-depth.
    - Edge cracking must be repaired prior to overlay construction.
    - Areas on existing pavement with debonding signs should be patched.

- **Traffic Volume:** The capacity of the roadway in terms of amount and type of traffic it receives should be considered. Specific factors such as the percentage of truck traffic, as well as the speed limit as an indicator of the predominant traffic speed, are helpful. Traffic volume categories were defined based on pavement type and AADT as shown in Table 5.

Table 5. Traffic volume categories

Pavement type	Traffic level	AADT
Flexible and composite	Low/Very low	<1,000
	Medium	1,000–15,000
	High	>15,000
Rigid	Low/Very low	<7,500
	High	≥7,500

- **Climate and Environmental Conditions:** The local climate, typical temperature ranges, freeze-thaw cycles, and potential exposure to chemicals or corrosive substances should be considered.

- **Project Budget and Time Frame:** Extraneous factors such as available budget and project schedule automatically put financial and time constraints, respectively, into the decision-making process. The estimated unit cost for thin HMA overlay is \$3.00–\$6.00/yd^2.

- **Work Zone Duration Restrictions**

- **Expected Treatment Performance:** Thin PMA overlays offer between 6 and 12 years of treatment life. The performance of the overlay is greatly influenced by the condition of the pavement prior to the preservation (Zimmerman and Peshkin 2004).

- **Structural Coefficient:** These coefficients are obtained through fatigue cracking analysis under different factors. They help to account for the strength and stiffness characteristics of different pavement layers. Including the structural coefficient in the decision-making process can help to determine whether the existing underlying pavement layer can adequately support the overlay layer. From exiting guidance reports, a structural coefficient of 0.54 is appropriate for the design of the PMA overlay.

Define Performance Objectives

Defining performance objectives are an agency-specific requirement in terms of aligning the project outcomes with the performance goals of rehabilitation. Typically, performance is defined as achieving a service life extension of the pavement structure. Other goals could be improving pavement durability, reducing maintenance frequency and needs, or enhancing skid resistance. The primary measure of performance used for the purpose of this project is life extension. This is juxtaposed with the cost/benefit of the respective scenarios in determining the suitability of the preservation technique.

Establish Suitability Criteria

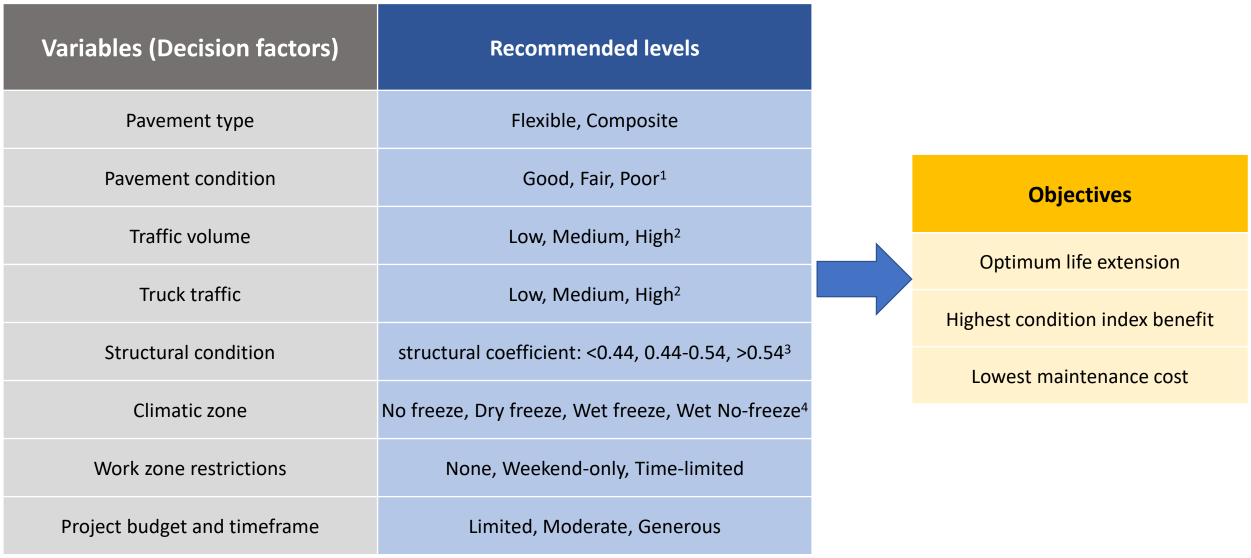
Based on the determinations in the previous sections, an established set of criteria is defined for assessing the suitability of PMA overlays under different scenarios. Typically, these criteria should include limits, thresholds, or compatibility situations based on the identified key factors, e.g., traffic volume limit for which a PMA overlay can be considered.

Assign Suitability Ratings

In the present study, suitability ratings are assigned based on a combination of the different constraints and agency performance objectives. Typical ratings include categories like recommended treatment under specified set of constraints (R), feasible treatment but application depends on other project constraints (F), and treatment is not recommended under specified set of constraints (NR). These ratings should be kept as simple and as direct as possible.

Categorize Different Application Scenarios

A table or matrix is typically used in categorizing the different combinations of the established suitability criteria. A recommended framework for developing decision trees (or matrices) for PMA overlay application is shown in Figure 4. The figure presents the recommended variables and their levels in the decision tree and the objectives to optimize project selection under each given scenario.



Variables (Decision factors)	Recommended levels
Pavement type	Flexible, Composite
Pavement condition	Good, Fair, Poor[1]
Traffic volume	Low, Medium, High[2]
Truck traffic	Low, Medium, High[2]
Structural condition	structural coefficient: <0.44, 0.44-0.54, >0.54[3]
Climatic zone	No freeze, Dry freeze, Wet freeze, Wet No-freeze[4]
Work zone restrictions	None, Weekend-only, Time-limited
Project budget and timeframe	Limited, Moderate, Generous

Objectives
Optimum life extension
Highest condition index benefit
Lowest maintenance cost

[1] Based on the specifications used.
[2] May include intermediate values depending on the location and specifications.
[3] After Habbouche et al. (2019)
[4] These categories are used in the Long-Term Pavement Performance (LTPP) climatic data.

Figure 4. Model framework for PMA application decision-making

Material Selection: Types of Polymer Modifiers and Binder Grades

Materials selection in asphalt pavement construction entails carefully considering the polymer modifiers and binder grades. Polymer modifiers enhance the performance characteristics of asphalt binders, and the choice of binder grade impacts the pavement's response to temperature variations and traffic loads. Some of the commonly employed polymer modifiers include SBS for its suitability in high-traffic areas prone to rutting and cracking; styrene-ethylene-butylene-styrene for its enhanced elasticity and durability, making it suitable for locations with extreme temperature fluctuations; ethylene-propylene-diene-monomer for its high binder flexibility and aging resistance; natural rubber for improved flexibility and low-temperature cracking resistance, making it suitable for colder climates.

Binder grades, on the other hand, define the temperature susceptibility of asphalt binders and their performance across diverse climates and regions. Commonly used grades include the penetration grading system, viscosity grading system, and PG systems (Ghuzlan and Al-Khateeb 2013). The PG system is tailored to specific climate and traffic conditions, assessed using the Superpave Performance Grade test, thereby ensuring that the binder properties align with the pavement requirements. FDOT, for instance, utilizes the PG 76-22 PMA in roadways with traffic levels of at least 10,000 ESALs. For this, the top 1.5 in. of the structural layer is required to use PG 76-22 PMA when the traffic level is at least 10 million but less than 30 million ESALs. Indiana DOT also utilizes PG 76-22 binder on its highest volume PMA overlay roads. Missouri DOT leaves the material selection decision to the contractor. Generally, the agency does allow PG or MSCR grading of asphalt cements. Virginia DOT's PMA overlays are generally either 9.5 mm or 12.5 mm dense-graded mixes, or 9.5 mm or 12.5 mm SMAs produced with PG 64E-22 binder. The SMAs are mostly used on interstates, although they sometimes are used on high-volume primary routes. The dense-graded mixes are used on any high-volume route. Specific mix choices often come down to the experiences and preferences of the individual districts. Nebraska DOT previously utilized binder grades PG 58-34 and PG 64-34 in their polymer mixes prior to moving to MSCR grading.

DATA-DRIVEN EVALUATION OF PMA OVERLAY AS A PAVEMENT PRESERVATION TREATMENT

Overview

In the pursuit of a robust and comprehensive analysis, a diligent effort was made to engage with multiple DOTs across various regions including Wisconsin, Minnesota, Indiana, Nebraska, Ohio, Missouri, Tennessee, Virginia, North Dakota, Montana, Illinois, Michigan, California, Florida, Mississippi, and Iowa. While several DOTs were approached for their insights and data, it emerged that the Iowa DOT and FDOT stood out as the primary sources of pertinent information. These two agencies demonstrated a unique combination of having experience with PMA applications, specifically PMA overlays, and possessing a wealth of performance-related data. This allowed for an in-depth exploration into the outcomes of PMA overlay implementation and its subsequent influence on pavement performance. The project team's partnership with the Iowa and Florida DOTs serves as a foundation for the rigorous evaluation of the effectiveness of PMA overlays, further bolstering the credibility and comprehensiveness of the study's findings.

The Iowa and Florida DOTs' data sets provide a comprehensive and diverse collection of information on pavement sections that have been subjected to various forms of PMA applications as overlays. By leveraging these data sets, the study aims to rigorously assess the effectiveness and benefits of polymer modification on pavement performance. The analysis considered key indices including ride quality, rutting, cracking, and the IRI, allowing for a comprehensive evaluation of the impact of PMA mixes. Through a systematic comparison of performance indicators before and after the application of these modified mixes, this evaluation seeks to offer valuable insights into the contribution of polymer modification toward enhancing pavement durability, minimizing distresses, and extending the service life of roadways.

Data Description

Iowa DOT Data

The study draws upon data from the Pavement Management Information System (PMIS) and Iowa HPTO projects. The PMIS contributes essential condition and traffic information, cross-referenced with HPTO project data through the Origkey identifier. Key condition indices such as pavement condition index (PCI), IRI, rutting index, and cracking index, along with specific distress measures, are included. The research team sourced project-specific details, including costs, from historical bid tabulations via the Iowa DOT contracts portal and the Bid Express subscription service. Then, the team compiled a comprehensive data set encompassing 1,180 projects, from 1998 to 2020. The analysis centers on PCI, determined by the Iowa DOT's formula, as the key parameter for life extension and life-cycle cost evaluation. The team included a minimum of two distinct projects for each analyzed section, forming the foundation of this comprehensive analysis.

The team employed a systematic approach for a more refined investigation. The researchers initially categorized the data set into three tiers based on daily traffic volume, as depicted in Figure 5.

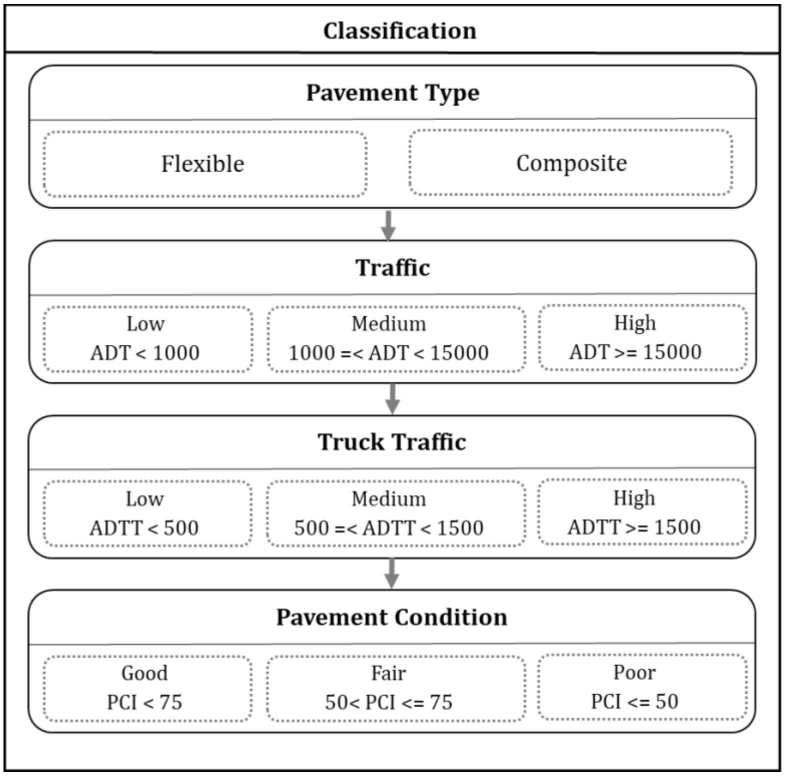


Figure 5. Traffic volume classification used for Iowa DOT data analysis

The team performed subsequent classification according to truck traffic levels, followed by grouping based on pavement condition, as determined by the PCI. This stepwise classification facilitated a detailed assessment. The team conducted average life extension and index benefit calculations for each category, providing valuable inputs for subsequent performance modeling and benefit-cost analysis (BCA).

FDOT Data

The data set obtained from FDOT included pavement sections where some form of PMA mix, including highly modified mixes, were applied in the surface/friction course of the most recent paving job. The data set contains condition rating indices (ride, rutting, cracking, and IRI) dating back to 1976 when the agency started data collection. It includes resurfacing and capacity work, representing 23,109 of the 45,517 total lane miles on the SHS as of December 31, 2022 (50.8%). The condition category utilized in the research was based on FDOT’s Deficient or Not Deficient system, determined based on the cracking and ride ratings as well as the prevailing speed limit along the section. IRI is used as the index of analysis for the life extension and index benefit performance measures.

FDOT does not directly tie its state sufficiency ratings to the FHWA grading. Instead, they both consider cracking, ride (IRI), and rutting (flexible pavements only), but have different grading criteria. In general, FDOT translates data into a 0–10 rating scale, where anything in the 0–6.4 range is considered deficient. An exception is made for ride ratings in which only 0–5.4 is considered deficient when the posted speed limit is less than 50 mph. It is based on these scales that the pavement condition classification upon which the analysis and performance evaluation conducted was premised. The traffic volume classification used for the analysis is as shown in Figure 6.

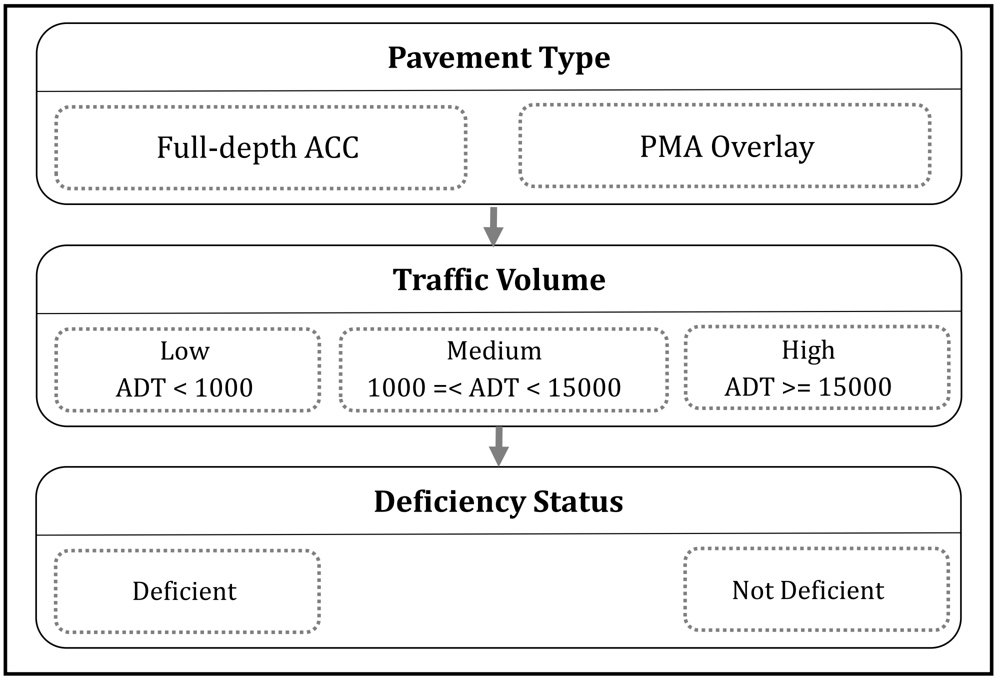


Figure 6. Traffic volume classification used for FDOT data analysis

Data Analysis and Performance Evaluation

The effectiveness of a pavement maintenance and repair treatment can be evaluated by analyzing pavement performance before and after applying a specific treatment; in this case, the treatment is a PMA overlay. This analysis considers condition indices and pavement deterioration rate, which are capable of quantifying the pavement’s life extension and index benefit for each project. In order to assess the treatment’s effectiveness, life extension is defined as the number of years by which the PMA overlay can extend the service life of a pavement segment and can be determined by solving the post-preservation deterioration curve function for the latest pre-preservation index value. Index benefit was also used as an additional metric to evaluate the treatment effect with respect to a specific condition index and can be defined as the area between the pre-project performance curve and the post-project performance curve over the range of the extended life. It is important to extrapolate the pre-project performance curve onto the extended life range for this evaluation. Figure 7 demonstrates the improvement in pavement condition, the corresponding pavement service life extension, and index benefit resulting from a PMA overlay project for a sample segment.

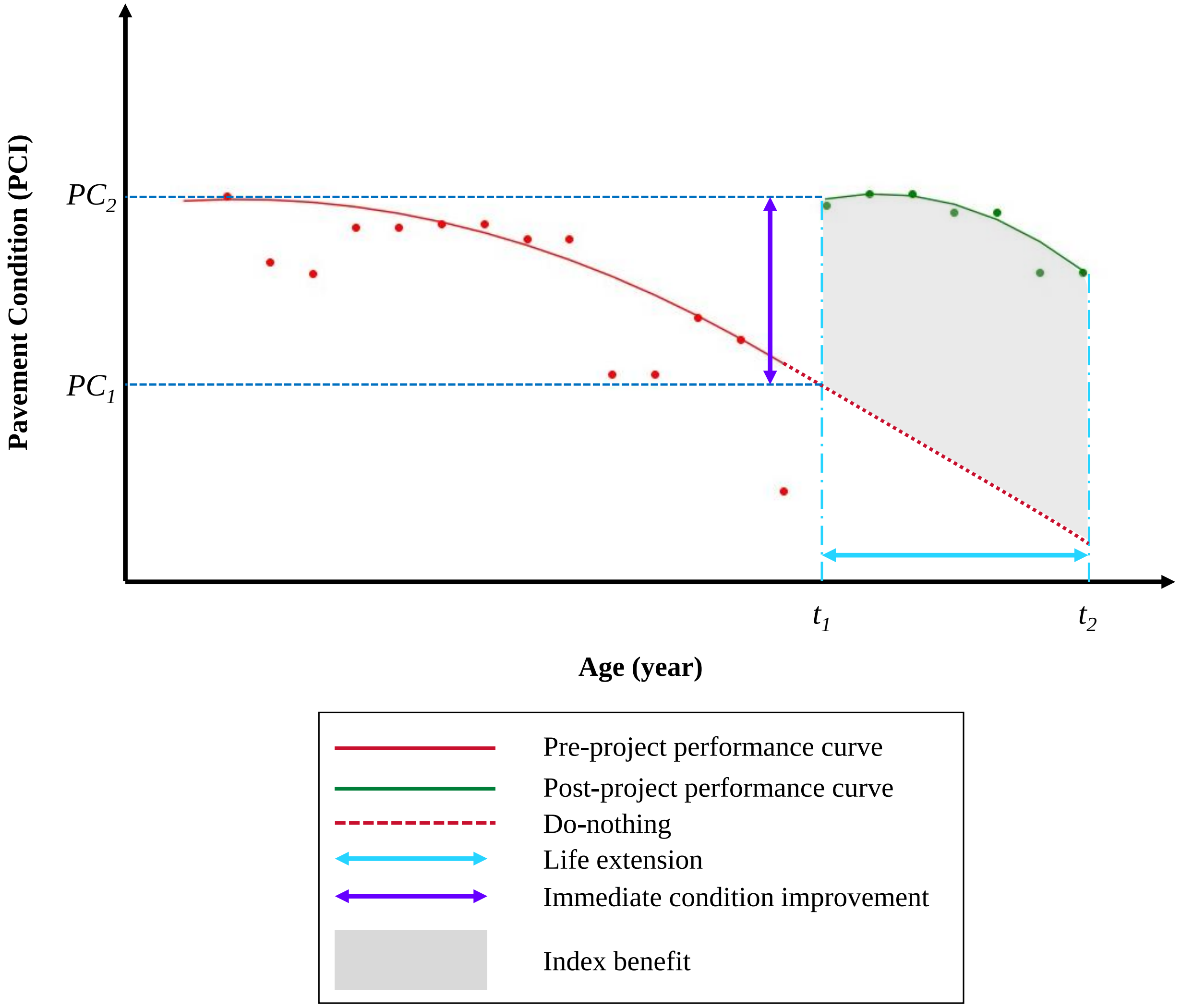


Figure 7. Quantifying performance resulting from PMA overlay project

It is important to note that the Iowa DOT data set used suffered from some irregularities because of unrecorded maintenance and data defects. However, the potential outliers were retained to avoid reducing the already small data set and were handled using robust regression models such as the random sample consensus (RANSAC) algorithm.

To determine the expected effectiveness of thin (less than 1.5 in.) PMA overlay treatment, the life extension and index benefit were calculated for all segments undergoing preservation in Iowa. The condition index used for the analysis is PCI because it considers all the important distress indices for pavements. The Iowa DOT calculates the PCI using equation 1.

$$PCI = 0.4 \times Cracking\ Index + 0.4 \times Riding\ Index + 0.2 \times Rutting\ Index \tag{1}$$

where, the cracking index is calculated by equation 2 as follows:

$$Cracking\ Index = 0.2 \times TCI + 0.1 \times LCI + 0.3 \times LWPCI + 0.4 \times ACI \tag{2}$$

where, TCI is transverse cracking index, LCI is longitudinal cracking index, LWPCI is longitudinal wheel path cracking index, and ACI is alligator cracking index.

Riding index was determined using the IRI provided by the Iowa DOT, which was scaled from 0–100. The IRI values below 0.5 m/km (31.68 in./mi) were considered perfect and scored 100, while values above 4.0 m/km (253.44 in./mi) were assigned a score of 0. Intermediate values between 0.5 and 4 m/km were calculated using linear interpolation. Finally, rutting index can be calculated using equation 3.

$$Rutting\ Index = 100 - [(\frac{Rut(mm)}{12(mm)}\ or\ \frac{Rut\ (inch)}{0.47244(inch)}) \times 100] \tag{3}$$

The team averaged the results of each project segment to determine the life extension for PMA overlay. According to the results, applying PMA overlay could extend the pavement life by about 8.3 years for composite pavement, while its effectiveness for flexible pavement showed an extension of almost 9.8 years. Life extension is a good indicator to show the treatment's effectiveness, while index benefit provides more precise information regarding the effectiveness by integrating the immediate performance improvement alongside life extension. For instance, when two treatments have the same service life extension, but one shows a greater immediate performance improvement, it results in a higher index benefit than the other. This indicates that the treatment can offer better ride quality within the same service life and improve user satisfaction.

Benefit-Cost Analysis

Using the service life extension and index benefits, the next step was a BCA. BCA uses cost and life extension as the primary inputs to determine the treatment cost over the life cycle. The implementation cost for a PMA overlay in Iowa is calculated to be around $98,600 based on the bidding tabulation data. BCA considers different factors such as implementation cost, maintenance cost, salvage cost, analysis period, and discount rate to calculate economic indicators such as equivalent uniform annual costs (EUAC) and the benefit-cost ratio (BCR) to assess the cost efficiency of the treatment. The life-cycle cost analysis accounted for preservation cost, maintenance cost, and salvage cost, while factoring in the discount rate based on the year of expenditure and a selected analysis period. EUAC is obtained from equation 4.

$$EUAC = NPV \times \frac{discount\ rate(1+discount\ rate)^{analysis\ period}}{(1+discount\ rate)^{analysis\ period}-1} \tag{4}$$

where the analysis period used is 15 years and NPV is the net present value, calculated using equation 5.

$$NPV = \sum_{0}^{n_k} Preservation\ Cost \left[\frac{1}{(1+i)^{n_k}}\right] + \sum_{0}^{n_k} Maintanance\ Cost \left[\frac{1}{(1+i)^{n_k}}\right] - Salvage\ value \times \left[\frac{1}{(1+i)^{n_k}}\right] \quad (5)$$

Where n_k is the year of expenditure and i is the real discount rate according to the Office of Management and Budget Circular by the United States government (1.75%).

Maintenance costs were capped at $2,500 annually, and calculated using equation 6 based on a five-year sliding scale.

$$Maintenance\ cost = \begin{cases} \frac{year}{5} \times 2{,}500 & if\ year \leq 5 \\ 2{,}500 & if\ year > 5 \end{cases} \quad (6)$$

The salvage value, which considers the remaining service life and preservation cost, can be calculated using equation 7:

$$Salvage\ value = \frac{remaining\ service\ life\ after\ analysis\ period}{Total\ amount\ of\ service\ life} \times Preservation\ Cost \quad (7)$$

The BCR used the index benefit values and divided them by the EUAC during the analysis period. This ratio quantifies the benefit of each individual unit area relative to its cost. BCR can be calculated by equation 8.

$$BCR = \frac{Index\ Benefit}{EUAC} \quad (8)$$

Life Extension and Benefit-Cost Analysis

In this section, the team presents and analyzes the outcomes of the present study, considering the synergistic effects of the combined conditions of ADT, truck traffic, and pavement condition on the metrics of interest including EUAC, index benefit, BCR, and life extension.

Iowa DOT

As shown previously in Figure 5, the project team classified the data set for each pavement type into three levels according to daily traffic volume. The team then categorized the data based on truck traffic levels; and finally, the team formed groups based on pavement condition classification, determined by the PCI. After calculating the EUAC, average life extension, and index benefit for each category, these results were used as inputs for the BCA.

The results of the analysis under combined conditions revealed noteworthy trends in EUAC values. For scenarios with higher ADT and intense average daily truck traffic (ADTT), EUAC values exhibited an expected increase, indicative of the heightened maintenance costs associated with heavy loads as shown in Table 6.

Table 6. EUAC analysis with Iowa DOT data

		Low-ADT			**Medium-ADT**			**High-ADT**		
Pavement type	**PCI**	Low-ADTT	Medium-ADTT	High-ADTT	Low-ADTT	Medium-ADTT	High-ADTT	Low-ADTT	Medium-ADTT	High-ADTT
Flexible	Good	15,939	N/A	N/A	35,281	N/A	N/A	N/A	N/A	N/A
	Fair	15,858	N/A	N/A	15,951	13,416	41,593	N/A	N/A	N/A
	Poor	14,026	N/A	N/A	15,312	14,926	13,497	N/A	N/A	N/A
Composite	Good	21,991	N/A	N/A	21,895	22,846	27,765	N/A	N/A	N/A
	Fair	13,581	N/A	N/A	14,653	14,761	15,431	13,880	22,832	20,714
	Poor)	13,651	N/A	N/A	14,113	14,654	15,557	15,779	14,649	28,036

Data source: Iowa DOT
* N/A here means no implementation

The result also shows the significant sensitivity of pavement condition to EUAC, with a fairly consistent trend in the values exhibited across condition variations as depicted in Figure 8.

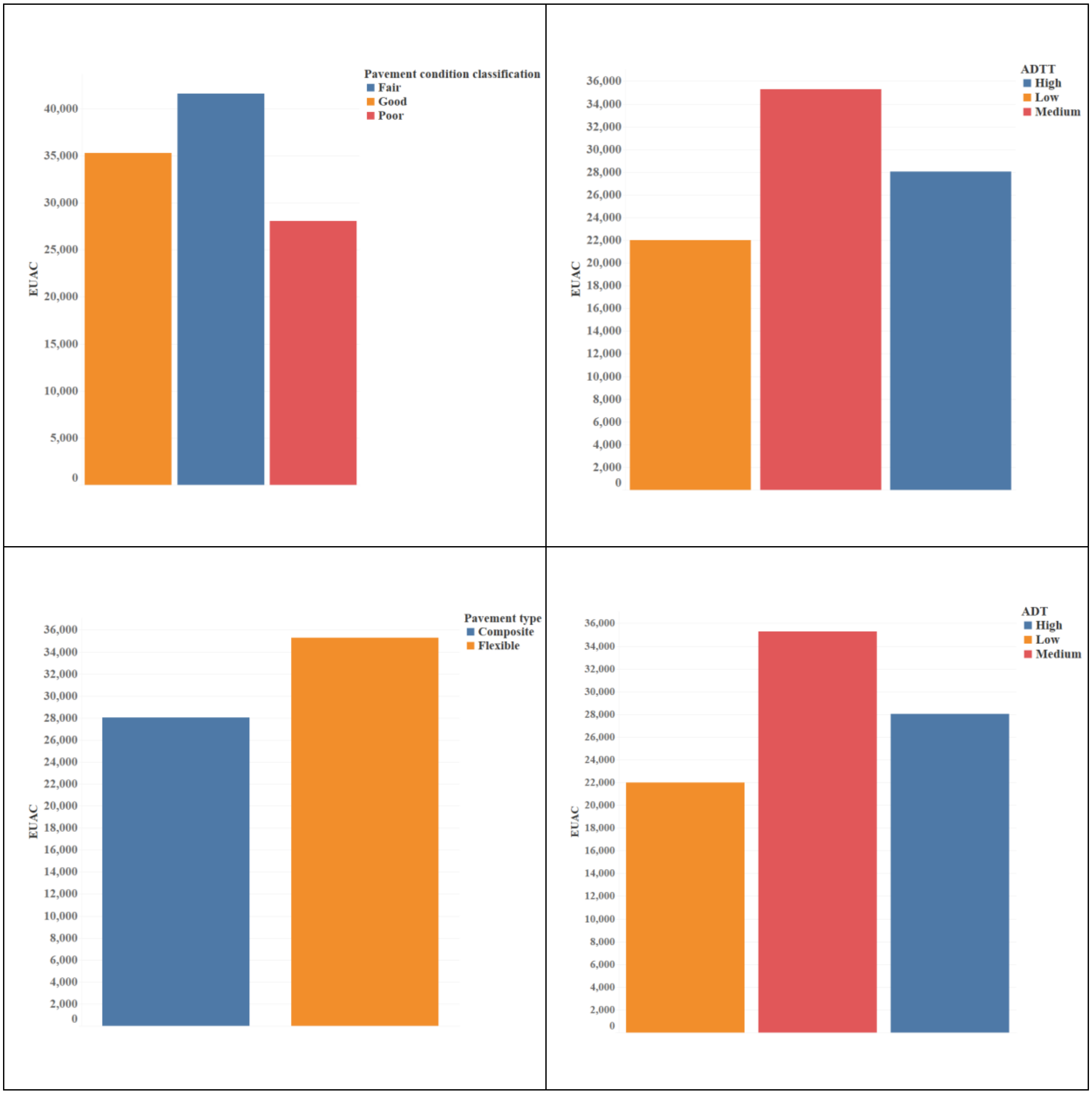


Figure 8. Sensitivity of EUAC to different factors (pavement condition classification, ADTT, ADT, and pavement type, clockwise from top left) for optimal scenarios

The analysis demonstrates that scenarios characterized by higher ADT, moderate truck traffic intensity, and poor initial pavement condition exhibit the highest index benefit values as shown in Table 7.

Table 7. Index benefit analysis with Iowa DOT data

Pavement type	**PCI**	**Low-ADT**			**Medium-ADT**			**High-ADT**		
		Low-ADTT	Medium-ADTT	High-ADTT	Low-ADTT	Medium-ADTT	High-ADTT	Low-ADTT	Medium-ADTT	High-ADTT
Flexible	Good	89	N/A	N/A	19	0	0	N/A	N/A	N/A
	Fair	308	N/A	N/A	376	562	29	N/A	N/A	N/A
	Poor	599	N/A	N/A	512	584	649	N/A	N/A	N/A
Composite	Good	46	N/A	N/A	96	78	125	N/A	N/A	0
	Fair	548	N/A	N/A	379	379	341	608	178	270
	Poor	664	N/A	N/A	579	590	421	412	515	256

Data source: Iowa DOT

* N/A here means no implementation for application scenario

The results suggest that PMA overlays are most effective in scenarios where heavy traffic loads, including truck traffic, subject pavements to substantial stresses. Additionally, the overlays' ability to rehabilitate deteriorated pavements significantly contributes to the observed high index benefit values. For composite pavement, the highest index benefit was realized from applications with low ADT, low ADTT, and poor pavement condition. The sensitivity of index benefit to the different factors for the optimal scenarios is shown in Figure 9.

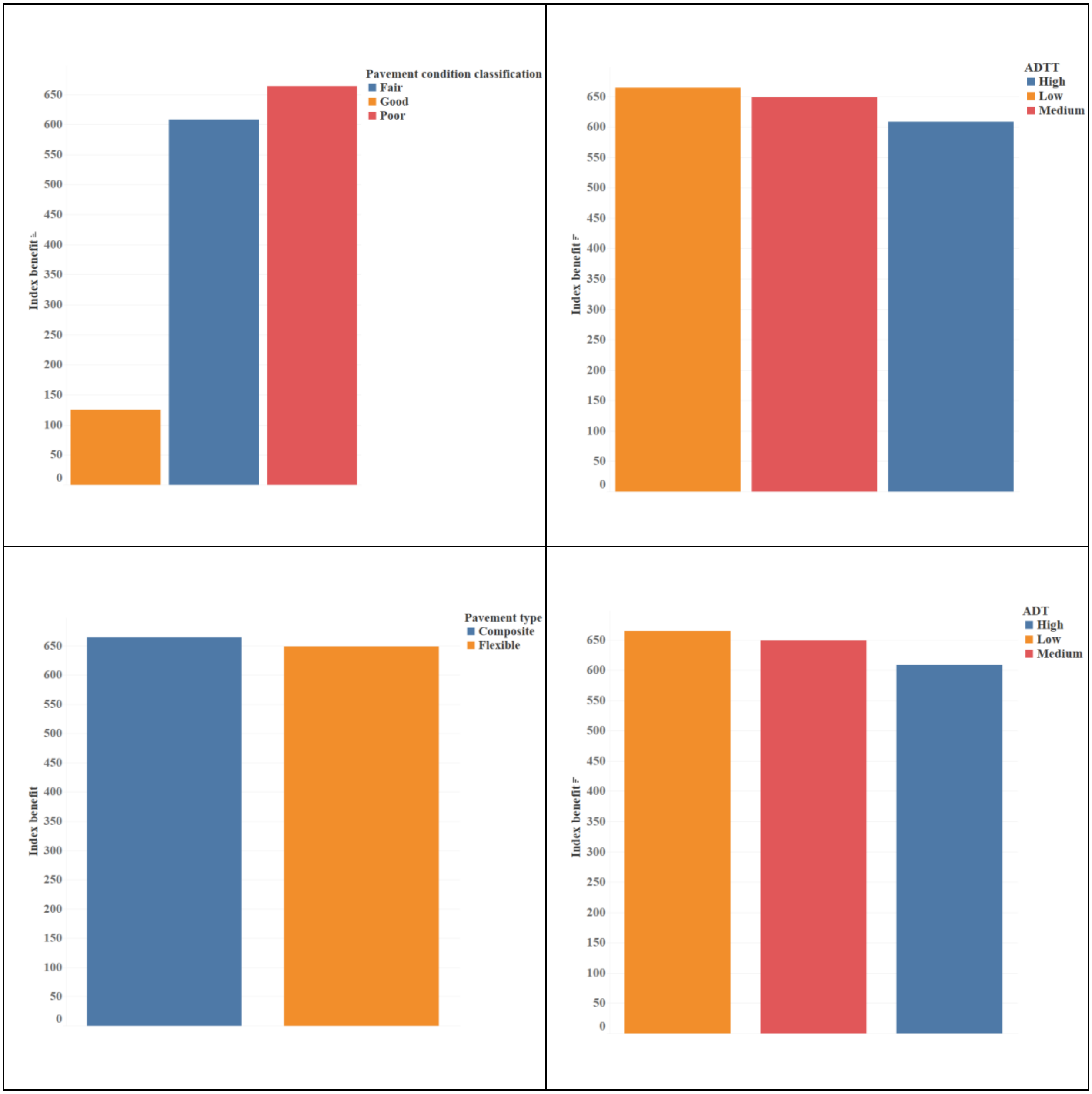


Figure 9. Sensitivity of index benefit to different factors (pavement condition classification, ADTT, ADT, and pavement type, clockwise from top left) for optimal scenarios

The life extension results under combined conditions were illuminating as shown in Table 8.

Table 8. Life extension analysis with Iowa DOT data

Pavement type	**PCI**	**Low-ADT**			**Medium-ADT**			**High-ADT**		
		Low-ADTT	Medium-ADTT	High-ADTT	Low-ADTT	Medium-ADTT	High-ADTT	Low-ADTT	Medium-ADTT	High-ADTT
Flexible	Good	7.9	N/A	N/A	3.3	0.0	0.0	N/A	N/A	N/A
	Fair	8.0	N/A	N/A	7.9	12.5	2.8	N/A	N/A	N/A
	Poor	11.0	N/A	N/A	8.7	9.3	12.2	N/A	N/A	N/A
Composite	Good	5.7	N/A	N/A	5.7	5.0	4.7	N/A	N/A	0.0
	Fair	12.0	N/A	N/A	9.8	9.6	8.6	11.3	5.0	6.8
	Poor	11.9	N/A	N/A	10.8	9.8	8.4	8.1	9.8	4.5

Data source: Iowa DOT
* N/A here means no implementation for application scenario

Flexible pavements with medium ADT and medium truck traffic and in fair condition exhibited the most substantial life extension. Composite pavement with low ADT, with low truck traffic, and in fair condition showed the most substantial life extension in this category. Pavements in fair to poor condition reaped the most significant benefits, attesting to the efficacy of overlays in rehabilitating deteriorated structures. The sensitivity of life extension to the different factors for the optimal scenarios is shown in Figure 10.

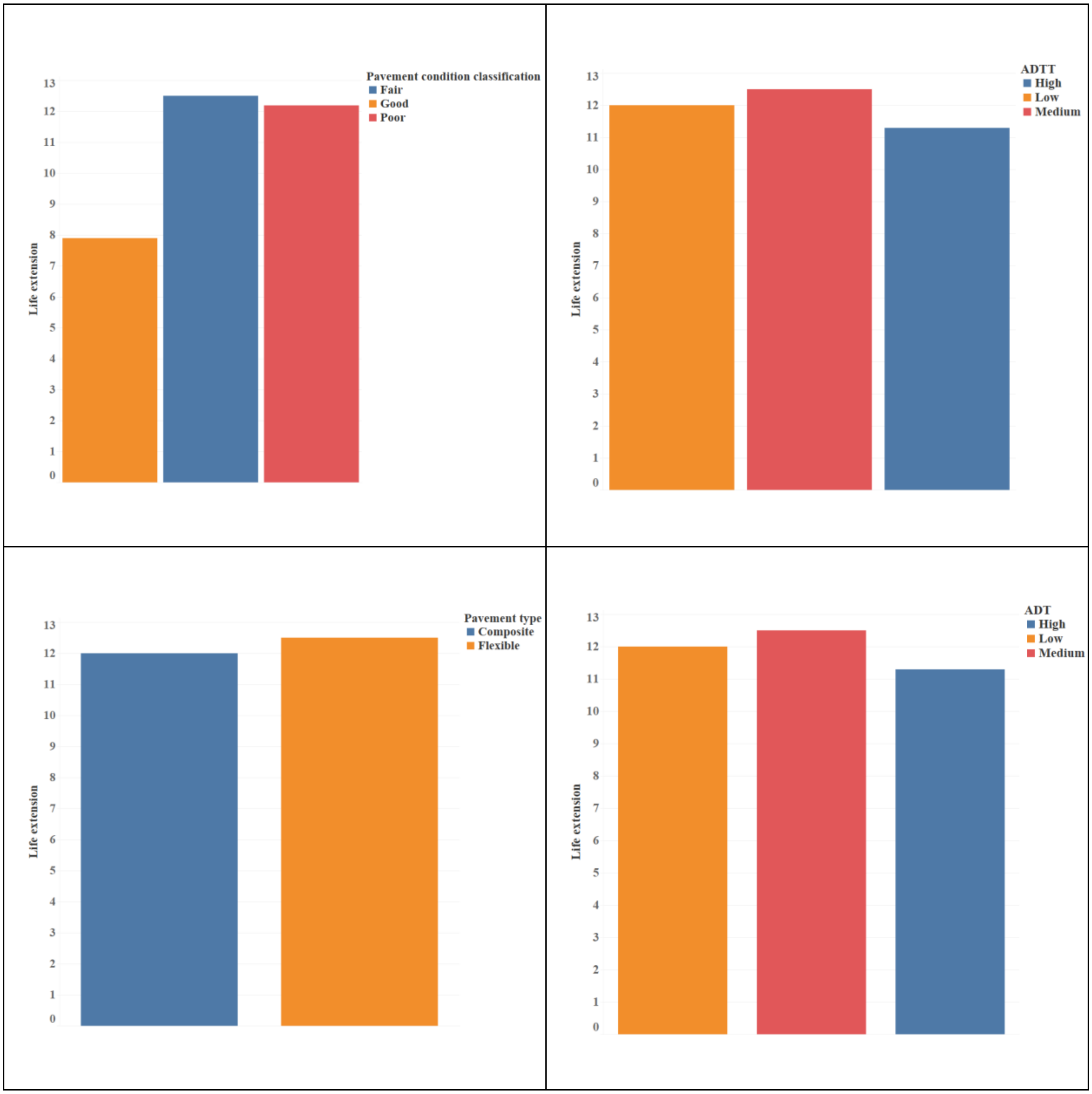


Figure 10. Sensitivity of life extension to different factors (pavement condition classification, ADTT, ADT, and pavement type, clockwise from top left) for optimal scenarios

Recommendations for Performance-Based Decision-Making

Previous sections provided the BCA for different scenarios where HPTO made with HiMA were chosen as the preferred alternative for pavement preservation. The findings of the BCA based on EUAC, life extension, index benefit, and BCR could serve as guiding information for targeted overlay selection. Informed decision-making based on BCR could help agencies harness the potential of PMA overlays through actionable strategies to optimize performance, extend the service life, and achieve favorable economic outcomes. The BCR in this analysis encompasses two vital performance indicators, i.e., index benefit and EUAC, and it is based on the straightforward assumption that scenarios with the highest BCR hold the most promise. These scenarios not only offer superior index benefits, closely linked to extended pavement life, but also strike a balance with the life-cycle cost incurred through treatment application. Illustrated in Figures 11 and 12, respectively, for composite and flexible pavement types, the gradation of blue shades underscores the preference hierarchy for PMA overlay application, with darker shades indicating the most favorable scenarios and white shades representing no implementation of the application scenario.

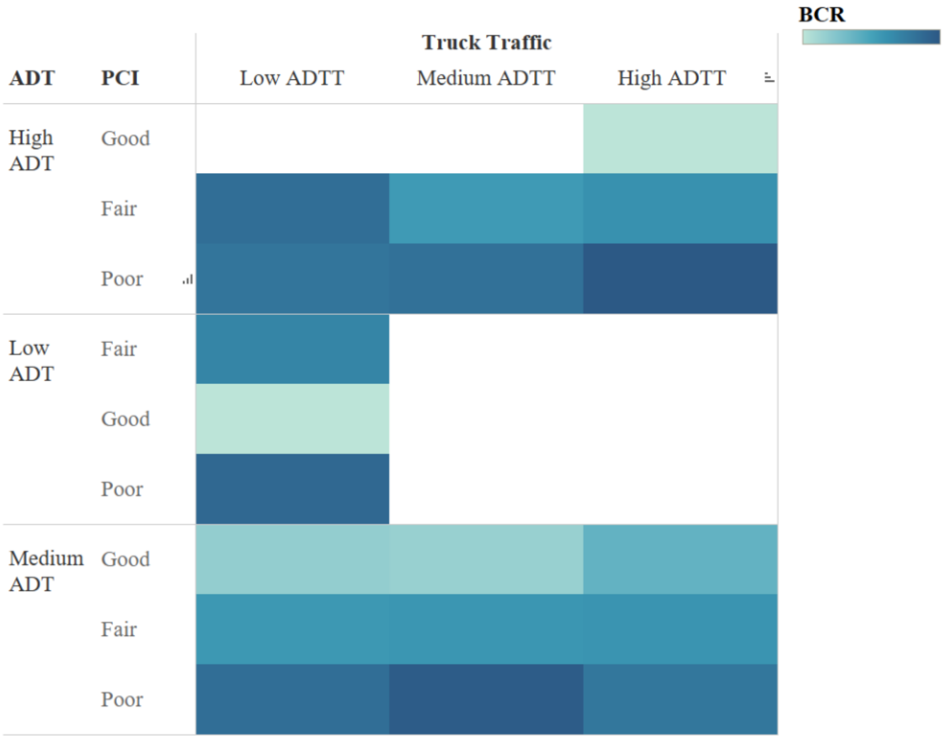


Figure 11. BCR heatmap for composite pavements under different application scenarios

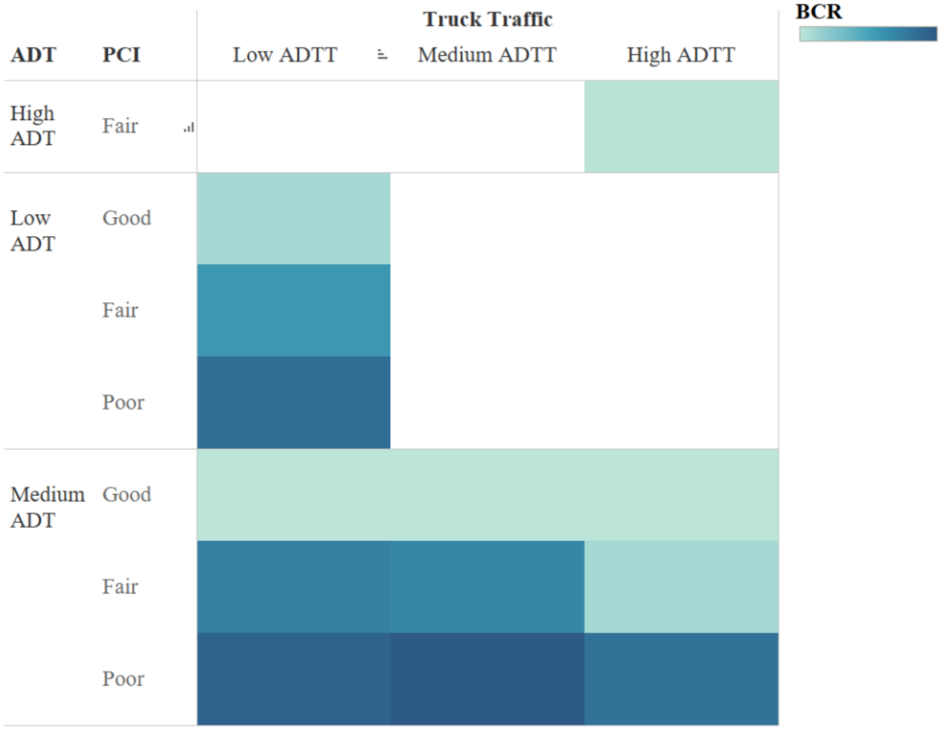


Figure 12. BCR heatmap for flexible pavements under different application scenarios

With the core objective of this research centered around methodically structuring the decision-making process, the integration of PMA overlays as a preservation treatment gains significance. This approach enables the strategic application of PMA overlays, ensuring their deployment precisely when and where needed, as informed by the outcomes of the heatmap analysis in the previous two figures.

FDOT

In this section, the project team adopted a refined approach to facilitate a detailed investigation. As depicted previously in Figure 6, for FDOT, the team meticulously classified the data sets pertaining to each pavement type into three tiers based on daily traffic volume. Subsequently, the team further stratified these tiers according to the pavement condition herein termed as deficiency status. Once these categorizations were in place, the team computed the average life extension and index benefit for each category. The life extension analysis and index benefit analysis, together with their benefit comparisons, are shown in Table 9 and Table 10 respectively, and in Figure 13 and Figure 14, respectively.

Table 9. Life extension analysis with FDOT data

Pavement type	Pavement condition	Low-ADT	Medium-ADT	High-ADT
Flexible	Deficient	15.0	14.2	14.3
	Not deficient	N/A	12.3	13.3
Surface treatment	Deficient	N/A	11.1	14.5
	Not deficient	12.1	7.6	11.2

Data source: FDOT

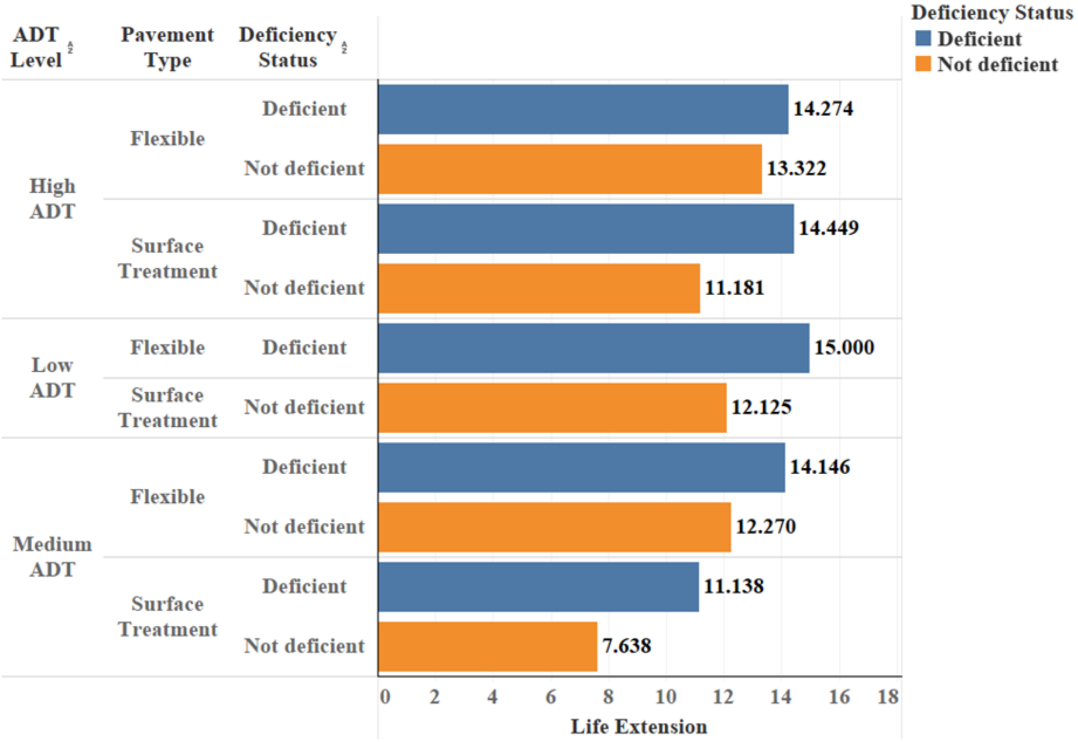
* N/A here means no implementation for application scenario

Table 10. Index benefit analysis with FDOT data

Pavement type	Pavement condition	Low-ADT	Medium-ADT	High-ADT
Flexible	Deficient	829.1	630.8	668.7
	Not deficient	N/A	533.5	516.9
Surface treatment	Deficient	N/A	279.1	906.2
	Not deficient	262.4	476.7	965.3

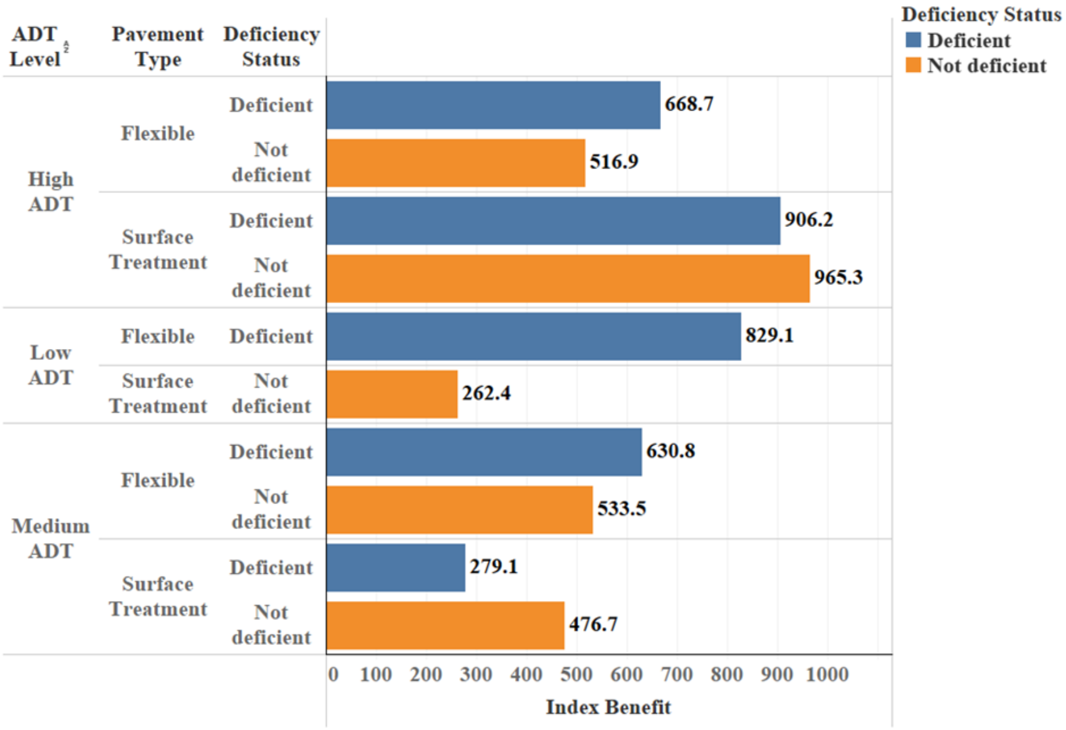
Data source: FDOT

*N/A here means no implementation



Data source: FDOT

Figure 13. Life extension for different application scenarios



Data source: FDOT

Figure 14. Index benefit for different application scenarios

CONCLUSIONS AND RECOMMENDATIONS

This chapter brings together the comprehensive findings and insights gleaned from a review of the literature, case studies on PMA overlay implementations, and a performance evaluation based on data from two transportation agencies. The culmination of the present study offers a synthesis of valuable information that underscores the significance of PMA overlays in enhancing pavement performance and durability. Guided by the robust empirical evidence and observations obtained from multiple DOT applications, the research team presents a series of informed conclusions and actionable recommendations. These conclusions shed light on the broader implications for pavement engineering practices and provide a roadmap for optimizing the utilization of PMA overlays to address multifaceted challenges in the realm of transportation infrastructure.

Summary of Findings

The following two sections provide a summary of the findings unearthed through the development of this guidebook.

Literature Survey Findings

Drawing from an extensive exploration of existing literature, the following key points summarize the insights from the team’s findings:

- Enhancing asphalt binder properties through the addition of polymers has become a well-established practice, aiming to address major distresses like thermal cracking, fatigue cracking, and rutting, which significantly impact pavement performance. The introduction of polymers, primarily elastomers and plastomers—such as SBS, SBR, and EVA—alter asphalt binder properties, resulting in benefits like improved resistance to rutting, crack resistance, increased durability, flexibility, and elasticity.

- The application of PMA overlays offers substantial benefits to asset managers and agencies. Although initial construction costs are higher, the reduced maintenance requirements and extended service life lead to significant life-cycle cost savings. PMA overlays provide superior performance, resilience, and durability, reducing disruptions to traffic and ensuring a robust pavement network.

- Research findings emphasize the significance of considering binder selection, asphalt composition, job mix formula, and volumetric properties in achieving resilient and sustainable asphalt mixtures.

- Specific considerations for PMA overlay mix design include using RAP to offset polymer costs. RAP materials should be within the limits of fine-graded mixtures due to the thin overlay's nature. Incorporating minimal RAP with PMA binder avoids blending problems. Fatigue and low-temperature cracking tests might be necessary for high RAP compositions.

- The selection of aggregate gradation and characteristics is crucial to the performance of PMA overlays. While different agencies adopt varying aggregate sizes, the typical range is found to be within 0.375–0.492 in. nominal aggregate size.

- There is an important relationship between the polymer loading rate and residual asphalt content in terms of overall performance. Research tends to recommend a practical range of 2%–10% polymer loading, with most manufacturers' specifications within the 3%–5% range. Conventional polymer modification typically employs up to 3% SBS, while highly polymer-modified solutions use approximately 6%–8% SBS content.

- The evaluation of high polymer-modified binders has relied on performance-based specifications and testing methods. Various tests measure stiffness, elastic response, and fracture resistance, such as DSR, MSCR, and IDT.

- To implement PMA overlays successfully, construction practices must be precise and efficient.

- Pre-construction planning and coordination are foundational to achieving desired outcomes.

- To enhance structural integrity and pavement longevity, proper mix production and placement techniques are essential. Noteworthy practices gleaned from diverse examples highlight the significance of temperature control and minimizing hand work.

- PMA overlays require quality control and assurance measures to ensure mix reliability and performance. Ensuring the quality of the mixture through well-structured quality control procedures is pivotal in ensuring the success of polymer-modified mixtures.

- During the construction process, various challenges and troubleshooting scenarios may arise, potentially affecting efficiency and quality. While no specific additional health, safety, or environmental challenges arise from PMA overlays, temperature sensitivity during production must be accounted for.

- Achieving optimal workability can be intricate due to polymer-induced viscosity changes, demanding a delicate balance between viscosity and workability. Attention to transition zones and construction joints is vital to ensure seamless connections and avert distress.

Recommendations for Future Research

Based on the focus of this guidebook—consisting of a literature survey, case study examples, and a performance evaluation based on obtained data—several areas of related research can be further explored to enhance and deepen the understanding of PMA and its application in pavement construction. Recommendations for future research include the following evaluations and investigations:

- **Long-Term Performance:** Comprehensive field studies should be conducted to assess the long-term performance of PMA overlays under various traffic conditions, climate variations, and load levels. This research should focus on monitoring distresses, such as rutting, cracking, and fatigue, to validate the effectiveness of polymer modification in extending pavement service life.

- **Effect of Aging:** The long-term aging effects should be investigated on different types of PMA binders. This could help researchers understand how mechanical and rheological properties change over time and explore potential strategies to mitigate the degradation of these properties due to oxidative aging.

- **Polymer Interaction:** The interaction of different polymer types and concentrations with different asphalt sources should be studied. This can provide insights into the compatibility of various polymers with specific asphalt binders and aid in optimizing the selection of polymer type and content for different applications.

- **Environmental Impact:** The environmental impact of using PMA overlays should be evaluated, considering factors such as the energy consumption during production, greenhouse gas emissions, and recyclability of the materials. Further, the evaluation could compare these impacts with conventional asphalt and other pavement preservation techniques to determine the overall sustainability of polymer-modified overlays.

- **Mix Design Optimization:** Advanced mix design methodologies could be developed that incorporate polymer-modified binders. These studies should investigate how different aggregate gradations, binder types, polymer concentrations, and other additives influence the volumetric and mechanical properties of the mixture. This could lead to more efficient and effective mix designs tailored to specific pavement conditions.

- **Binder Testing Protocols:** Testing protocols specifically designed for PMA binders should be standardized. Current binder testing methods might not fully capture the unique properties of these modified binders. This could include the development of new test methods or the modification of existing ones to better characterize the performance of polymer-modified binders.

- **Effect on Pavement Structure:** Future studies should explore how the addition of PMA overlays affects the structural behavior of pavements. Additionally, researchers should investigate the interlayer bonding between existing pavement layers and the overlay, as well as the potential for reflective cracking. This can guide the development of overlay designs that minimize distresses.

- **Optimal Polymer Content:** Future studies should determine the optimal polymer content for different types of overlays and pavement conditions. Researchers could investigate the relationship between polymer content and key performance indicators like rutting resistance, cracking resistance, and durability to establish guidelines for polymer content selection.

- **Recycling of PMA:** Future studies should examine the feasibility and challenges of recycling PMA materials. Researchers could investigate methods to effectively separate and reuse polymer-modified binders, aggregates, and other components from aged pavements.

- **BCA:** With more performance data, driven by the adoption of this preservation strategy by transportation agencies, a more robust cost-benefit analysis that considers initial construction costs, maintenance savings, and extended service life associated with PMA overlays across multiple jurisdictions can be assessed. This analysis can provide decision-makers with a clearer understanding of the economic advantages of using these overlays.

- **Advanced Testing Techniques:** Future studies should explore advanced testing techniques such as imaging technologies, nondestructive testing, and advanced rheological analysis to gain deeper insights into the behavior of PMA materials and their interaction with pavement structures.

- **Climate Resilience:** Future studies should investigate the performance of PMA overlays in extreme climate conditions, including very high and very low temperatures, heavy rainfall, and freeze-thaw cycles. Understanding the material's response to these conditions is crucial for ensuring its long-term resilience.

By addressing these research areas, the asphalt industry can further optimize the use of PMA overlays, enhance pavement performance, and contribute to the development of more sustainable and durable transportation infrastructure.

Call to Action for Transportation Agencies and Industry Stakeholders

The significance of PMA overlays as a pavement preservation technique is resounding in the successful experiences of numerous transportation agencies. After decades of PMA overlay implementations and insights from several transportation agencies, as well as an in-depth literature review, it is now the time to encourage DOTs and industry stakeholders to recognize the benefits of adopting PMA overlays as a proactive strategy for enhancing pavement longevity and performance that can offer formidable benefits if utilized at the right time and with the right methods.

As documented in this present study, the implementation of PMA overlays offers transportation agencies numerous benefits that include the following:

- Address crucial considerations substantial to the selection and implementation of PMA overlays
- Unlock the potential of PMA overlays
- Promote informed decision-making at the edge levels of the agency
- Support a multifaceted approach to pavement preservation
- Advance sustainable infrastructure
- Chart a future path for structuring preservation techniques

By developing a structured process for state DOTs for the selection and application of PMA overlays under diverse pavement and service conditions, the guidebook presented herein could be a significant step toward promoting the adoption of this technique and ensuring efficient use of its capabilities.

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APPENDIX. PMA OVERLAY LITERATURE GUIDE

Table A-1. PMA overlay literature guide

Main topic	Focus area 1	Focus area 2	References
Materials	Design and production	Superpave	McDaniel and Shah 2003, Yildirim 2007
		Production process	Roberts et al. 1996, Alataş and Yilmaz 2013, Haddadi et al. 2008, Jasso et al. 2013, Al-Hadidy and Yi-qiu 2009, Yu et al. 2007
		Polymer-modified binder design and evaluation (includes material selection and dosages)	Polacco et al. 2006, 2008; Redelius 2004; Jew et al. 1986; Jasso et al. 2013; Fang et al. 2012
Effect of polymer modification on binder properties	Material characterization	Mechanical properties	Airey 2003, 2004; Lee et al. 1999; Alataş and Yilmaz 2013; Fawcett and McNally 2000, 2001, 2003; Wang et al. 2007; Jew et al. 1986; Fuentes-Audén et al. 2008; Lewandowski 1994; Isacsson and Lu 1999; Ait-Kadi et al. 1996; Iskender et al. 2012; Li et al. 2021
		Rheological properties	Airey 2002, 2003, 2004; Bonemazzi et al. 1996; Zhang et al. 2009; Fernandes et al. 2008; Lee et al. 1999; Navarro et al. 2004; Wong et al. 2004; Alataş and Yilmaz 2013; Zhang and Yu 2010; Fawcett and McNally 2000, 2001, 2003; Carrera et al. 2009; Polacco et al. 2008; Rojo et al. 2004; Yu et al. 2007; Rossi et al. 2015; Li et al. 2021
		Microstructure	Habbouche et al. 2020; Yildirim 2007; Carrera et al. 2010; Soenen et al. 2008, 2009; Oliver et al. 2012; Pérez-Lepe et al. 2005; Shivokhin et al. 2012; Jasso et al. 2013
		Review	Habbouche et al. 2020, Yildirim 2007
Effect of polymer modification on	Performance prediction	N/A	Bahia et al. 2001, Gorkem and Sengoz 2009, Al-Hadidy and Yi-qiu 2009

Main topic	Focus area 1	Focus area 2	References
pavement performance		Rheological properties	Vargas et al. 2013, Martin-Alfonso et al. 2008
	Field performance evaluation		Quintus et al. 2007, Airey 2003, Oliver et al. 2012
		Durability	Wright et al. 2011, Roque et al. 2004
	Laboratory performance evaluation	N/A	Habbouche et al. 2021b, 2022b; Tayfur et al. 2007; Becker et al. 2001; Bernier et al. 2012; da Silva et al. 2004; Sengoz and Isikyakar 2008a, 2008b; Zhang et al. 2009; Zhang et al. 2011; Vargas et al. 2005
	Durability improvement	Moisture damage	Gorkem and Sengoz 2009, Iskender et al. 2012
		Rutting	Uddin 2003, Tayfur et al. 2007, Kim et al. 2009, Bernier et al. 2012, Lee et al. 1999, Wong et al. 2004, Yu et al. 2007, Fang et al. 2012, Iskender et al. 2012
		Cracking	Kim et al. 2009, Lee et al. 1999, Roque et al. 2004, Fang et al. 2012
		Aging	Wright et al. 2011, Zhang et al. 2010, 2011
Decision-making	Maintenance	Life-cycle cost analysis	Huang et al. 2021, He et al. 2021
		Material selection	Jalali and Vargas-Nordcbeck 2021, Roberts et al. 1996
	Material selection	Cost considerations	Haddadi et al. 2008
Implementation	Implementation by state DOTs	Durability/Rutting	Tia et al. 2002
		Superpave	McDaniel and Anderson 2001, Tia et al. 2002
State-of-practice review	High PMA binders	N/A	Habbouche et al. 2021a, Habbouche et al. 2020, Yildirim 2007, Zhao et al. 2020, Vargas-Nordcbeck and Mussleman 2021

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