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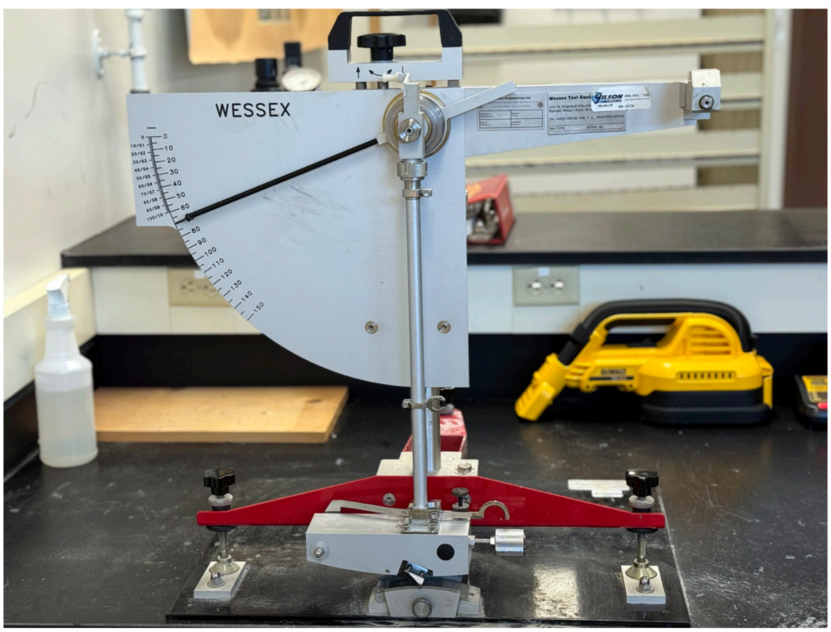
Stone Matrix Asphalt (SMA) Overlay Performance Evaluation



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16. Abstract

Stone matrix asphalt (SMA) is a specialized asphalt mixture designed to improve pavement performance by combining a coarse aggregate skeleton with a high-binder content mortar. This innovative design, adopted by the Indiana Department of Transportation (INDOT) in the late 1990s, offers distinct advantages over conventional hot mix asphalt (HMA). Currently, INDOT SMA-surfaced pavements are undergoing a second round of rehabilitation, which presents a valuable opportunity to assess their performance and return on investment (ROI). In Indiana, steel slag is used as the primary SMA coarse aggregate because of its toughness and durability. However, it may be possible to use other, more locally available coarse aggregates in SMA without loss of mixture performance. Field performance evaluations highlight the superior performance of SMA over HMA on U.S. Highways. The significant percentage differences in roughness and cracking demonstrate SMA's enhanced durability and ability to resist deformation and cracking. The LCCA results demonstrate that, despite higher initial construction costs, SMA overlays exhibit superior long-term cost performance relative to HMA. The ROI analysis reveals that SMA overlays yielded a 69.3% ROI over the 29-year analysis period. Exploring steel slag alternative aggregates for Indiana provides important insights into coarse aggregate selection for SMA in Indiana. With strict coarse aggregate requirements, steel slag and dolomite have been the main choices for Indiana SMA mixtures. However, the study results indicate that crushed gravel can perform similarly to steel slag in laboratory testing, possibly expanding options for aggregate selection. Although increasing dolomite content to replace steel slag is possible, it would require careful consideration of the aggregate toughness requirements.

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EXECUTIVE SUMMARY

Introduction

Stone matrix asphalt (SMA) is a specialized asphalt mixture designed to improve pavement performance by combining a coarse aggregate skeleton with a high-binder content mortar. This innovative design, adopted by the Indiana Department of Transportation (INDOT) in the late 1990s, offers distinct advantages over conventional hot mix asphalt (HMA). One of the most notable benefits of SMA is its extended service life beyond that of a conventional HMA mixture. Compared to HMA, SMA is well-known for its improved resistance to deformation and cracking—critical factors in maintaining pavement integrity under heavy traffic loads. In Indiana, SMA is more expensive than conventional HMA mixtures due to the necessity for high-quality, durable aggregates, increased asphalt binder content, and often-modified asphalt binders and fibers. SMA production involves a more meticulous process than HMA, which also contributes to the higher cost.

Currently, INDOT SMA-surfaced pavements are undergoing a second round of rehabilitation, presenting a valuable opportunity to assess their performance and return on investment (ROI). By quantitatively examining SMA-surfaced pavement performance, the aim of this study was to determine if SMA mixtures have extended years of service and reduced pavement maintenance needs when compared to pavements with conventional asphalt mixture surfaces.

In addition to performance assessment, questions have been raised about SMA coarse aggregate requirements. SMA coarse aggregate must be sufficiently durable to support traffic loads through its stone-on-stone aggregate skeleton. In Indiana, steel slag is used as the primary SMA coarse aggregate because of its toughness and durability. However, it may be possible to use other, locally available coarse aggregates in SMA without a loss of mixture performance.

Given the opportunity to assess SMA performance, and the need to investigate the possibility of using additional coarse aggregate types in SMA mixture, the objectives of this study were to (1) evaluate the SMA mixture performance compared to conventional HMA mixtures, and (2) to conduct a comprehensive life cycle cost analysis (LCCA) of pavement preventive maintenance treatments. Specifically, the study evaluated the cost-effectiveness of two overlay materials, SMA and HMA, under varying conditions, as well as identified alternative aggregates for use in SMA that reduce reliance on steel slag in Indiana.

Findings

Field performance evaluations of SMA and HMA mixtures used on two road classifications, U.S. highways and interstates, highlight the superior performance of SMA on U.S. highways. The significant percentage differences in roughness (as measured by the International Roughness Index (IRI)) and cracking demonstrate SMA's enhanced durability and ability to resist deformation and cracking. Performance differences were less pronounced on interstates, but in many cases, SMA still outperformed conventional HMA, especially regarding rutting resistance. However, for road classifications, there were instances where HMA demonstrated performance comparable to SMA, underscoring the importance of selecting the appropriate asphalt mixture type based on road classification, traffic conditions, and performance expectations.

U.S. highways were presented as an example of LCCA, and the results demonstrate that, despite higher initial construction costs, SMA overlays exhibited superior long-term cost performance relative to conventional HMA. The net present value (NPV) for SMA was calculated as $112,448 per lane mile, compared to $190,373 per lane mile for HMA, which reflects a 40.9% reduction in lifecycle costs. Additionally, the ROI analysis revealed that SMA overlays yielded a 14.6% ROI over the 29-year analysis period.

Exploring steel slag alternative aggregates for Indiana provided important insights into coarse aggregate selection for Indiana SMA mixtures. With strict coarse aggregate requirements, steel slag and dolomite have been the main choices for Indiana SMA mixtures. However, the study results indicated that crushed gravel could perform similarly to steel slag in laboratory testing, possibly expanding options for aggregate selection. Although increasing dolomite content to replace steel slag is possible, it would require careful consideration of the aggregate toughness requirements.

Recommendations

Although SMA is more expensive than conventional HMA, field performance evaluations demonstrated its superior overall performance. ROI analysis confirmed that SMA is worth the initial cost investment. This economic advantage is primarily attributed to the extended service life of SMA mixtures, which delays the need for costly rehabilitation activities, thereby reducing total maintenance expenditures.

This study also found that crushed gravel can effectively replace steel slag to meet aggregate requirements and maintain SMA mixture performance. While dolomite showed no significant difference from steel slag in overall mixture performance, higher dolomite content indicated a potential reduction in friction. Further research is needed to better understand the impact of dolomite content on friction characteristics.

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1. INTRODUCTION

Stone matrix asphalt (SMA) is a specialized asphalt mixture designed to improve pavement performance by combining a coarse aggregate skeleton with a high-binder content mortar. This innovative design, adopted by the Indiana Department of Transportation (INDOT) in the late 1990s, offers distinct advantages over conventional hot mix asphalt (HMA). The structure of SMA features a higher proportion of coarse aggregates that interlock to form a stone-on-stone skeleton, enhancing stability. Simultaneously, the high-binder mortar, often reinforced with fibers, adds durability and ensures the mixture can withstand heavy traffic and harsh weather conditions.

One of the most notable benefits of SMA is its extended service life beyond that of a conventional HMA mixture. Compared to HMA, SMA is well-known for its improved resistance to deformation and cracking—critical factors in maintaining pavement integrity under heavy traffic loads. Additionally, SMA's rough surface texture enhances friction resistance, improving roadway safety. This texture also reduces noise, making SMA pavements particularly advantageous for urban or high-traffic areas where noise pollution is a concern.

In Indiana, SMA is more expensive than conventional HMA mixtures due to the necessity for high-quality, durable aggregates, increased asphalt binder content, and often modified asphalt binders and fibers. SMA production involves a more meticulous process than HMA, which also contributes to the higher cost. However, INDOT considers this investment worthwhile for high-performance applications, especially on heavily trafficked roads, as the longevity and performance benefits justify the higher upfront expense.

1.1 Problem Statement

Currently, INDOT SMA-surfaced pavements are undergoing a second round of rehabilitation, presenting a valuable opportunity to assess their performance and return on investment (ROI). By quantitatively examining SMA-surfaced pavement performance, the aim is to determine if SMA mixtures have extended years of service and reduced maintenance needs of pavements, as compared to pavements with conventional asphalt mixture surfaces. A critical aspect of this evaluation is comparing SMA's performance metrics, such as IRI, cracking resistance, and rutting resistance, against those of HMA pavements under similar conditions.

In addition to performance assessment, questions have been raised about SMA coarse aggregate requirements. SMA coarse aggregate must be sufficiently durable to support traffic loads through its stone-on-stone aggregate skeleton. In Indiana, steel slag is used as the primary SMA coarse aggregate because of its toughness and durability. However, it may be possible to use other, more locally available coarse aggregates in SMA without loss of mixture performance.

1.2 Research Objectives

The primary objective of the research is to understand Indiana SMA pavements. The following goals are the milestones to achieve the objective.

- Evaluate the Indiana SMA performance compared to conventional HMA (Chapter 2).
- Evaluate the cost-effectiveness of two overlay materials, SMA and HMA (Chapter 3).
- Review SMA coarse aggregates and provide their selection options (Chapter 4).

2. UNDERSTANDING THE PERFORMANCE OF INDIANA SMA PAVEMENTS

The primary objective of this chapter is to analyze the performance of Indiana SMA pavements in relation to HMA pavements.

2.1 Methodology

2.1.1 Experimental Plan

Achieving the objectives of this research project requires the completion of several key tasks, each designed to ensure a comprehensive evaluation of SMA performance. The first step is conducting a detailed literature review to gather relevant information from prior research. This review will focus on SMA performance evaluation methods, highlighting current practices, identifying limitations, and providing recommendations for improved implementation. The findings will also shed light on factors influencing SMA performance, paving the way for an in-depth analysis.

The second task involves reviewing SMA performance through a comparative study of SMA and HMA projects under varying conditions, such as material properties, structural configurations, traffic levels, climate, and contractor involvement. This process will involve selecting appropriate projects and gathering construction-related data, including placement dates and unit costs for both SMA and HMA.

Furthermore, the research team will collect historical performance data for SMA, drawing from existing databases. Key performance indicators such as the IRI, rut depths, and cracking percentages will be analyzed to assess the durability and effectiveness of SMA under diverse conditions. By systematically addressing these tasks, the research aims to generate actionable insights into the performance and optimization of SMA in pavement construction.

2.1.2 Study Methodology

Pavement performance is evaluated using various indices, including the pavement distress index, distress manifestation index, pavement condition rating, and present serviceability index (Chamorro et al., 2009; Pérez-Acebo et al., 2020). Previous research has employed various other performance parameters (Kaloop et al., 2022, Marcelino et al., 2018, 2020; Nitsche et al., 2014, Piryonesi & El-Diraby, 2020). In addition, the International Roughness Index (IRI) is a globally recognized standard for assessing pavement smoothness, a key indicator of ride quality. It measures the cumulative vertical displacement experienced over a specific road segment, providing a quantitative basis for evaluating driver comfort and vehicle wear. Surface roughness is measured by evaluating a road's vertical deviations from a flat surface over a set distance, using sensor data from a moving vehicle to calculate the IRI in m/km or in/mi (Alnaqbi et al., 2024; De Blasiis et al., 2020). The IRI is a function of pavement distress, such as fatigue cracking, block cracking, cracking percentages and the average rut depth per lane, roughness measurements and visual inspections, patching, pavement roughness, potholes, raveling, longitudinal and transverse cracks, delamination, potholes (Ali et al., 2021; Chandra et al., 2013; Mactutis et al., 2000). Following the significance of IRI, the year of service was determined based on the following conditions.

- *Year of Service Definition:* The year of service is defined as the period from the construction of an overlay to the first maintenance activity. This includes actions such as crack sealing, patching, lane changes, applying a new overlay, or any maintenance work that introduces a lower trend in IRI value.
- *Trend Consideration:* The IRI trend was a primary factor in cases where the maintenance history was not updated. Observations began from the initial to the final year, ensuring a consistent positive trend in the data.
- *Data Range:* Data was considered only within the last 20 years of service to maintain relevance and accuracy in the analysis.
- *Initial IRI Value:* The maximum allowable IRI value was set at 60 or below for the first 2 years of service to represent acceptable pavement conditions during the initial period.
- *Outlier Removal:* Outlier data points were identified and removed for any specific service year to improve the analysis's reliability and eliminate anomalies.

For a comprehensive pavement performance evaluation, the IRI data for a specific year served as the foundation for the analysis. To provide a more holistic understanding of pavement behavior, additional distress data, such as rutting and cracking, were also collected. This multi-faceted approach enabled a systematic and precise assessment of the year of service of pavements, ensuring that all critical parameters influencing pavement performance were considered. By incorporating these essential factors, the dataset was refined and enhanced, allowing for a more accurate and detailed evaluation of pavement longevity.

The analysis was conducted for two types of asphalt mixtures: SMA and HMA. Three distinct road types were initially considered to capture variations in performance across different roadway categories: interstate highways, U.S. highways, and state roads. However, due to limitations in the availability of distress data, the focus was narrowed to include only interstate highways and U.S. highways in the subsequent sections of the study. This decision was based on the completeness and reliability of the available datasets for these two road types, which provided sufficient information for a meaningful comparison of pavement performance between SMA and HMA.

The dataset for HMA and SMA categorizes road infrastructure into two main functional groups, as shown in Table 2.1. For HMA, interstate roads dominate the dataset, with 58 entries across nine unique routes, including major routes like I-74, I-65, and I-69, as well as other routes like I-465 and I-469. U.S. highways, though fewer in number, complement this network with 18 entries across eight unique routes such as US 30, US 12, and US 41. Interstate roads cover all climate zones—North, Central, South, and different counties like Marion, Hendricks, and Allen, etc. U.S. highways span similar climate zones as interstate roads, with prominent counties such as Porter, Ripley, and Vanderburgh. For SMA, interstate roads dominate the data, with 58 entries spread across nine unique routes. These routes include major interstates such as I-74, I-65, and I-70, as well as other interstates like I-465 and I-469. Interstate roads, covering all three climate zones—North, Central, and South, have data from major counties such as Marion, Hendricks, and Vanderburgh are well-represented in this group. On the other hand, U.S.

TABLE 2.1
Summary of road networks considered for HMA and SMA

Mix Type	Functional Class	Total Route	Routes	Climate Zones	Key Counties (Examples)
HMA	Interstate Road	58	I-74, I-65, I-64, I-69, I-70, I-80, I-94, I-465, I-469	North, Central, South	Marion, Hendricks, Allen, Jasper, Boone
	U.S. Highway	18	US 30, US 12, US 31, US 20, US 40, US 41, US 421		Porter, Ripley, Lake, Vanderburgh
SMA	Interstate Road	58	I-74, I-65, I-64, I-69, I-70, I-465, I-469, I-80, I-94		Marion, Hendricks, Allen, Shelby, Vanderburgh
	U.S. Highway	18	US 30, US 12, US 20, US 31, US 40, US 41, US 421, US. 50		Lake, St. Joseph, Vanderburgh, Clay, LaPorte

highways, with 18 data points across eight unique routes, include key highways like US 30, US 41, and US 50. The U.S. highways also span the three climate zones, with notable counties such as Lake, St. Joseph, and Clay being part of this network. Overall, the considered routes for HMA and SMA emphasize the integration of the dataset by considering climate zones, county-level distribution, and functional classifications within Indiana's road infrastructure network.

The inclusion of multiple distress parameters such as IRI, rutting, and cracking ensures a comprehensive evaluation of pavement behavior under real-world conditions. While IRI provides insights into pavement roughness and ride quality, rutting measures the degree of surface deformation caused by traffic loads, and cracking indicates the structural integrity and resistance to surface fractures. By analyzing these parameters together, the study captures a more nuanced understanding of how SMA and HMA perform over time and under varying traffic and environmental conditions.

The decision to focus on interstate and U.S. highways also aligns with the primary application areas of SMA, which is often used in high-traffic and high-performance roadways. These road types are subject to heavy vehicular loads and frequent use, making them ideal candidates for evaluating the durability and performance advantages of SMA compared to HMA. Additionally, the consistent availability of data for these roads ensures that the analysis remains robust and reliable, avoiding potential biases or inaccuracies that might arise from incomplete datasets.

In summary, the integration of IRI, rutting, and cracking data provides a well-rounded framework for year of service calculations, highlighting the critical factors influencing pavement performance. The selection of interstate and U.S. highways for this study ensures a targeted and data-driven approach, focusing on high-priority roadways where pavement performance is most critical. By refining the dataset and incorporating multiple performance metrics, the analysis offers valuable insights into the comparative advantages of SMA and HMA in real-world applications.

2.2 Development of Prediction Model for Pavement Year of Service

One of the most critical aspects of pavement performance is determining its expected year of service. Knowing how long a pavement is likely to remain functional and safe under specific conditions is essential for planning maintenance, optimizing costs, and ensuring uninterrupted serviceability. This assessment becomes even more significant when the pavement approaches the end of its initial year of service. Developing reliable predictive models to evaluate pavement performance under various scenarios is vital for ensuring timely and effective interventions that extend the pavement's longevity and optimize resources.

In this regard, predictive models play a key role in informed pavement management. Predictive models are indispensable tools for pavement management systems. They help forecast the performance and year of service of pavements based on various field scenarios. These models are built using a combination of empirical data, engineering principles, and computational techniques. and enable pavement engineers to understand when and why pavement may fail or require maintenance. Such insights allow decision-makers to establish targeted intervention strategies, reducing the likelihood of unexpected failures and minimizing costs associated with emergency repairs. These models often rely on predetermined threshold levels or triggers to recommend preservation treatments. Threshold levels, such as surface roughness, cracking severity, or rut depth, serve as benchmarks for determining when a pavement section requires maintenance or rehabilitation. By identifying these thresholds early, agencies can implement preservation strategies that maintain pavement functionality and extend lifespan. Integrating predictive models into pavement management systems helps optimize maintenance schedules and budget allocations, ensuring better resource utilization.

In addition, data-driven decision-making in pavement management also plays a key role. In practice, network-level pavement management systems, data on surface condition and pavement roughness are typically used to develop treatment intervention levels. For instance, surface condition data may include information on cracking, raveling, or potholes, while pavement roughness data, often measured using the International Roughness Index (IRI), quantifies the ride quality of pavement. These parameters form the foundation for developing maintenance strategies that address specific issues and enhance pavement performance. A Joint Transportation Research Program (JTRP) report (Ong et al., 2010) concluded that typical procedures used to select appropriate treatments were as follows.

Approaches to Treatment Selection

Selecting appropriate pavement treatments involves various methodologies. Each approach has its strengths and limitations, and choosing the most suitable method depends on the specific context and objectives of the pavement management program. Common approaches include the following.

- *Ad-Hoc Methods:* Decisions based on ad-hoc methods rely heavily on experience, subjective judgment, or personal preference. While these methods may work in some cases, they lack consistency and objectivity, often leading to suboptimal outcomes. Ad-hoc approaches may overlook critical factors such as evolving traffic patterns, environmental conditions, or advancements in materials and technologies.
- *Composite Index-Based Methods:* These methods use a composite index, such as the pavement condition rating (PCR), which combines various distress attributes and IRI values into a single metric. Composite indices simplify decision-making by providing a clear and concise measure of a pavement's condition. However, they may not capture the nuances of individual distress

types or their interactions, potentially leading to generalized treatment recommendations.

- *Life-Cycle Cost Analysis (LCCA):* LCCA involves calculating the costs and benefits of different treatment options over the pavement's entire lifecycle. This approach considers factors such as roughness, distress attributes, and the economic impact of maintenance activities. By identifying the most cost-effective intervention, LCCA helps agencies make informed decisions that maximize long-term value. However, LCCA can be time-intensive and may require extensive data, making it less practical for quick decision-making.
- *Decision Tree Approaches:* Decision tree methodologies systematically evaluate all distress types and condition attributes to identify the most appropriate treatment. By following a structured process, these approaches ensure consistency and transparency in decision-making. Nevertheless, they may become overly complex when dealing with large datasets or diverse pavement conditions, limiting their practicality for extensive networks.
- *Artificial Intelligence (AI) Technologies:* Modern AI techniques, such as machine learning and neural networks, are increasingly being applied to pavement management. AI algorithms can analyze vast amounts of data, identify patterns, and make accurate predictions about pavement performance. These technologies have the potential to revolutionize pavement management by providing highly reliable and adaptive solutions. However, their adoption may require significant investments in infrastructure, data acquisition, and personnel training.

While the methods offer valuable insights and frameworks for pavement management, they are not without limitations. The study highlights several challenges associated with these procedures. For instance, ad-hoc methods lack standardization, making them prone to errors and inconsistencies. Composite index-based methods may oversimplify complex pavement conditions, while decision tree approaches can become unwieldy when applied to large networks. Additionally, life-cycle cost analyses often require extensive data that may not always be readily available. AI technologies, though promising, face barriers related to data quality, algorithm transparency, and implementation costs.

Following the scope of the study, which aims to compare SMA and HMA by integrating IRI, cracking, and rutting data, a predictive model is essential to provide insights into their year of service. The IRI is a critical metric for pavement smoothness, directly influencing ride quality and user comfort. In the context of HMA and SMA, IRI is a valuable indicator for assessing pavements' long-term performance and year of service. An increasing IRI value often signifies the development of surface irregularities, such as undulations and depressions, resulting from material degradation, subgrade instability, or traffic-induced stresses. Monitoring IRI over time allows for predicting when these pavements may require maintenance or rehabilitation. Pavements with lower initial IRI and slower rates of increase are generally associated with longer service lives. The roughness data also helps evaluate the effectiveness of different asphalt mix designs, construction practices, and environmental influences. By correlating IRI trends with maintenance records and traffic loads, engineers can develop predictive models that inform decision-making for pavement preservation strategies. In addition to IRI, cracking is one of the most visible and detrimental forms of pavement distress, providing a crucial metric for estimating the year of service of HMA and SMA. Cracks, whether they are fatigue cracks, longitudinal cracks, or block cracks, compromise pavement integrity by allowing moisture infiltration and weakening the underlying layers. SMA, known for its durable aggregate skeleton and high asphalt content, generally exhibits better resistance to cracking compared to conventional HMA. By tracking the onset and progression of cracking, engineers can predict the pavement's remaining year of service and the timing of necessary interventions. Crack propagation rates are influenced by factors such as traffic loads, temperature fluctuations, and material properties. Regularly monitoring cracking patterns and severity levels enables the development of models anticipating pavement failure points. Moreover, incorporating these models into maintenance planning helps optimize resource allocation and extend the functional life of pavements.

Finally, rutting, characterized by the permanent deformation of the pavement surface in wheel paths, is a significant performance indicator for predicting the year of service of HMA and SMA. This form of distress is typically caused by repeated traffic loads and inadequate resistance to shear deformation in the pavement structure. SMA, with its high stone content and superior interlocking, generally shows better rutting resistance than HMA. Engineers can estimate the onset of structural failure or reduced functional capacity by analyzing rut depth data over time. Early detection of rutting trends allows for timely maintenance interventions, such as overlay applications or surface treatments, which can mitigate further deterioration. Factors such as mix composition, binder properties, and climatic conditions play a pivotal role in rutting behavior. Incorporating rutting data into predictive models provides valuable insights for designing more resilient pavements and scheduling maintenance activities to maximize years of service. Various laboratory test methods, such as the Asphalt Pavement Analyzer, dynamic modulus, flow number, flow time, repeated load permanent deformation, and Hamburg wheel tracking test, among others, have been employed to address rutting resistance performance. However, no single laboratory test has been universally accepted as having a strong correlation with the field performance of flexible pavements (Li et al., 2014; Zhang et al., 2013). Numerous efforts across different states in the U.S. have aimed to correlate laboratory rutting results with field performance, as summarized in a study (Walubita et al., 2019). Despite these attempts, no definitive correlation between laboratory tests and field data has been established.

While numerous studies have attempted to develop models to predict IRI, cracking, and rutting, most of these models focus on regional aspects. They often did not consider the remaining year of service, showed limited correlation with field data, and lacked categorization based on road functional types. To address these gaps, this study aims to develop predictive models for HMA and SMA that incorporate these considerations. Additionally, it seeks to compare the remaining years of service to traditional maintenance and rehabilitation practices.

In this chapter, we introduce a newly developed predictive model that addresses some of the limitations of existing procedures. This model builds on the framework discussed in the previous chapter, integrating advanced analytical techniques with field data to provide a comprehensive tool for pavement performance evaluation. Understanding the expected year of pavement service and implementing timely preservation treatments are fundamental to maintaining safe and efficient road networks. Predictive models are crucial in achieving these goals by providing actionable insights and data-driven recommendations. While current approaches to treatment selection offer valuable frameworks, their limitations underscore the need for continuous improvement and innovation. As outlined in this chapter, developing and implementing advanced predictive models represent a significant step forward in the quest for sustainable and cost-effective pavement management. The following section discusses the IRI, cracking and rutting, and the year of service of HMA and SMA.

2.2.1 Pavement Year of Service and IRI

2.2.1.1 Predictive model for IRI in HMA-based roads. Figure 2.1 shows that the IRI growth rate over years of service is significantly higher for U.S. highways compared to interstates, indicating more rapid IRI deterioration on U.S. highways. Furthermore, the higher R^2 value for U.S. highways suggests a stronger correlation between IRI and years of service than interstates. Although interstates start with a slightly higher initial IRI, the steeper growth rate and better model fit for U.S. highways highlight a scenario of accelerated deterioration and greater predictive accuracy.

2.2.1.2 Predictive model for IRI in SMA-based roads. Comparing the IRI for the SMA (Figure 2.2), interstates have a lower initial IRI, and a higher deterioration rate compared to U.S. highways but degrade more slowly. Additionally, the interstates model has a stronger fit to the data than the U.S. highways model, indicating greater consistency in the IRI trends over years of service for interstates. Overall, interstates begin with better surface conditions but experience faster degradation over time.

2.2.2 Pavement Year of Service and Cracking

2.2.2.1 Predictive model for cracking HMA-based roads. In Figure 2.3, it is observed that for cracking vs. years of service, interstates have a lower initial cracking value and a slower growth rate, indicating a weaker fit. In contrast, U.S. highways start with a slightly lower initial cracking value but experience a much faster-cracking growth rate, indicating a strong fit. Overall, U.S. highways crack much faster over time, while the interstate model demonstrates less cracking but with a weaker correlation to the data.

2.2.2.2 Predictive model for SMA-based road cracking. For SMA, the predictive model for the interstate shows a cracking growth with a high correlation, indicating a strong and consistent exponential increase in cracking with years of service (Figure 2.4). In contrast, the U.S. Highway predictive model has a negligible correlation, suggesting almost no observable relationship between cracking and years of service. Overall, interstates exhibit a significant and predictable cracking progression, while U.S. highways show little to no trend in cracking over time.

2.2.3 Pavement Year of Service and Rutting

2.2.3.1 Predictive model for rutting in HMA-based roads. In comparing the rutting performance of two predictive models for HMA (Figure 2.5), interstate shows a rut progression equation with a strong correlation, indicating a consistent, moderate exponential increase in rutting over time. U.S. highway presents a slightly higher initial rut value and a slightly lower growth rate, with a comparable correlation, indicating a similar trend. Overall, both models show strong and consistent rutting progression, with U.S. highways starting with a slightly higher rut value but experiencing marginally slower growth over time than interstates.

2.2.3.2 Predictive model for rutting in SMA-based roads. In comparing the developed equations for rutting vs. years of service for SMA, U.S. highway shows a slightly higher initial rut depth but a significantly steeper growth rate (exponent coefficient) than the interstate (Figure 2.6). The higher R^2 value for the U.S. highway indicates a stronger correlation between years of service and rutting progression than the interstate.

Table 2.2 summarizes the years of service of different SMA and HMA-based roads based on the above predictive model.

Table 2.2 compares pavement performance metrics for two pavement types, SMA and HMA, under different threshold values of IRI, rutting, and cracking. The percentage difference between the two materials for each metric is also provided for U.S. highways and interstate roads. The percentage difference was calculated using the formula (SMA/HMA) $\times$ 100.

IRI measures the smoothness or roughness of pavement, with lower values indicating smoother surfaces and higher values signifying rougher roads. At an IRI threshold of 100, SMA and HMA show similar performance on U.S. highways, with SMA slightly outperforming HMA (7.51 vs. 7.31), representing

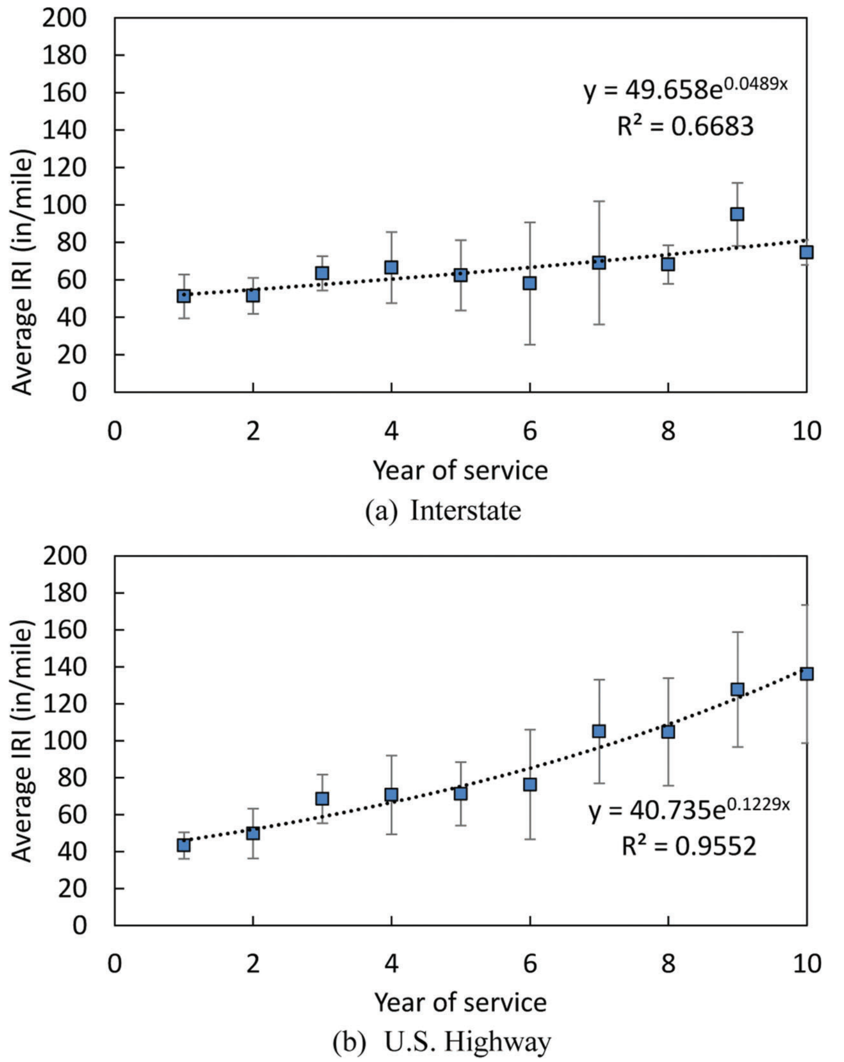


Figure 2.1 IRI vs. year of service for HMA: (a) interstate, (b) U.S. highway.

a percentage difference of 102.77%. However, on interstates, SMA performs worse than HMA, showing values of 8.74 and 14.32, respectively, highlighting a significant difference of 61.06%, indicating greater roughness for HMA.

At an IRI threshold of 120, SMA continues to outperform HMA on U.S. highways, with values of 11.09 for SMA and 8.79 for HMA, yielding a growing percentage difference of 126.17%. This shows that the performance disparity between SMA and HMA becomes more pronounced as the IRI threshold increases. On interstates, SMA performs slightly worse than HMA, with values of 10.95 and 18.04, respectively, maintaining a consistent percentage difference of 60.70%, similar to the lower threshold.

At an IRI threshold of 150, the performance gap widens further on U.S. highways, with SMA demonstrating superior performance (15.48 vs. 10.61) and a significant percentage difference of 145.91%. On interstates, SMA still performs better than HMA (13.66 vs. 22.61), with a percentage difference of 60.43%, remaining relatively stable across thresholds. Overall, SMA consistently outperforms HMA in reducing pavement roughness across both types of highways, with the difference in performance being more substantial on U.S. highways compared to interstates, likely due to variations in traffic load and environmental factors.

Cracking measures the pavement's susceptibility to surface fractures, with lower values indicating better resistance. At a threshold cracking value of 0.15, SMA demonstrates exceptional performance on U.S. highways compared to HMA, with values of 45.45 and 5.44, respectively, resulting in a very significant percentage difference of 835.68%. This highlights SMA's impressive ability to resist cracking under lighter traffic conditions. On interstates, SMA (5.63) and HMA (9.34) show a closer performance, with a percentage difference of 60.31%, suggesting reduced variability under higher traffic loads.

At a threshold cracking value of 20, SMA's superior resistance becomes even more evident on U.S. highways, achieving a value of 93.39 and significantly

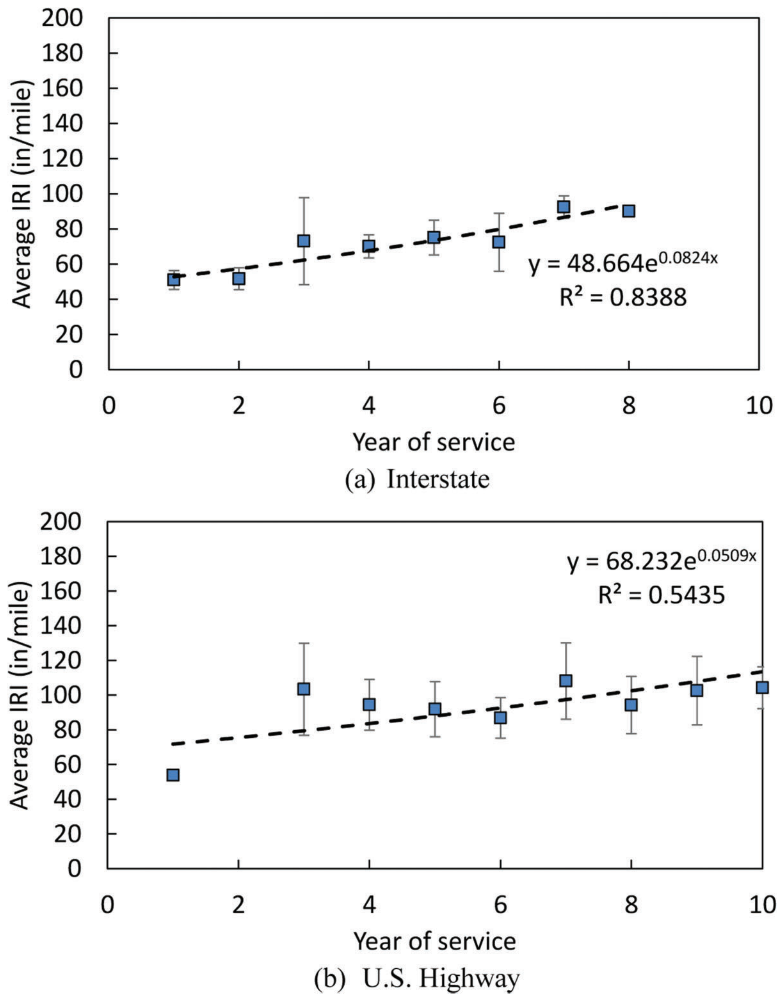


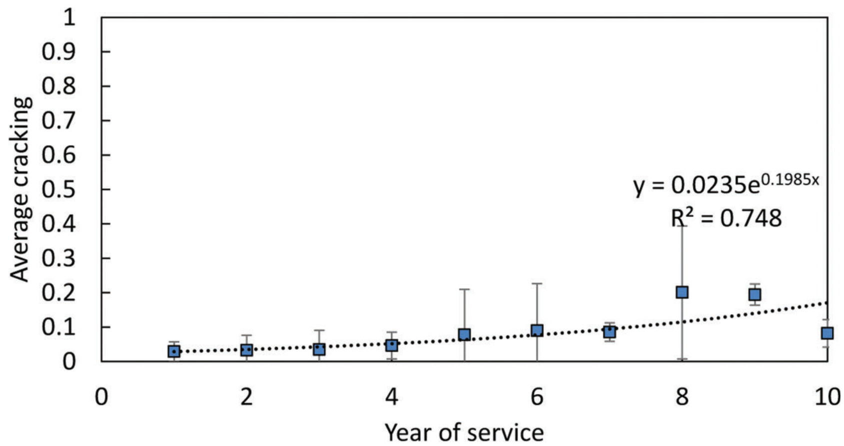
Figure 2.2 IRI vs. year of service for SMA: (a) interstate, (b) U.S. highway.

outperforming HMA at 6.20, which leads to an extraordinary percentage difference of 1,505.57%. This further underscores SMA's exceptional durability. While Table 2.2 highlights SMA's impressive resistance to cracking under lighter traffic conditions, the weak correlation observed in the predictive model suggests that further study is needed to establish a coherent relationship for estimating a more realistic life expectancy. On interstates, SMA (6.66) continues to outperform HMA (10.79) with a percentage difference of 61.69%, maintaining a trend similar to the lower threshold. In summary, SMA provides outstanding cracking resistance, particularly on U.S. highways, where it significantly outperforms HMA. While SMA still performs better on interstates, the difference is less pronounced, likely due to higher traffic stress levels that diminish its relative advantage.

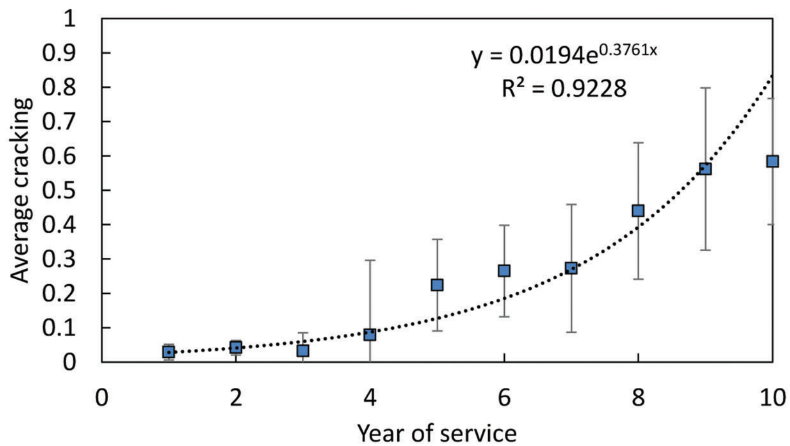
Rutting measures the depth of pavement deformation caused by traffic loads, with lower values indicating better performance. At a rutting threshold of 0.15, SMA demonstrates superior resistance on both U.S. highways and interstates. SMA achieves a value of 12.22 on U.S. highways compared to HMA's 9.45, resulting in a percentage difference of 129.38%. On interstates, SMA performs even better, with a value of 16.33 compared to HMA's 11.89, yielding a higher percentage difference of 137.32%. This suggests that SMA effectively resists rutting under higher traffic loads.

At a rutting threshold of 0.3, the performance gap between SMA and HMA narrows on U.S. highways, with SMA achieving a value of 26.23 compared to HMA's 23.37, leading to a reduced percentage difference of 112.24%. However, on interstates, SMA's advantage becomes more pronounced, reaching a value of 39.43 compared to HMA's 24.45, with a significant percentage difference of 161.27%. This indicates that SMA's rutting resistance becomes more evident as the threshold increases.

At the highest rutting threshold of 0.45, the performance gap continues to narrow on U.S. highways, with SMA (34.42) and HMA (31.51) showing similar rutting depths and a percentage difference of 109.24%. On interstates, however, SMA maintains its superior performance with a value of 52.95 compared to HMA's 31.80, resulting in a percentage difference of



(a) Interstate



(b) U.S. Highway

Figure 2.3 Cracking vs. year of service for HMA: (a) interstate, (b) U.S. highway.

166.51%. This highlights SMA's ability to withstand heavy traffic loads and high rutting thresholds. Overall, SMA consistently outperforms HMA in rutting resistance, particularly on interstates, where heavy traffic loads emphasize SMA's advantages.

2.2.4 Findings

On U.S. highways, SMA consistently outperforms HMA across all metrics, including IRI, rutting, and cracking. The differences in performance are particularly pronounced in terms of cracking, where SMA shows exceptional durability. On interstates, the performance gap between SMA and HMA is smaller, likely due to the heavier traffic loads and more challenging conditions, which limit the advantages of each asphalt mix type.

As threshold values increase, the differences between SMA and HMA become more apparent on U.S. highways, especially regarding IRI and cracking. This suggests that SMA's benefits are more visible under severe conditions. In contrast, on interstates, the performance differences for IRI and cracking remain relatively stable across various thresholds, indicating that SMA and HMA experience similar challenges under high traffic volumes.

SMA is better suited for applications requiring durability and cracking and rutting resistance, especially on roads with moderate traffic loads (such as U.S. highways). Although slightly less durable, HMA can still be a cost-effective choice for roads that require lower maintenance or where initial construction costs are a priority.

Overall, the service level provided by SMA and HMA varies depending on the functional class of the road and factors such as IRI, cracking, and rutting. Several studies have reported that SMA performs better, leading many agencies to adopt it with the expectation of improved outcomes compared to traditional HMA. However, findings have occasionally differed, highlighting the importance of considering specific conditions and road characteristics when selecting an asphalt mix type.

One study concluded that HMA demonstrates a higher stiffness modulus and better fatigue resistance than SMA, resulting in a longer service life for HMA (Nejad et al., 2010). It has also been observed that the rutting resistance of both SMA and HMA can vary

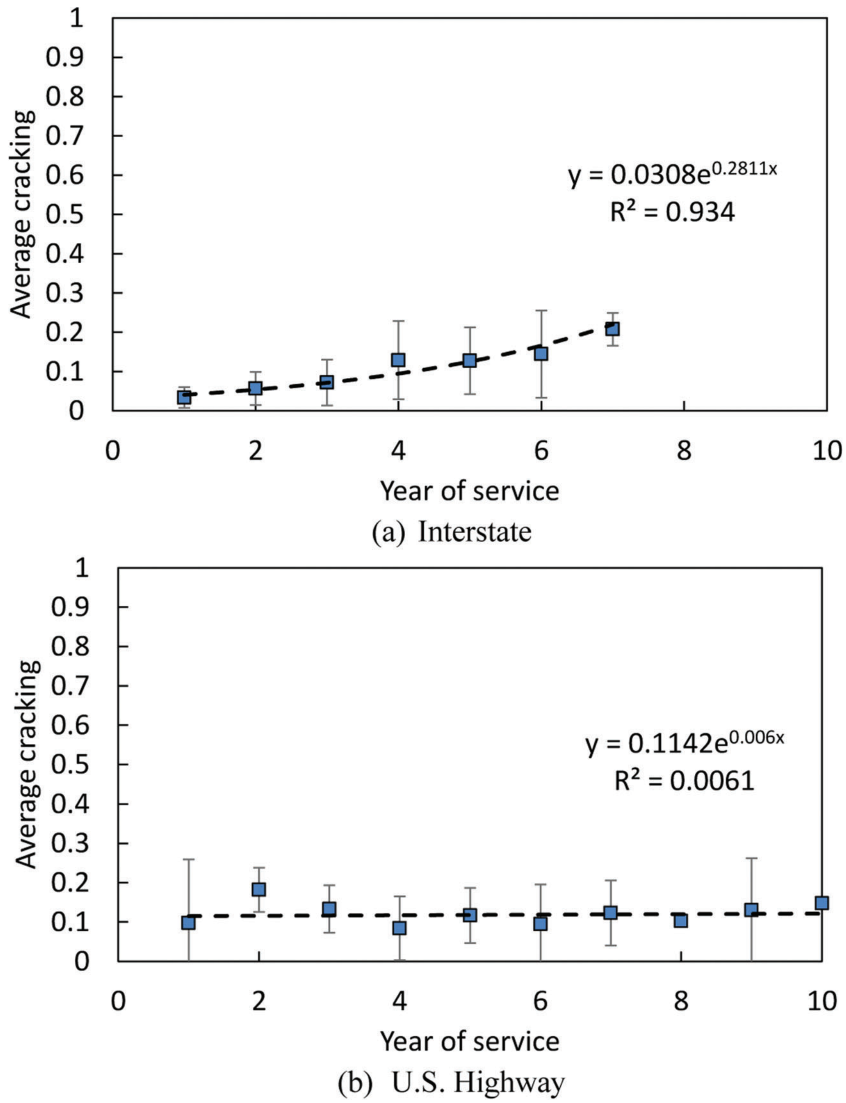


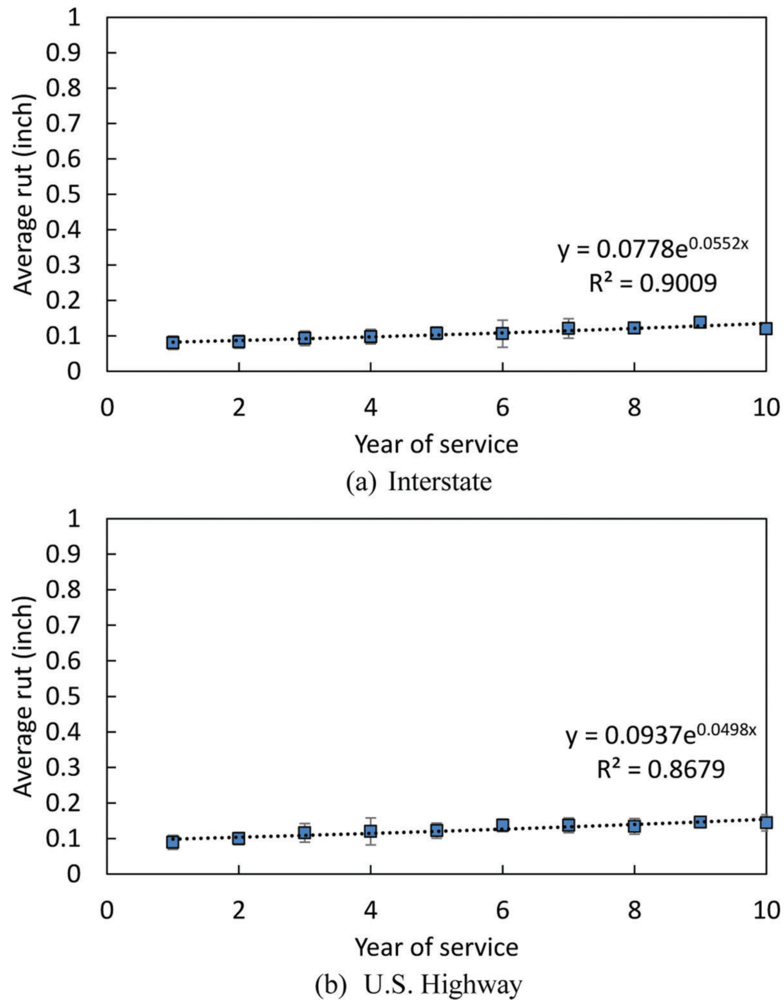
Figure 2.4 Cracking vs. year of service for SMA: (a) interstate, (b) U.S. highway.

based on the nominal aggregate size of the mix, with either mix potentially outperforming the other. Understanding the effect of aggregate type on the overall performance of the mixture is essential (Ghani et al., 2020).

Additionally, a study by the Wisconsin Department of Transportation concluded that SMA overlays tend to exhibit slightly lower life-cycle costs compared to conventional HMA when applied to low-volume asphalt pavements, although the cost difference is not significant. However, when used for overlays on moderate- to high-volume concrete pavements, SMA overlays demonstrate considerably higher life-cycle costs than their HMA counterparts, indicating a significant disparity in cost-effectiveness based on pavement type and traffic volume (Smith et al., 2006).

2.3 Summary

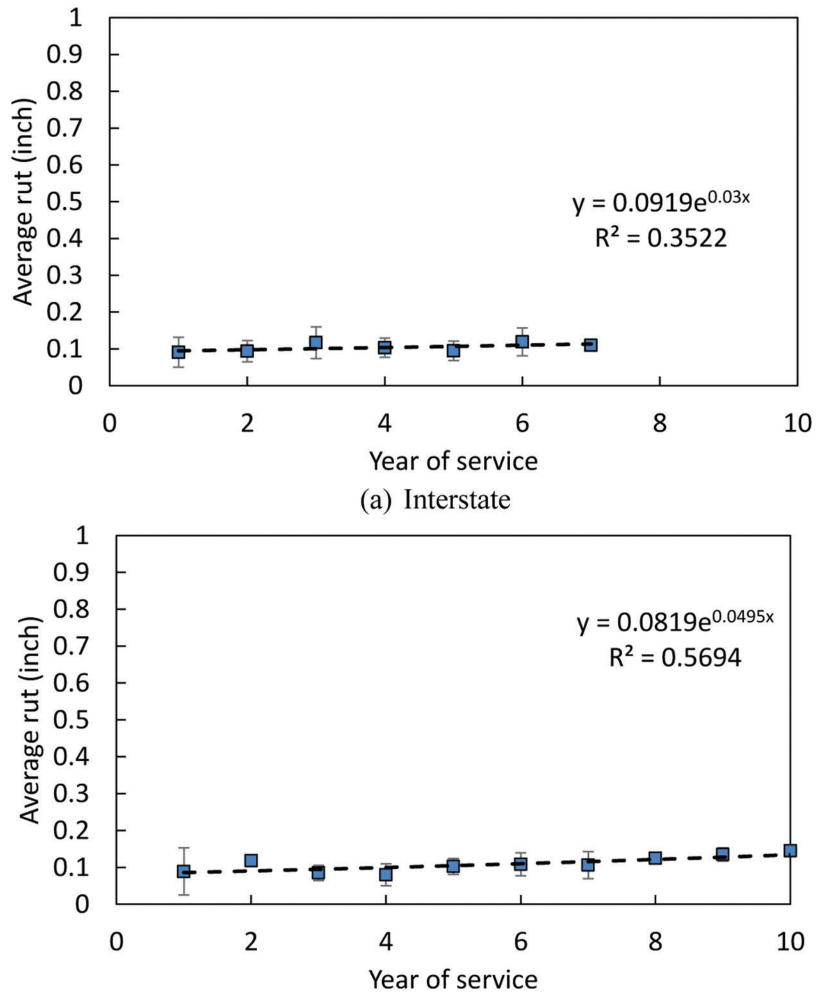
This chapter highlights the superior performance of SMA over HMA on U.S. highways. The significant percentage differences in roughness (as measured by the IRI) and cracking demonstrate SMA's enhanced durability and ability to resist deformation and cracking. Performance differences are less pronounced on interstates, but in many cases, SMA still outperforms conventional HMA, especially regarding rutting resistance. However, for road classifications, there are instances where HMA demonstrates performance comparable to SMA, underscoring the importance of selecting the appropriate asphalt mixture type based on road classification, traffic conditions, and performance expectations.



(a) Interstate

(b) U.S. Highway

Figure 2.5 Rutting vs. year of service for HMA: (a) interstate, (b) U.S. highway.



(b) U.S. Highway

Figure 2.6 Rutting vs. year of service for SMA: (a) interstate, (b) U.S. highway.

TABLE 2.2
Year of service for SMA-based and HMA-based roads

		U.S. Highway			Interstate		
Threshold Value		**SMA**	**HMA**	**Percent Difference**	**SMA**	**HMA**	**Percent Difference**
IRI (in/mile)	100	7.51	7.31	102.77	8.74	14.32	61.06
	120	11.09	8.79	126.17	10.95	18.04	60.70
	150	15.48	10.61	145.91	13.66	22.61	60.43
Cracking	0.15	45.45	5.44	835.68	5.63	9.34	60.31
	0.20	93.39	6.20	1,505.57	6.66	10.79	61.69
Rutting (inch)	0.30	26.23	23.37	112.24	39.43	24.45	161.27
	0.45	34.42	31.51	109.24	52.95	31.80	166.51

3. EVALUATION OF COST EFFECTIVENESS OF INDIANA SMA

Given the constraints of budget allocation, state highway agencies require reliable guidance to determine the optimal timing and appropriate treatment types for pavement maintenance. Economic analyses, particularly life-cycle cost analysis (LCCA), are widely employed as decision-making tools to identify cost-effective approaches for implementing transportation projects by comparing the total costs of competing design or preservation alternatives (Wang & Wang, 2019). LCCA provides a framework for evaluating all relevant costs over the lifecycle of each alternative, including initial expenditures, maintenance activities, and user costs resulting from agency actions (FHWA, 2002; Suwarto et al., 2024). LCCA supports transparent and well-documented decision-making processes by balancing trade-offs between costs and benefits. As outlined by the Federal Highway Administration (FHWA), LCCA involves defining design alternatives, establishing activity timing, estimating agency and user costs, applying economic discounting to calculate present-value life-cycle costs, and interpreting the results to inform decision-making (FHWA, 2002; Suwarto et al., 2024). Figure 3.1 summarizes these key LCCA components.

A critical feature of LCCA is its ability to provide a holistic assessment of all costs associated with an investment's acquisition, ownership, and disposal. This enables a comprehensive evaluation of a facility or project's total ownership or operational expenses. Figure 3.2 presents the key cost components considered in LCCA (Jasim et al., 2024).

Recent research highlights the importance of employing probabilistic LCCA to account for the statistical variability of input parameters, including their mean, variance, and probability distributions, alongside deterministic values. This approach enables a more comprehensive representation of the inherent random variations in pavement performance data. The following section summarizes selected studies, highlighting their methodologies and key findings.

Li and Madanu (2009) introduced an uncertainty-based LCCA framework that integrates deterministic, risk-based, and uncertainty-based methodologies to evaluate project-level benefits. Their findings underscore the limitations of deterministic approaches in capturing variability and uncertainty in critical input parameters such as traffic growth and discount rates. Similarly, Swei, Gregory, and Kirchain (2015) developed a probabilistic LCCA framework to statistically characterize uncertainties in construction costs, maintenance timing, and material price fluctuations. Through case studies, the framework demonstrated its efficacy, using cumulative distribution functions (CDFs) to enhance decision-making. However, the study acknowledged limitations, including fixed rehabilitation assumptions, insufficient consideration of user costs, and the need for empirical validation against historical project outcomes.

Tighe (2001) demonstrated the benefits of probabilistic LCCA for pavements, revealing that material costs and pavement thickness are better modeled using a log-normal distribution rather than the traditionally assumed normal distribution. This adjustment reduces biases and prevents overdesign, as shown in a case study where normal distributions increased life-cycle costs by $62,000 per kilometer. Similarly, Harvey, Rezaei, and Lee (2012) developed stochastic pavement performance models, including probabilistic parametric (Weibull) and semi-parametric (Cox) models, to evaluate the life-cycle costs of preventive maintenance (PM) strategies. Their findings emphasized the cost-effectiveness of applying PM strategies earlier in the pavement deterioration cycle, achieving up to 39% savings depending on the treatment and traffic conditions. Wang and Wang (2019) examined the impact of pre-overlay pavement conditions on overlay performance and cost-effectiveness using both deterministic and probabilistic LCCA approaches. Their analysis revealed that overlay life follows a log-normal distribution and that pre-overlay conditions significantly influence performance deterioration rates, particularly for minor rehabilitation treatments. Suwarto et al. (2024) highlighted the integration of deterministic and

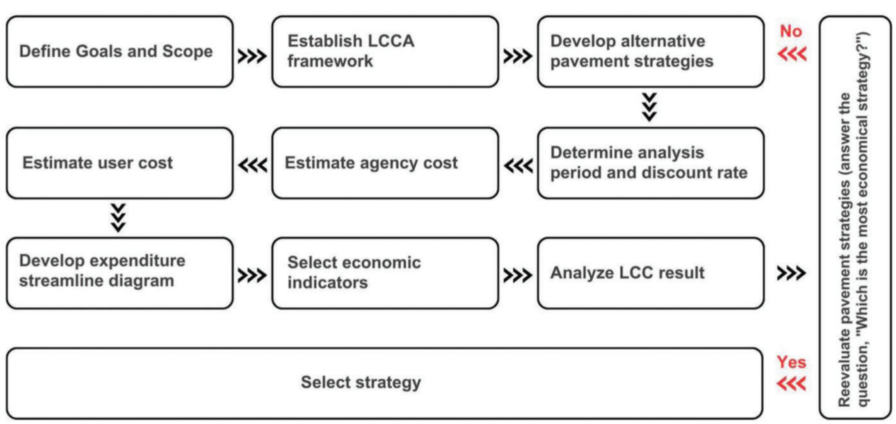


Figure 3.1 Basic pavement LCCA framework (based on FHWA, 2002).

probabilistic methods, emphasizing gaps in accounting for uncertainties related to treatment timing (Abdelaty et al., 2016), IRI values (Wang & Wang, 2017), and deterioration predictions (Guo et al., 2019; Salameh & Tsai, 2020).

Mechanistic-empirical methods (Praticò et al., 2011; Qiao et al., 2019; Souliman et al., 2020) have also been recognized as superior in predicting maintenance schedules and accommodating future uncertainties.

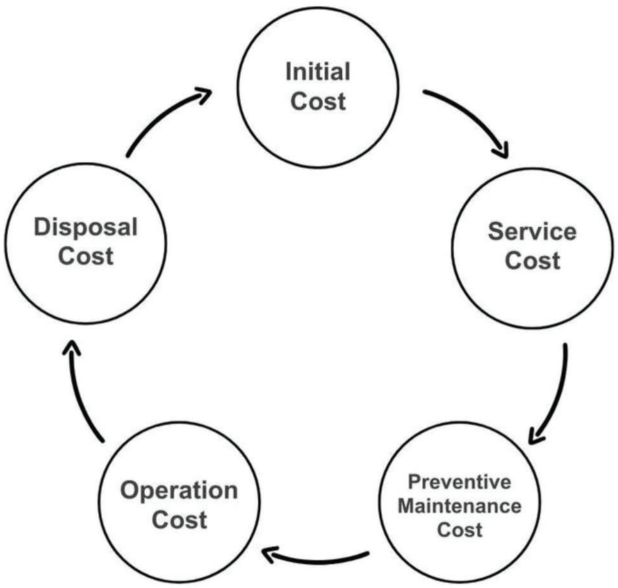


Figure 3.2 LCCA approach.

For instance, Swei et al. (2015) highlighted significant cost variations in LCCA when applying sensitivity analyses to discount rates, with potential shifts in results of up to 14%. Babashamsi et al. (2016) discussed challenges related to selecting appropriate discount rates and advocated for improved data documentation and analysis to enhance LCCA applicability in decision-making across public and private sectors. More recently, Mohamed, Xiao, and Hettiarachchi (2022) called for innovative frameworks that integrate pavement performance and reliability metrics to optimize economic, environmental, and social objectives in pavement management systems. They identified significant research gaps in comparing deterministic and probabilistic methods, particularly regarding their relative effectiveness in pavement performance modeling. Some studies that have analyzed maintenance and rehabilitation (M&R) strategies, the economic factors considered, along with the corresponding discount rates and analysis periods for pavements, are summarized in Table 3.1.

INDOT has widely implemented SMA in pavement projects exceeding three million ESALs over a 20-year design life, adhering to AASHTO M 325 and R 46-08 specifications. Between 2011 and 2015, over 591,000 tons of SMA and approximately 4.95 million tons of Superpave dense-graded mixtures were produced, reflecting the increased adoption of SMA. Based on previous studies, the tonnage of SMA increased significantly from 22,000 tons in 2011 to 210,000 tons in 2015, reflecting its growing prominence in high-traffic applications (Yin & West, 2018). According to

TABLE 3.1
LCCA studies of asphalt pavement

Study	Analysis Scope	Economic Factors	Evaluation Indicator	Discount Rate (%)
Abdelaty et al. (2016)	M&R	Agency cost	EUAC[1]	4
Nazzal et al. (2016)	Construction, M&R	Agency cost	NPV[2]	N/A
Wang and Wang (2017)	M&R, use phase	Agency cost, user cost	NPV, EUAC	4
Santos et al. (2017)	Material production, construction, M&R, use, end of life	Agency cost, user cost	NPV	2.3
Qadir et al. (2018)	Construction, M&R	Agency cost	NPV	N/A
Coleri et al. (2018)	Material production	Agency cost	NPV	4
Chen et al. (2019)	M&R, use phase	Agency cost, user cost	NPV	4
Guo et al. (2019)	M&R, use phase	Agency cost, user cost	NPV	4
Qiao et al. (2019)	M&R, use phase	Agency cost, user cost	NPV	4
Yao et al. (2019)	M&R	Agency cost	EUAC	4
Souliman et al. (2020)	Material production, construction	Agency cost	N/A	N/A
Salameh and Tsai (2020)	M&R	Agency cost	NPV	3
Paul et al. (2021)	Material production, construction, M&R	Agency cost	NPV	N/A
Habte (2021)	Material production, construction, M&R	Agency cost, user cost	NPV	10.2
Ma et al. (2022)	M&R	Agency cost	EUAC	4
Jung et al. (2022)	M&R	Agency cost, user cost	N/A	N/A

[1]EUAC: equivalent uniform annual costs.
[2]NPV: net present value.

their findings, despite its benefits, SMA remains 21% to 65% more expensive than comparable Superpave mixtures, with weighted mix bid price differences ranging from $12 to $38 per ton during this period. This cost premium highlights the necessity for thorough life-cycle cost evaluations to justify the adoption of SMA based on its long-term performance benefits in Indiana (Yin & West, 2018).

While LCCAs have been applied extensively to evaluate pavement performance, there is a notable lack of comprehensive studies assessing the cost-effectiveness of SMA pavements in Indiana compared to conventional HMA mixtures. Given that the INDOT is undergoing its second round of SMA pavement rehabilitation, there is a timely need for detailed economic analysis to evaluate SMA performance, quantify its return on investment (ROI), and determine conditions under which SMA treatments are cost-effective. This analysis is critical to optimizing rehabilitation treatment selection and advancing decision-making for sustainable pavement management.

This chapter aims to conduct a comprehensive LCCA of pavement preventive maintenance treatments. Specifically, it evaluates the cost-effectiveness of two overlay materials, SMA and HMA, under varying conditions.

While the performance analysis chapter considers various distress types, including rutting and cracking, alongside roughness, the LCCA presented in this chapter is limited to roughness as the performance indicator. This choice is justified by roughness being a key measure of surface functional deterioration in pavements. The study evaluates the impact of aging on overlay performance models using field data and employs the EUAC method to assess the economic feasibility of each treatment.

EUAC was selected as the primary economic indicator due to its utility in comparing different maintenance strategies, particularly within the constraints of annual pavement maintenance budgets. Additionally, it facilitates a standardized comparison of LCCA results across varying analysis periods. To further investigate the influence of treatment costs and discount rates on LCCA outcomes, a sensitivity analysis was conducted.

3.1 Study Methodology and Data Collection

3.1.1 Methodology

In the subsequent sections, a comprehensive explanation of the theoretical foundations underpinning the models and statistical methods employed in this study is presented. First, the data collection process is described, followed by the preparation of data for further analysis. The deterministic approach and associated formulas are then outlined. As this research is ongoing, the probabilistic approach for comparing SMA and HMA pavements will be conducted in future phases. These approaches aim to address two key objectives: firstly, to evaluate how the costs associated with SMA pavements compare to those of conventional HMA pavements, and secondly, to determine whether SMA pavements are cost-effective compared to conventional mixtures.

3.1.1.1 Data collection and evaluation of pay item unit costs. This study investigates Indiana's road network from 2014 to 2023 to identify factors that affect pavement conditions and their deterioration over time. To compare the life-cycle costs (LCCs) of SMA and conventional HMA mixtures, it is essential to establish the initial construction and future maintenance and rehabilitation (M&R) costs for the LCCA. Kuennen (2004) and Hein et al. (2003) have noted that SMA construction costs are typically 10%–50% higher than those of HMA. However, SMA's superior fatigue and rut resistance result in a longer service life and reduced maintenance costs. To achieve the objectives of this study, unit costs for all major pay items associated with SMA and HMA pavements were determined using data from the INDOT cost database (2010–2023) and Midwest regional pavement studies. Due to the limited availability of maintenance history data, this study focuses solely on initial construction costs, excluding maintenance costs from the analysis. To ensure a fair comparison, each SMA project was paired with an HMA project under similar traffic conditions and with comparable mixture properties, including binder content and aggregate size. Historical trends in SMA average prices are illustrated in Figure 3.3. The graph illustrates a progressive increase in the unit price of SMA over time, which underscores the necessity of adjusting for inflation in cost analyses. Over the past 5 years, the unit price has fluctuated within a range of 98 to 110, which highlights the variability in material costs and the importance of incorporating these trends into economic evaluations.

3.1.1.2 Unit cost variability. Probabilistic LCCA requires calculating the mean unit costs and standard deviations for all pay items, with cost variability characterized by the coefficient of variation (COV), defined as the ratio of the standard deviation to the mean. For pay items with insufficient historical data, a COV of 10% was assumed.

3.1.1.3 Adjustment for inflation. The mean costs of the relevant activities were calculated using data derived from contractors' bids for all projects of SMA and HMA. These mean unit costs were subsequently adjusted to 2023 price levels, employing a 2% annual inflation rate and Equation 3.1.

$$\$F = \$P \times (1+i)^n \qquad \text{(Eq. 3.1)}$$

$F = Current year cost adjusted for inflation, $
$P = Past year cost, $
I = Inflation rate, 2%
N = Number of years between 2023 and base year

3.1.1.4 Formulation of LCCA. In this study, pavement performance data were utilized to assess

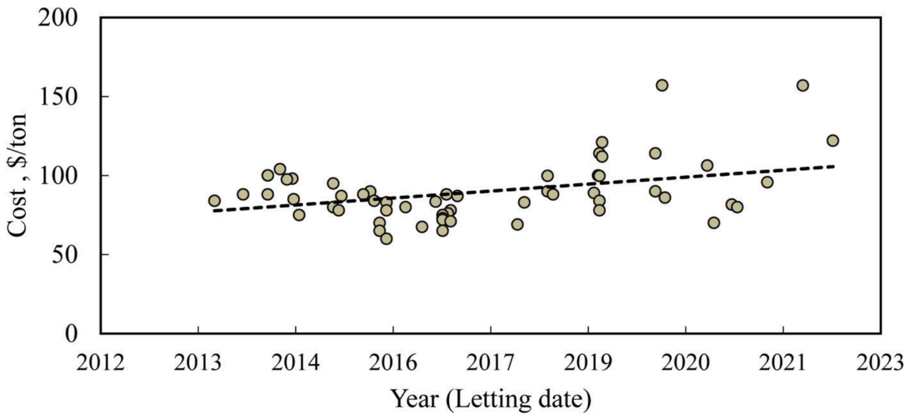


Figure 3.3 Historic trend of average contract unit prices for Indiana SMA mixtures.

and compare the net present value (NPV) and equivalent uniform annual cost (EUAC) of SMA and HMA overlays applied on highways with similar traffic conditions. The LCCA aimed to determine whether the higher initial costs of SMA could be justified by its superior performance and extended service life. The analysis assumed the construction of asphalt overlays was less than two inches thick, using the most recent weighted bid prices of INDOT (2022) and predicted service lives specific to Indiana.

3.1.1.5 Discount rate. Discount is a critical step when analyzing long-term public investments, as it allows for comparing costs and benefits across different time periods (Jawad & Ozbay, 2006). Since a dollar spent in the future is valued less than a dollar spent today, reflecting the time value of money, it becomes essential to convert costs and benefits occurring at various points in time to their equivalent values at a common reference point (Ferreira & Santos, 2013). The discount rate, representing the difference between interest and inflation rates, captures the real value of money over time (AAPTP, 2006). This relationship is mathematically expressed in Equations 3.2 and 3.3. Studies suggest that over extended time horizons, the real value of money, reflected by the discount rate, typically ranges between 2% and 4% (Ang & Tang, 1975; FDOT, 2005). However, for this study, discount rates of 3.5% were applied based on the INDOT design manual and current practice (INDOT, 2022).

$$PW = C \times \left[{(1 + i_{\text{inf}})}/{(1 + i_{\text{int}})} \right]^n \quad \text{(Eq. 3.2)}$$

or

$$PW = C \times \left[{1}/{(1 + i_{dis})} \right]^n \quad \text{(Eq. 3.3)}$$

PW = present-worth cost ($)
C = future cost in present-day terms ($)
i_{inf} = annual inflation rate (decimal)
i_{int} = annual interest rate (decimal)
n = time until cost CCC is incurred (years)
i_{dis}= annual discount rate (decimal)

As illustrated in the following equations, the NPV and EUAC calculations incorporated the present value of the initial overlay cost, the future value of subsequent overlay costs, and the salvage value at the end of the analysis period. The projected costs, expressed in terms of present value, were utilized to account for initial construction expenses, M&R costs, and salvage value (AAPTP, 2006; Prasada et al., 2008; Walls & Smith, 1998; Zimmerman et al., 2000). Present and future expenditures are converted into a uniform annual cost to calculate the EUAC, which serves as a preferred indicator for annual budgeting purposes (Roberts et al., 1997).

$$NPV = Initial\ Cons.\ Cost + \sum_{K=1}^{N} Future\ Cost_k \left[\frac{1}{(1+i)^{nk}} \right] - Salvage\ Value \left[\frac{1}{(1+i)^{n_e}} \right] \quad \text{(Eq. 3.4)}$$

N = number of future costs incurred over the analysis period
i = discount rate in percent
n_k = number of years from the initial construction to the Kth expenditure
n_e = analysis period in years

$$EUAC = NPV \times \left[\frac{r(1+r)^{n_s}}{(1+r)^{n_s} - 1} \right] \quad \text{(Eq. 3.5)}$$

i = discount rate in percent
n = years of expenditure

According to previous studies, at the end of the analysis period, certain pavement structures may still remain serviceable; however, if their condition has deteriorated beyond the point of maintenance, further action is required. For assets with remaining useful life, the salvage value or residual value must be accounted for in the analysis (Özbay & Özcan, 2006). The salvage value comprises two key components: the residual value, which represents the net value obtained from pavement recycling (Walls & Smith, 1998), and the serviceable life, referring to the remaining life of the pavement alternative beyond the analysis period. While the term "salvage value" is commonly used in LCCA, the FHWA adopts the term "remaining service life" (RSL) to emphasize that the pavement continues to provide service beyond the analysis period. Salvage value is often estimated as a percentage of the initial construction cost of the pavement.

3.2 Results and Discussion

In this study, data obtained from performance analyses and the 2023 INDOT weighted bid prices were utilized as inputs to evaluate and compare the NPV and EUAC of SMA and HMA mixtures on highways, as an example, with comparable traffic conditions. The presented example was intended to illustrate the LCCA methodology rather than provide definitive conclusions. The predicted service life values were preliminary estimates, subject to refinement following the completion of the performance analysis. The overarching objective of the LCCA was to assess whether the higher initial cost of SMA could be justified by its enhanced pavement performance, specifically its extended service life.

The LCCA was conducted under the assumption of constructing an asphalt overlay less than two inches thick using the two alternative mixtures. Its input parameters were derived from the most recent 2023 weighted bid prices and the predicted service lives specific to Indiana highways. Discount rates were applied in accordance with INDOT's current practices of 3.5%.

The NPV and EUAC calculations, presented in Equations 3.4 and 3.5, were used based on the present value of the initial overlay cost, the future value of subsequent replacement overlay costs, and the salvage value at the end of the analysis period.

Although traditional LCCA typically requires an analysis period of 35 to 40 years to account for at least one pavement rehabilitation activity, this study employed a shorter analysis period to compare the life-cycle cost benefits of SMA and HMA mixtures for similar pavement types. The analysis period was determined based on the predicted service life of SMA derived from performance analyses. For this study, only U.S. highways are presented as an example, while other functional classifications will be evaluated in subsequent phases of this ongoing research.

To ensure a fair comparison, SMA and HMA mixtures were analyzed under similar traffic conditions and pavement structures. User costs were excluded from the analysis, as they were assumed to be similar for both materials under comparable scenarios. Additionally, routine maintenance and traffic control costs were not considered in the deterministic approach, given their negligible impact on EUAC when discounted to present value. This approach ensures a focused evaluation of material and performance differences between SMA and HMA overlays.

A detailed analysis of the case study is presented in the subsequent sections. Table 3.2 provides a detailed summary of the input parameters employed in the LCCA case study of Indiana U.S. highways.

3.2.1 U.S. Highway

The recent average weighted bid prices for SMA and HMA mixtures were $130 and $120 per ton, respectively. The cost difference between SMA and HMA is influenced not only by material composition and production expenses but also by the mix adjustment factor (MAF). Since the MAF for SMA is greater than 1.0, contractors account for the adjusted tonnage when determining bid prices. The cost data used in this study already reflects this adjustment, meaning that the observed cost difference includes the impact of MAF. Based on the performance analysis, the predicted service life for SMA on U.S. highways, for both flexible and composite pavements, was determined to be 15.48 years. Accordingly, an analysis period of 15.48 years was adopted for the LCCA. Figure 3.4 illustrates the LCCA models and the corresponding cost expenditure streams for SMA and HMA mixtures.

3.2.1.1 Adjustment for inflation. To estimate the costs per lane mile for the SMA and HMA overlays, the standard practice employed by INDOT was utilized, assuming a 12-foot-wide lane with a total area of 7,040 square yards per mile. Historical cost data for a one-lift overlay (1.5-inch milling and 1.5-inch overlay) were used, with baseline costs of approximately $10 per square yard for HMA and $12 per square yard for SMA. These baseline values were adjusted for inflation using the average annual inflation rate, resulting in updated 2023 costs of $13.29 per square yard for HMA and $15.95 per square yard for SMA.

Adjustment 1: SMA Overlay. In this alternative, the SMA overlay was expected to have a service life of 15.48 years. The agency cost for the initial construction (i.e., the present value at year 0) was calculated as $112,448 per lane mile, using the inflation-adjusted cost

TABLE 3.2
LCCA input summary

IRI Threshold	Pavement Type	Functional Classes	Discount Rate	Analysis Period	Service Life (*Years*)		Unit Cost (*$/ton*)	
					SMA	*HMA*	*SMA*	*HMA*
150	Flexible/Composite	U.S. Highway	0.035	15.48	15.48	10.6	$130	$120

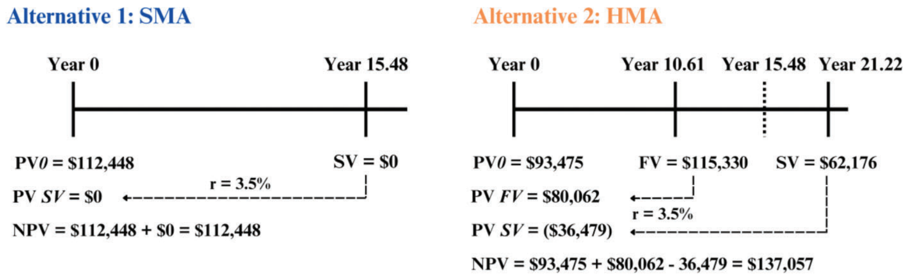


Figure 3.4 LCCA models and cost expenditure streams.

of $15.95 per square yard. As the overlay would be replaced at year 15.48 with a salvage value of $0 at the end of the analysis period, the NPV for Alternative 1 was calculated as $112,448 per lane mile.

Alternative 2: HMA Overlay. In this alternative, the HMA overlay was projected to have a service life of 10.6 years, with an initial construction cost of $93,475 per lane mile, based on the inflation-adjusted cost of $13.29 per square yard. At year 10.61, the overlay would require replacement, with the future replacement cost adjusted using a 2% inflation rate. Consequently, the cost of the replacement overlay after 10.61 years was estimated to be $115,330, and it was assumed to have a service life of 10.61 years. At the end of the 15.48-year analysis period, following the single replacement at year 10.61, the final overlay would have 5.72 years of remaining service life. As a result, the salvage value was determined to be $62,176, calculated as a prorated portion of the replacement overlay cost. The salvage value was computed using the formula.

$$Salvage\ Value = Overlay\ Cost \times \left(\frac{Remaining\ Life}{Service\ Life}\right) \quad \text{(Eq. 3.6)}$$

Using the agency-specified discount rate of 3.5%, the cost of the replacement overlay at year 10.61, as well as the salvage value at year 15.48, were discounted back to year 0. The present value of the replacement overlay at year 10.61 was calculated as $80,062, while the present value of the salvage value at year 15.48 was determined to be $36,479. These values were obtained using the following discount formulas:

$$Discounted\ Replacement\ (Year\ 0) = Replacement \times \left(\frac{1}{(1+r)^t}\right) \quad \text{(Eq. 3.7)}$$

$$Discounted\ Salvage\ Value\ (Year\ 0) = Salvage\ Value \times \left(\frac{1}{(1+r)^t}\right) \quad \text{(Eq. 3.8)}$$

The NPV for Alternative 2 was then calculated as the sum of the present value of the initial construction cost, the discounted replacement cost, and the discounted salvage value, resulting in an NPV of $137,057 per lane mile.

3.2.1.2 Comparison of LCCA result. The LCCA results indicated that the SMA overlay was more cost-effective than the comparable HMA mixtures in NPV over the 15.48-year analysis period. This represents a 17.96% reduction in lifecycle costs compared to the HMA alternative. These findings demonstrate that the higher initial cost of SMA on U.S. highways was justified by its superior pavement performance and improved cost-effectiveness over the analysis period.

Return on Investment (ROI) Analysis
To evaluate the economic feasibility of SMA overlays, the ROI was calculated based on the NPVs. of SMA and HMA alternatives. The NPV for the SMA overlay was calculated as $112,448 per lane mile, while the NPV for the HMA alternative was $137,057 per lane mile. The ROI was computed as the ratio of cost savings to the NPV of SMA, expressed as a percentage:

$$ROI = \left(\frac{Cost\ Savings}{NPV\ of\ SMA}\right) \times 100 \quad \text{(Eq. 3.9)}$$

This ROI highlights that investing in SMA yields a 21.89% return over the analysis period compared to HMA, validating its economic advantage. The results demonstrate that while SMA overlays incur higher initial costs, their improved performance and longer service life result in significant lifecycle cost savings. Specifically, SMA overlays reduce lifecycle costs by 17.96% and provide a 21.89% ROI, justifying their adoption for high-traffic roadways. These findings underscore the value of SMA as a cost-effective solution for pavement preservation and maintenance strategies.

3.3 Summary and Recommendations

The findings from this study present an analysis of the cost-effectiveness of SMA pavements compared to conventional HMA pavements. The research employed an LCCA framework, focusing on NPV and EUAC, to evaluate the long-term economic implications of adopting SMA overlays for Indiana's highway network. The analysis was conducted under deterministic conditions with a planned extension to incorporate probabilistic modeling in future work. The primary motivation for this study stemmed from the INDOT's second round of SMA pavement rehabilitation, creating a timely opportunity to evaluate the economic viability of SMA as a sustainable maintenance strategy. The study's methodology centered on an evaluation of pavement performance and financial metrics. NPV and EUAC were computed to assess the present and future cost streams of both overlay alternatives, accounting for inflation, salvage value, and discount rates set at 3.5% per INDOT's design standards.

U.S. highways are presented as an example in the LCCA, and the results demonstrate that, despite higher initial construction costs, SMA overlays exhibit superior long-term cost performance relative to conventional HMA. NPV for SMA is calculated as $112,448 per lane mile, compared to $137,057 per lane mile for HMA, reflecting a 17.96% reduction in lifecycle costs. Additionally, the ROI analysis reveals that SMA overlays yield a 21.89% ROI over the 15.48-year analysis period. This economic advantage is primarily attributed to the extended service life of SMA, which delays the need for costly rehabilitation activities, thereby reducing total maintenance expenditures.

4. EXPLORING STEEL SLAG ALTERNATIVE AGGREGATES FOR INDIANA SMA

Stone matrix asphalt (SMA) is a stable and durable asphalt mixture initially developed in Germany in the 1960s to address pavement rutting and durability (Lee et al., 2022). This premium pavement material is more expensive than conventional dense-graded hot mix asphalt (HMA). The cost difference is primarily due to using more durable aggregates, a higher binder content, modified asphalt binders, and the inclusion of fibers. SMA's design relies on a strong stone-on-stone aggregate skeleton to support traffic loads, necessitating strict aggregate strength and durability requirements.

Steel slag has been utilized in Indiana's SMA because of its exceptional strength and durability. However, supply challenges during the COVID-19 pandemic have underscored the need for alternative aggregates to replace steel slag in Indiana's SMA.

This chapter outlines a study that examines SMA performance using different coarse aggregates. It begins with a review and comparison of Indiana's coarse aggregate requirements for SMA against those of other states. Next, the aggregates commonly used in Indiana's SMA are identified. Field performance data are then collected and analyzed to evaluate SMA performance based on the type of aggregate used. Following this, laboratory tests are conducted to validate aggregate performance and determine whether changes in aggregate requirements are necessary. Finally, the study proposes alternative aggregates to replace steel slag and recommends adjustments to aggregate specifications based on the findings.

4.1 Coarse Aggregate Requirements for SMA

4.1.1 Requirements for Indiana SMA

Not all INDOT aggregate specifications for SMA are detailed here. Complete information on INDOT's SMA and aggregate specifications can be found in the INDOT Standard Specifications, Sections 410 and 904.

Section 410 specifies that coarse aggregates used in SMA should meet the requirements for Class AS aggregates defined in Section 904. Table 4.1 outlines these requirements, with one of the most critical being an LA abrasion loss of no more than 30%. Acceptable materials for SMA mixtures include steel furnace slag, sandstone, crushed dolomite, and polish-resistant aggregates, provided the mixtures comply with ITM 220 design procedures.

ITM 220 covers the procedures to evaluate Class AS coarse aggregates for use in SMA. The procedure includes determining the Micro-Deval abrasion value of the aggregate or aggregate blend and the aggregate degradation of the SMA mixture. Micro-Deval abrasion loss is determined for each coarse aggregate of the aggregate blend in accordance with AASHTO T 327. The coarse aggregate or blend of coarse aggregates shall have the total abrasion loss value determined by proportioning the individual coarse + loss value with the blend percentage for each coarse aggregate. The total Micro-Deval abrasion loss value for an acceptable coarse aggregate or blend of coarse aggregate shall be 18.0% or less. The aggregate degradation loss value for an acceptable coarse aggregate or blend of coarse aggregates shall be 3.0% or less.

Therefore, in summary, the three critical physical requirements that coarse aggregates meet for use in SMA are the following:

(1) LA abrasion loss ≤ 30.0%,
(2) Micro-Deval abrasion loss ≤ 18.0%, and
(3) aggregate degradation loss ≤ 3.0%.

4.1.2 Requirements for SMA in Other States

Indiana's aggregate requirements were reviewed and compared with specifications from 15 other states in 2023 to explore the possibility of using alternative aggregate types in SMA. Among the 16 states surveyed (including Indiana), 10 had distinct aggregate requirements for SMA, while the remaining six states integrated SMA requirements with those for HMA, lacking separate criteria. A summary of the SMA aggregate requirements across these states is provided in Table 4.2.

All states that included SMA specifications set maximum requirements for LA abrasion loss. These requirements ranged from 30% to 45%, with an average maximum value of approximately 35.5%. Indiana, together with Maryland and Texas, had the most stringent LA abrasion loss requirement at 30%. Additionally, only three states, including Indiana,

TABLE 4.1
Classification of aggregate

Characteristic Classes	AP	AS	A	B	C	D	E	F
Quality Requirements								
Freeze and Thaw Beam Expansion, % max.[1]	.060	–	–	–	–	–	–	–
Los Angeles Abrasion, % max.[2]	40.0	30.0	40.0	40.0	45.0	45.0	50.0	–
Freeze and Thaw, AASHTO T 103, Procedure A,	–	–	–	–	–	–	–	–
% max.[3]	12.0	12.0	12.0	12.0	16.0	16.0	20.0	25.0
Sodium Sulfate Soundness, % max.[3]	12.0	12.0	12.0	12.0	16.0	16.0	20.0	25.0
Brine Freeze and Thaw Soundness, % max.[3]	30	30	30	30	40	40	50	60
Absorption, % max.[4]	5.0	5.0	5.0	5.0	5.0	–	–	–
Additional Requirements								
Deleterious, % max.	–	–	–	–	–	–	–	–
Clay Lumps and Friable Particles	1.0	1.0	1.0	1.0	2.0	4.0	–	–
Non-Durable[5]	4.0	2.0	4.0	4.0	6.0	8.0	–	–
Coke[6]	–	–	–	–	–	–	–	–
Iron[6]	–	–	–	–	–	–	–	–
Chert[7]	3.0	3.0	3.0	5.0	8.0	10.0	–	–
Weight per Cubic Foot for Slag, lb, min.	75.0	–	75.0	75.0	70.0	70.0	70.0	–
Crushed Particles, % min.[8]	–	–	–	–	–	–	–	–
Compacted Aggregates	–	–	20.0	20.0	20.0	20.0	–	–

Note:
[1]Freeze and thaw beam expansion shall be tested and re-tested by ITM 210.
[2]Los Angeles abrasion requirements shall not apply to BF.
[3]Aggregates may, at the discretion of the engineer, be accepted by the sodium sulfate soundness or brine freeze and thaw soundness requirements.
[4]Absorption requirements apply only to aggregates used in PCC and HMA mixtures except they shall not apply to BF. When crushed stone coarse aggregates from Category I sources consist of production from ledges whose absorptions differ by more than two percentage points, the absorption test will be performed every 3 months on each size of material proposed for use in PCC or HMA mixtures. Materials that have absorption values between 5.0 and 6.0 that pass AP testing may be used in PCC. If variations in absorption preclude satisfactory production of PCC or HMA mixtures, independent stockpiles of materials will be sampled, tested, and approved prior to use.
[5]Non-durable particles include soft particles as determined by ITM 206 and other particles which are structurally weak, such as soft sandstone, shale, limonite concretions, coal, weathered schist, cemented gravel, ocher, shells, wood, or other objectionable material. Determination of non-durable particles shall be made from the total weight (mass) of material retained on the 3/8-in. (9.5-mm) sieve. The scratch hardness test shall not apply to crushed stone coarse aggregate.
[6]ACBF and SF coarse aggregate shall be free of objectionable amounts of coke, iron, and lime agglomerates.
[7]The bulk specific gravity of chert shall be based on the saturated surface dry condition. The amount of chert less than 2.45 bulk specific gravity shall be determined on the total weight (mass) of material retained on the 3/8 in. (9.5 mm) sieve for sizes 2 through 8, 43, 53, and 73 and on the total weight (mass) of material retained on the No. 4 (4.75 mm) sieve for sizes 9, 11, 12, and 91.
[8]Crushed particle requirements apply to gravel coarse aggregates used in compacted aggregates. Determination of crushed particles shall be made from the weight (mass) of material retained on the No. 4 (4.75 mm) sieve in accordance with ASTM D5821.

required a maximum Micro-Deval abrasion loss value, which was consistently set at 18% across these states.

Among the surveyed states, Indiana's specifications were the most rigorous. It not only maintained strict LA abrasion and Micro-Deval abrasion loss requirements but was also the only state to impose a maximum aggregate degradation loss limit of 3.0%. This comprehensive set of stringent requirements highlights Indiana's high standards for the quality of SMA aggregate compared to other states.

4.2 Coarse Aggregates in Indiana SMA

4.2.1 Coarse Aggregates for SMA

INDOT began using SMA in the late 1990s. While Indiana is geologically rich in limestone, limestone has not been utilized as an aggregate for SMA due to its insufficient durability for SMA applications. Instead, steel slag, known for its durability, has become one of the primary coarse aggregates used in Indiana SMA (Haddock & Celaya, 2006).

To analyze the frequency and proportion of steel slag used in Indiana SMA and identify other aggregates employed, SMA design mix formulas (DMFs) from 2018 to 2021 were reviewed. Table 4.3 summarizes the frequency of use of steel slag and dolomite in SMA.

A total of 53 DMFs were examined, revealing that steel slag was used in 49 (92.5%) of the mixes, while dolomite was used in 44 (83%) of the mixes. The average proportions of steel slag and dolomite in SMA were 37.4% and 36.8%, respectively. Considering that coarse aggregates constitute about 75%–80% of SMA, these two aggregates accounted for approximately 74% of the total SMA mixture, highlighting their dominant role in Indiana SMA.

TABLE 4.2
Aggregate requirements for the SMA of other states

States	LA Abrasion Loss (%)	Micro-Deval (%)	Separate Specifications for SMA
Indiana	30	18	Yes
Alabama	48, 55	–	No
Maine	–	18	No
Ohio	35	–	Yes
South Carolina	HV: 55, LV: 60	–	No
Maryland	30	–	Yes
Georgia	45	–	Yes
Texas	30	18	Yes
Virginia	40	–	Yes
Wisconsin	LT: 50, MT: 45, HT: 45, SMA: 35	–	Yes
Minnesota	Class 1–5: 40, Class 6: 35, SMA: 35	–	Yes
Illinois	40	–	No
Michigan	40	–	No
Missouri	40	–	Yes
Pennsylvania	35	–	Yes
Iowa	45	–	No

TABLE 4.3
Use of steel slag and dolomite in SMA from 2018 to 2021

Year	2018	2019	2020	2021	Total
No. of DMFs	15	22	6	10	53
Steel Slag	15 100.0%	21 95.5%	3 50.0%	10 100.0%	49 92.5%
Dolomite	14 93.3%	19 86.4%	3 50.0%	8 80.0%	44 83.0%

In addition to steel slag and dolomite, other aggregates used in SMA included PRA (polish resistant aggregates), stone, and crushed gravel. PRA refers to dolomite or crushed limestone and gravel that meet the requirements of ITM 214.

4.2.2 Mechanical Properties of Dolomite

Despite being less durable than steel slag, Dolomite has been widely used in stone matrix asphalt (SMA) due to its availability and cost-effectiveness. The mechanical properties of dolomite from multiple sources across the state were analyzed to evaluate the suitability of Indiana-sourced dolomite for SMA. As part of the SPR-4646 project, 27 Los Angeles (LA) abrasion loss values and 23 Micro-Deval abrasion loss values were tested or gathered for 28 dolomite sources. A summary of these results is presented in Table 4.4.

The LA abrasion loss values ranged from 22.1% to 39.4%, with an average of 29.6%, while the Micro-Deval abrasion loss values ranged from 6.0% to 19.2%, averaging 8.7%. Among the 27 dolomite sources evaluated for LA abrasion loss, eight (29.6%) exceeded the maximum allowable limit of 30%. Only two of the 23 sources (8.7%) exceeded the 18% threshold for Micro-Deval abrasion loss.

Figures 4.1 and 4.2 illustrate the distribution of LA abrasion and Micro-Deval values, with dotted lines marking specification limits. Most dolomite sources met the Micro-Deval requirement, indicating strong resistance to moisture-induced abrasion. However, nearly 30% of the sources failed to meet the stricter 30% limit for LA abrasion loss.

The data suggests that relaxing the LA abrasion loss requirement from 30.0% to 35.0%—closer to the average requirement in other states—would allow most dolomite sources to qualify for SMA use. This indicates potential for broader utilization of dolomite in SMA with adjusted specifications.

4.3 SMA Field Performance Evaluation According to Aggregate Types

4.3.1 Performance Evaluation According to Steel Slag and Dolomite Content

SMA was introduced in the United States in the early 1990s, adapted from its European origins, where it was developed in Germany during the 1960s. Indiana adopted SMA shortly after its introduction in the U.S., as the state sought solutions to improve the longevity and performance of its asphalt pavements.

TABLE 4.4
Mechanical properties of dolomites in Indiana

Source Number	LA Abrasion	Micro-Deval Abrasion	Source Number	LA Abrasion	Micro-Deval Abrasion
AGG0021	30.05	11.80	2409	24.05	11.30
AGG0057	24.30	13.80	2421	25.80	7.40
2211	32.45	11.85	2423	27.33	18.70
2232	27.86	11.20	2428	26.95	10.25
2237	26.85	11.50	2440	24.95	5.95
2238	30.25	11.30	2445	31.60	–
2262	26.17	9.90	2449	27.63	10.30
2266	28.95	–	2461	27.83	8.57
2267	34.60	11.45	2472	25.47	9.90
2361	29.83	12.15	2503	22.07	12.30
2362	27.53	12.87	2510	28.50	–
2363	39.43	–	2538	32.80	19.20
2367	30.27	12.45	2588	–	–
2389	26.99	14.43	2798	27.47	15.30

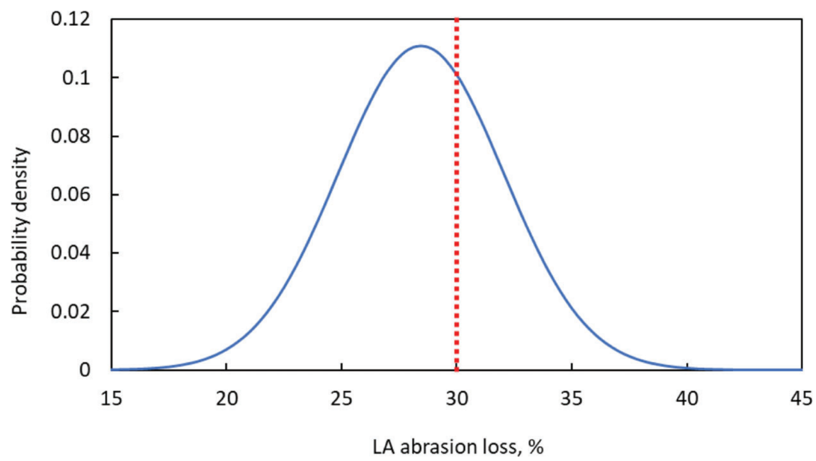


Figure 4.1 Distribution of LA abrasion loss.

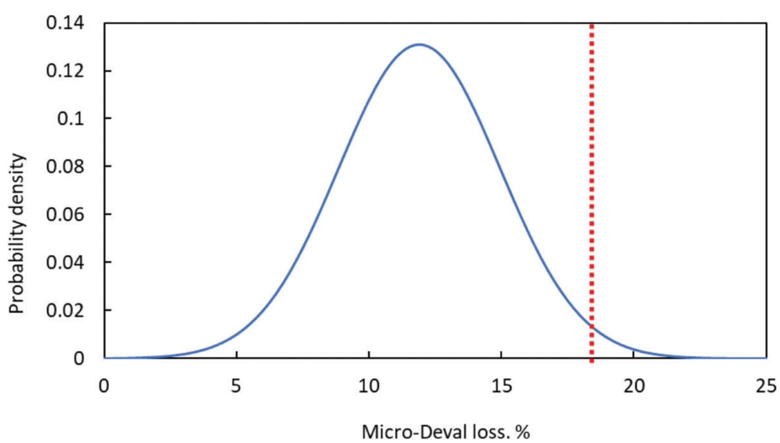


Figure 4.2 Distribution of Micro-Deval abrasion loss.

Steel slag was initially favored for its durability, but dolomite emerged as a widely used aggregate due to its local abundance and cost-effectiveness. The Indiana Department of Transportation (INDOT) continues to refine its SMA specifications to optimize material utilization and ensure performance. The last update to the SMA specification was in 2017.

Eight SMA projects with different aggregate combinations were selected to evaluate the field performance of SMA based on the proportions of steel slag and dolomite. The project details are summarized in Table 4.5. All selected projects were interstate projects constructed in 2019, chosen because SMA specifications were updated in 2017. Each project had a Nominal Maximum Aggregate Size (NMAS) of 9.5 mm, a binder grade of PG 76-22, and an ESAL Category of 4, differing only in aggregate combinations.

Field performance data from 2023, 4 years after construction, were collected using the Power BI-based INDOT pavement condition and inventory information developed by the INDOT Pavement Asset Team. The data included IRI, % cracking, rut depth, and friction number. Figures 4.3 through 4.6 illustrate correlations between these parameters and the aggregate types.

- *IRI:* Weak correlations were observed between IRI and steel slag (R^2 = 0.0003) and dolomite (R^2 = 0.0702).
- *Percent Cracking:* The correlation between % cracking and steel slag (R^2 = 0.0016) was weak, while the correlation with dolomite (R^2 = 0.2653) was relatively stronger. As dolomite content increased, % cracking also slightly increased at a rate of 0.0007, but all projects maintained less than 10% cracking, indicating good performance.
- *Rut Depth:* Correlations between rut depth and steel slag (R^2 = 0.1719) or dolomite (R^2 = 0.2317) were higher than other parameters, but rut depth increased minimally at a rate of 0.0002 as aggregate proportions rose. All projects had a rut depth below 0.1 inches, demonstrating strong rutting resistance.
- *Friction Number:* A notable correlation between friction number and aggregate type was found. Higher steel slag content corresponded to higher friction numbers (R^2 = 0.1415), while higher dolomite content correlated with lower friction numbers (R^2 = 0.2628). These results confirmed that dolomite is more susceptible to polishing.

Changes in friction numbers over time were examined for two projects with the lowest and highest dolomite contents, as shown in Figure 4.7. The project with 0% dolomite and 47% steel slag, shown as S47D00, showed a gradual decrease in friction number. In contrast, the project with 48% dolomite and 34.5% steel slag, shown as S35D48, exhibited a more pronounced decline in friction number, with an R^2 of 0.9999 indicating a strong correlation between dolomite content and friction number reduction.

If the friction number decreases at the same rate, the high-dolomite SMAs are projected to reach a friction number of 20, requiring a correction action within approximately 10 years.

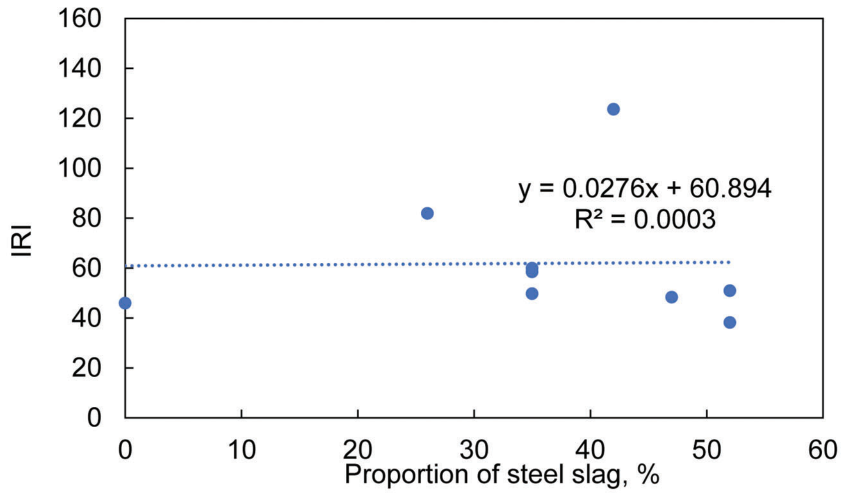
4.3.2 SR-63 Performance Comparison Between Steel Slag and Crushed Gravel

In 2003, a special demonstration section of SMA was constructed on State Road 63 (SR 63) in Indiana to evaluate and compare the performance of two aggregate types: crushed gravel and steel slag. This initiative was part of the state's effort to evaluate the suitability of locally available materials for SMA under real-world traffic and environmental conditions. The test section, approximately 6 miles in length, featured about 1.8 miles of crushed gravel pavement in the driving lane of the northbound side, with the remaining portion constructed using steel slag.

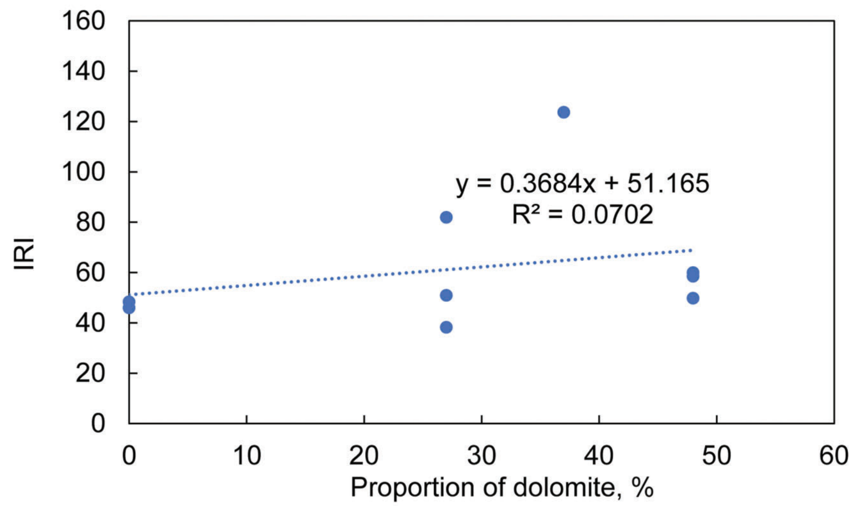
The demonstration section remained in service for 17 years, from 2003 to 2020, before being overlaid with new pavement. In 2018, a chip seal was applied as part of preventive maintenance. Field performance data collected between 2015 and 2017, prior to the chip seal, were analyzed to evaluate performance differences

TABLE 4.5
Information on selected projects for field performance evaluation

Design ID	Contract No.	Location	RP	Steel Slag	Dolomite
192xxx	R-40xxx	On I-69 from 0.93 miles south of SR 4 to 1.12 miles north of US 20	RP 339+0043 TO 348+0098	52.0	27.0
	RS-41xxx	On I-69 from 0.47 miles north of SR 1 to 9.46 miles north of SR 1	RP 316+0070 TO 325+0022		
192xxx	RS-38xxx	On I-69 from 0.68 miles of US 224 to 9.52 miles north of US 224	RP 285+0070 TO 295+0090	36.0	27.0
193xxx	RS-40xxx	On I-69 from 75th street to 0.11 miles north of SR 37	RP 200+0000 TO 205+0032	47.0	0.0
193xxx	RS-40xxx	On I-69 from 75th street to 0.11 miles north of SR 37	RP 200+0000 TO 205+0032	39.0	0.0
193xxx	R-41xxx	On I-465 from 1.17 miles south of I-65 to 0.80 miles north of I-65	RP 018+0075 TO 020+0070	34.5	48.0
		On I-465 from 0.80 mile north of I-65 to 0.40 mile east of US 31	RP 020+0070 TO 031+0010		
193xxx	R-41xxx	On I-70 from 0.63 miles west of I-65S to I-65S	RP 078+0008 TO 080+0096	42.0	37.0
196xxx	RS-40xxx	On I-64 from the Illinois state line to 0.60 miles west of SR 165	RP 000+0000 TO 011+0029	0.0	0.0



(a) Steel slag vs. IRI



(b) Dolomite vs. IRI

Figure 4.3 IRI measurements according to aggregate type: (a) steel slag, (b) dolomite.

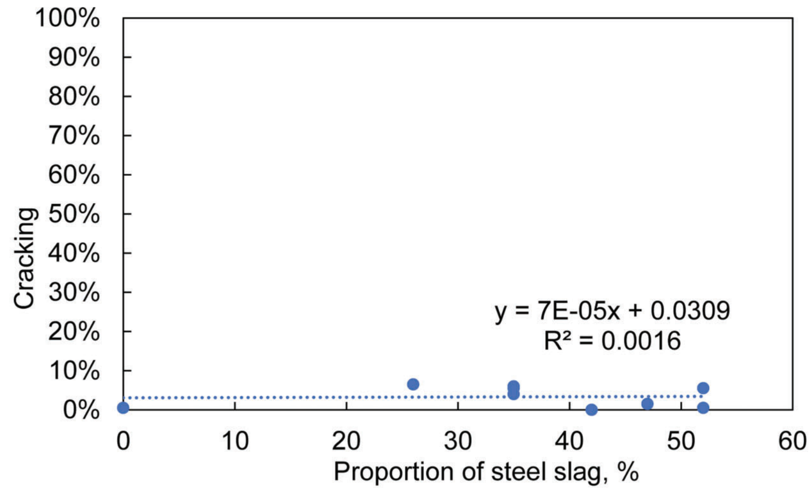
between the two aggregate types. Key parameters included IRI, percent cracking, rut depth, and friction number.

Figures 4.8 and 4.9 illustrate the yearly distribution and trends of performance parameters for both the crushed gravel and steel slag sections. Statistical significance for each parameter was assessed using a t-test, with the following findings.

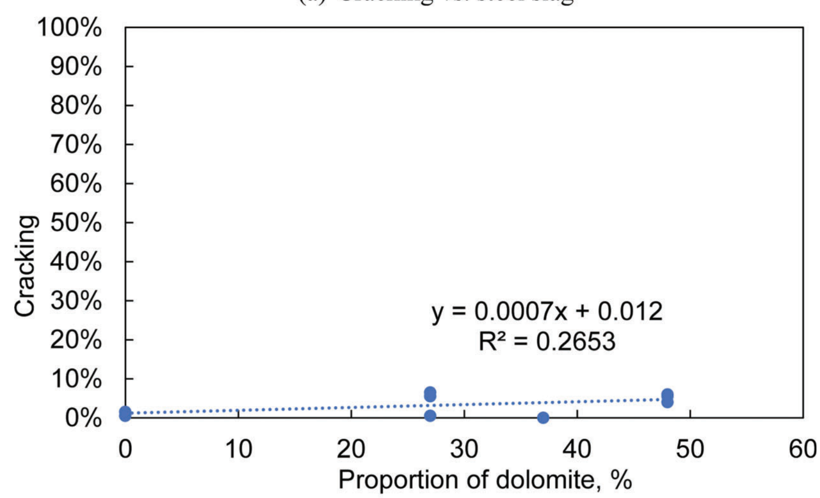
- *IRI:* The crushed gravel section had a slightly higher average IRI than the steel slag section. The P-values exceeded 0.05, indicating no significant difference in IRI between the two sections.
- *Percent Cracking and Rut Depth:* While statistical differences were observed for these parameters, the rut depth difference between the two sections was approximately 0.1 inches. This difference is minor, particularly considering the section's age of over 12 years. Both sections exhibited high levels of cracking, though the data showed considerable variability, likely due to inconsistencies in measurement techniques.
- *Friction Number:* Only 2017 data was available because the friction number is not measured annually for state road. The crushed gravel section had an average friction number of 63.7, while the steel slag section had an average of 71.7. Despite this difference, the P-value of 0.524 indicated no statistically significant difference. Notably, both sections maintained relatively high friction numbers after 14 years of service.

Key observations from the demonstration section are as follows.

- *IRI:* Both sections experienced a gradual increase in roughness over time, reflecting normal aging but remaining within acceptable limits for SMA pavements.
- *Rut Depth:* Rutting remained stable and minimal throughout the service life.
- *Cracking:* Significant year-to-year variability in cracking data suggested potential measurement inconsistencies, emphasizing the need for consistent evaluation methods.
- *Overall Performance:* After over 12 years in service, both SMA sections demonstrated excellent durability, with



(a) Cracking vs. steel slag



(b) Cracking vs. dolomite

Figure 4.4 Percent cracking measurements according to aggregate type: (a) steel slag, (b) dolomite.

IRI, rut depth, and friction numbers indicating good overall pavement condition. However, the high cracking levels highlight a need for maintenance to address surface distress.

The 2003 demonstration section provided valuable insights into the long-term performance of SMA using different aggregates. The crushed gravel and steel slag sections performed well over time, with minimal differences in key parameters. Steel slag showed marginally better friction and cracking resistance, but at a higher material cost.

4.4 Laboratory Testing for Evaluating SMA Performance

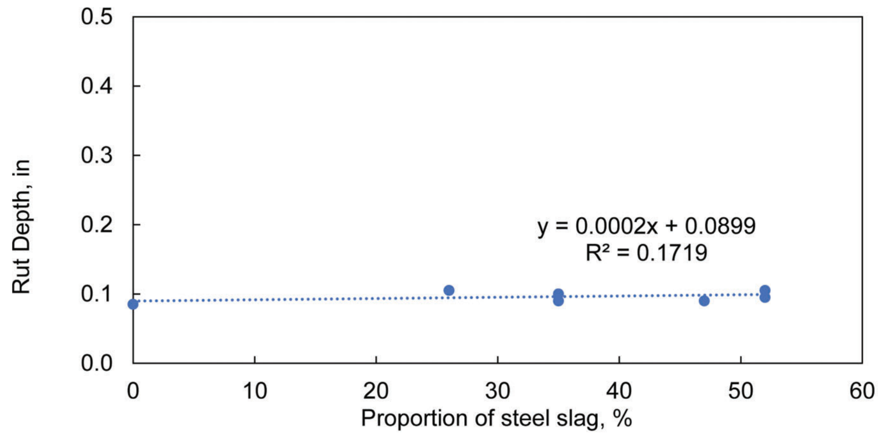
Laboratory tests were conducted to verify the results obtained from field performance data and evaluate aggregate degradation loss according to aggregate type. Laboratory tests included aggregate degradation tests, the Hamburg Wheel Tracking Test (HWTT), and the indirect tensile asphalt cracking test (IDEAL-CT) performed on both plant-produced and lab-prepared mixtures.

4.4.1 Test Method

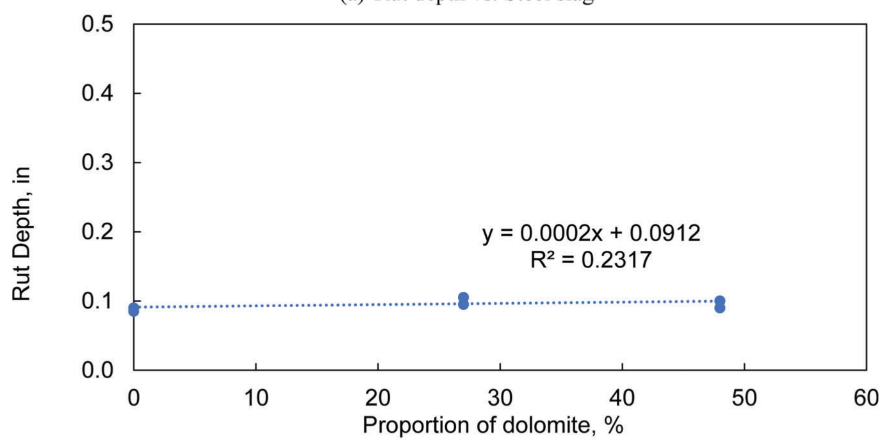
4.4.1.1 Degradation test. The degradation test evaluates aggregates' resistance to breaking down under mechanical and environmental stresses. This is essential for ensuring the durability of aggregates used in SMA in Indiana. The degradation test outlined in ITM 220 is designed to evaluate aggregates' resistance to wear and breakdown under simulated mechanical and environmental conditions.

The testing process is as follows.

1. Prepare a mix design by AASHTO R 46.
2. Compact two gyratory specimens at the optimum design binder content to N_{des} gyrations by AASHTO T 312. Mixture conditioning is not required.
3. Prepare an uncompacted mixture sample at the optimum design binder content by AASHTO T 312.



(a) Rut depth vs. Steel slag



(b) Rut depth vs. Dolomite

Figure 4.5 Rut depth measurements according to aggregate type: (a) steel slag, (b) dolomite.

4. Extract the uncompacted mixture and two gyratory specimens separately by ITM 571 or ITM 586. Determine the aggregate gradation of each by AASHTO T 30.
5. The aggregate degradation loss value is determined by Equation 4.1.

$$Aggregate\ loss, \% = A - B \qquad \text{(Eq. 4.1)}$$

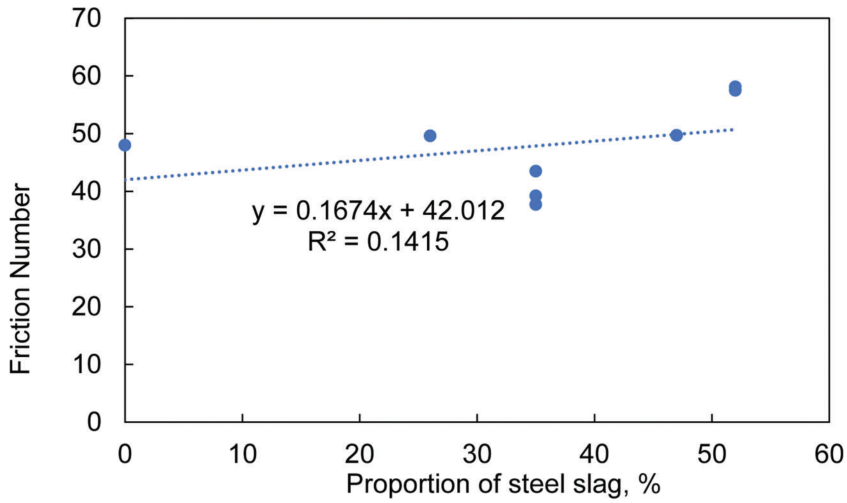
where:

A = average % passing the No. 8 sieve from the gyratory specimens.

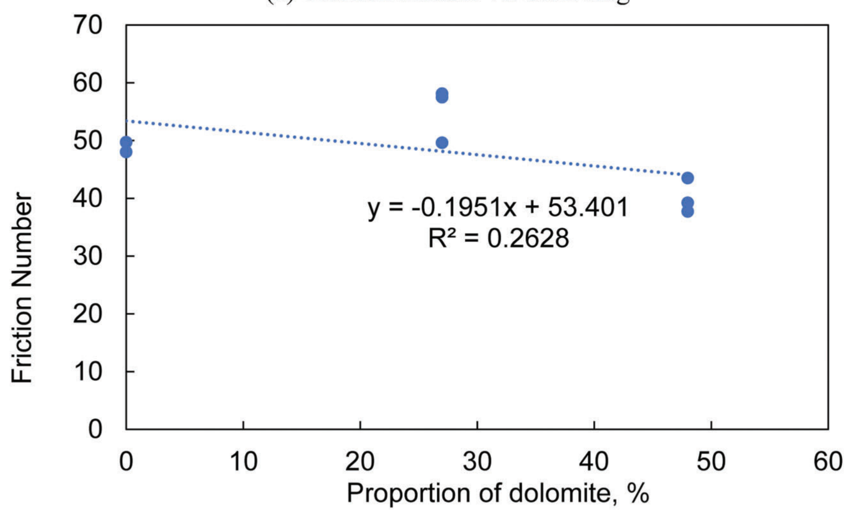
B = % passing the No. 8 sieve from the uncompacted mixture sample.

4.4.1.2 Hamburg Wheel Tracking Test (HWTT). The HWTT is the most widely used laboratory test method for evaluating asphalt mixture rut resistance. The standard test procedure is AASHTO T324-19, *Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures* (AASHTO, 2019). Compacted slab specimens or two cylindrical specimens are placed in the machine, submerged in a heated water bath, and tested by the method. The HWTT is a destructive test method that measures the rut depths of compacted asphalt specimens subjected to continuous loading imposed by a 47-mm-wide 705 N steel wheel for 20,000 passes. The recorded rut depth indicates a mixture's rutting resistance and the stripping inflection point (SIP). The standard test method allows testing of laboratory-prepared specimens, typically compacted using an SGC to a target V_a of 7.0 ± 0.%.

4.4.1.3 Indirect tensile asphalt cracking test (IDEAL-CT). The indirect tensile asphalt cracking test (IDEAL-CT) developed at the Texas A&M Transportation Institute (TTI) is a laboratory test that evaluates the potential for asphalt concrete to crack. The IDEAL-CT is an indirect tension test determining the cracking potential of asphalt mixtures with a fracture mechanics-based parameter: the cracking tolerance index (CTIndex). Asphalt mixture specimens are conditioned and fabricated to 150 mm in diameter and 62 mm in height, with 7.0±0.5% air voids, with no notching/cutting necessary. The test is typically run at 25°C with a monotonic loading rate of 50 mm/minute of cross-headed displacement.



(a) Friction number vs. Steel slag



(b) Rut depth vs. Dolomite

Figure 4.6 Friction number measurements according to aggregate type: (a) steel slag, (b) dolomite.

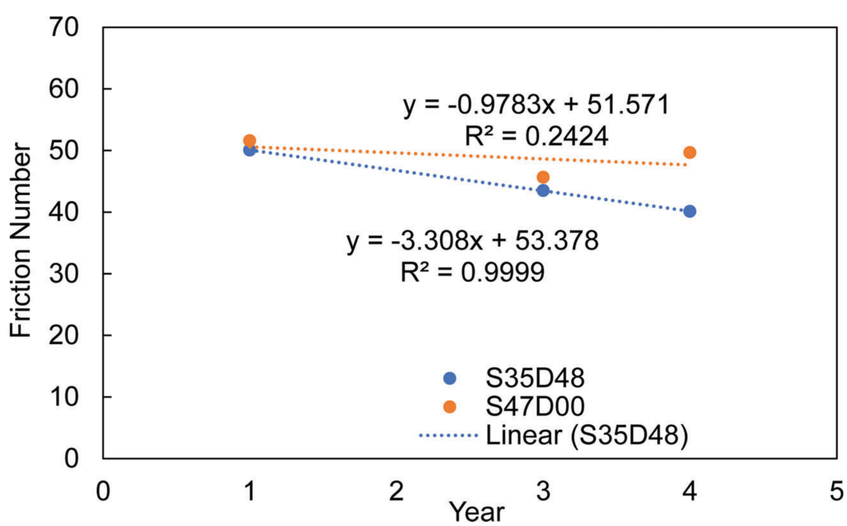
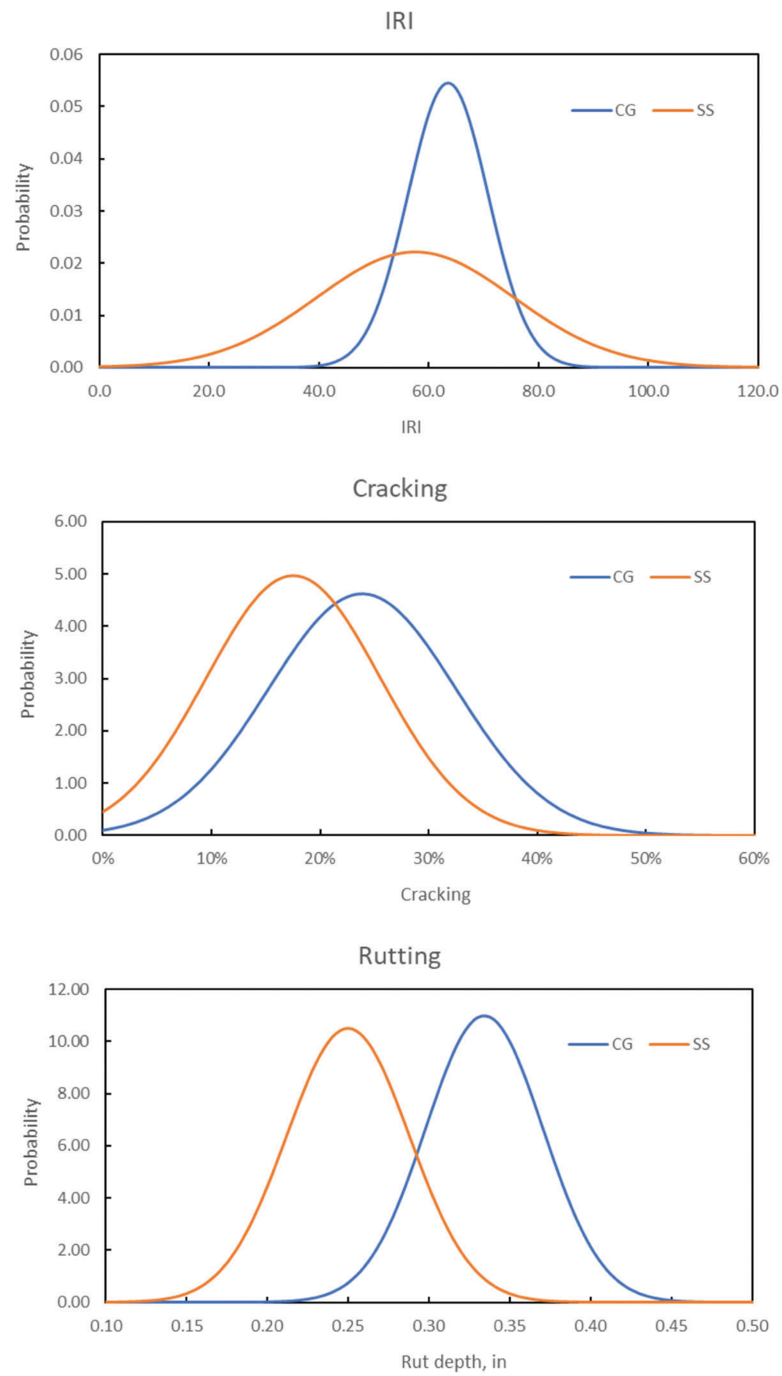
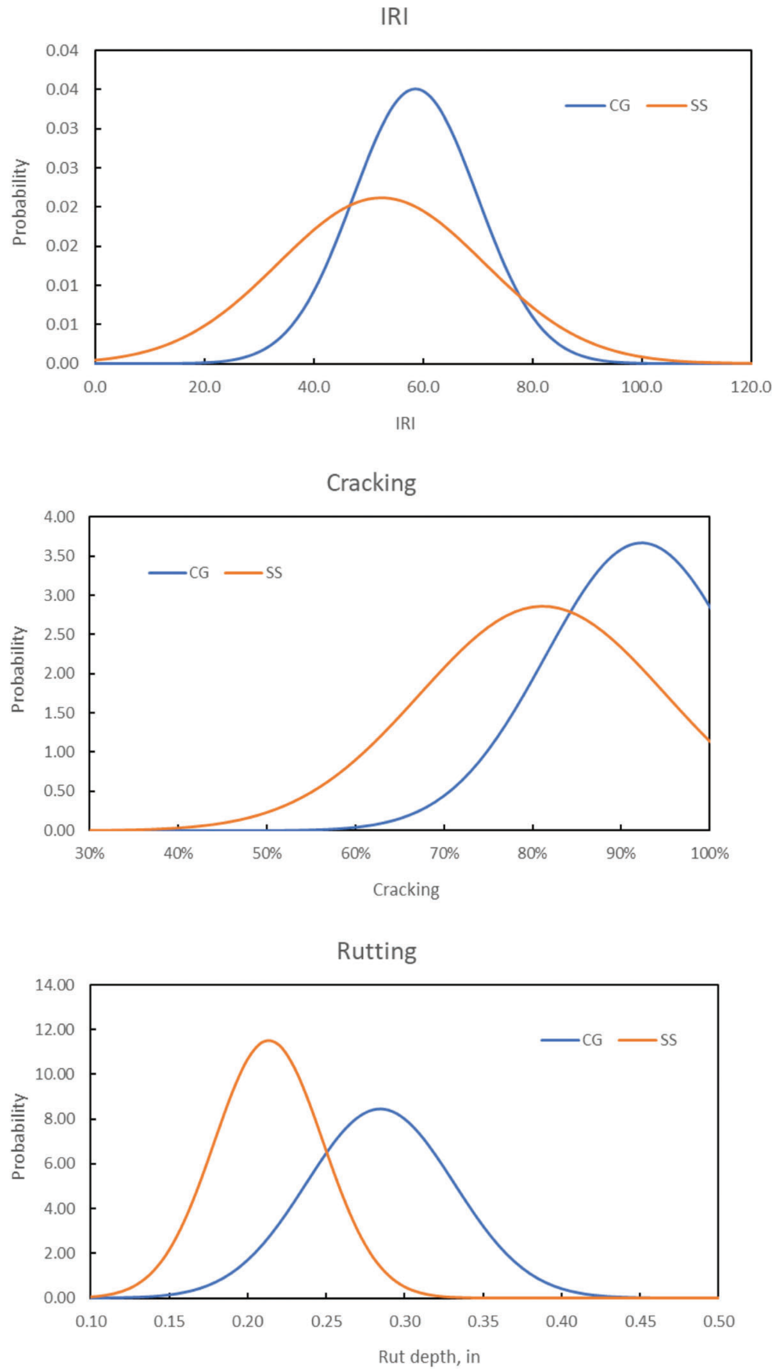


Figure 4.7 Friction number changes by year according to dolomite content.



(a) Distribution of each parameter in 2015

Figure 4.8 Continued.



(b) Distribution of each parameter in 2016

Figure 4.8 Continued.

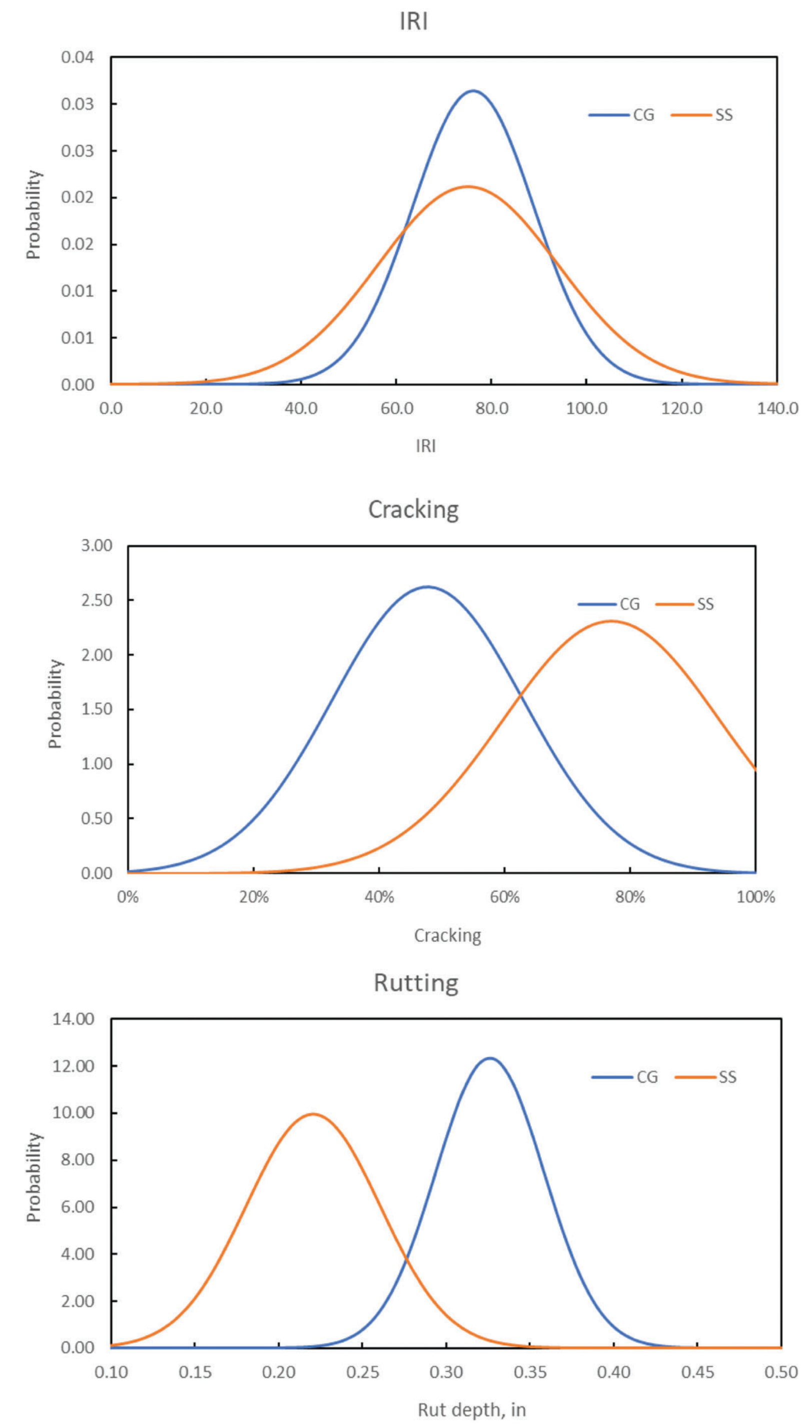
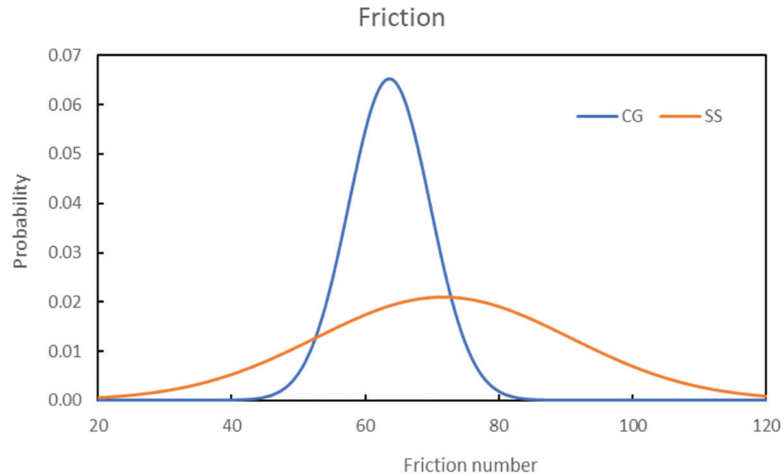


Figure 4.8 Continued.



(c)

(c) Distribution of each parameter in 2017

Figure 4.8 Distribution of each parameter of the demo section: (a) 2015, (b) 2016, and (c) 2017.

4.4.2 Tests on Plant-Produced Mixtures

4.4.2.1 Mixture collection. Three loose mixtures with different aggregate compositions were collected to evaluate performance and degradation loss based on aggregate type. Two mixtures from the SPR-4332 project in 2019 were used, along with one additional 2023 QA sample. All mixtures had the same NMAS of 9.5 mm and the same PG 76-22 binder. The first mixture contained the highest proportion of dolomite, the second had the highest proportion of steel slag, and the third used only crushed gravel as the coarse aggregate, excluding steel slag and dolomite. The sample IDs were assigned according to each mixture's steel slag and dolomite proportion. Details of the collected mixtures are summarized in Table 4.6.

4.4.2.2 Lab tests on plant-produced mixes

Degradation Test. Three collected mixtures were subjected to degradation tests following the procedures outlined in ITM 220. Gyratory specimens were compacted with a design gyration of 75, as specified in AASHTO T 312. The aggregate degradation loss for each mixture was determined using Equation 4.1.

The results showed that the aggregate degradation loss for S00D00 (with 0% dolomite content) and S52D27 (with 27% dolomite content) was 1.0% and 2.9%, respectively, which met the degradation requirement. In contrast, the aggregate degradation loss for S35D44 (with a high dolomite content of 44%) was 4.2%, which exceeded the required maximum of 3.0% and thus did not meet the degradation criterion.

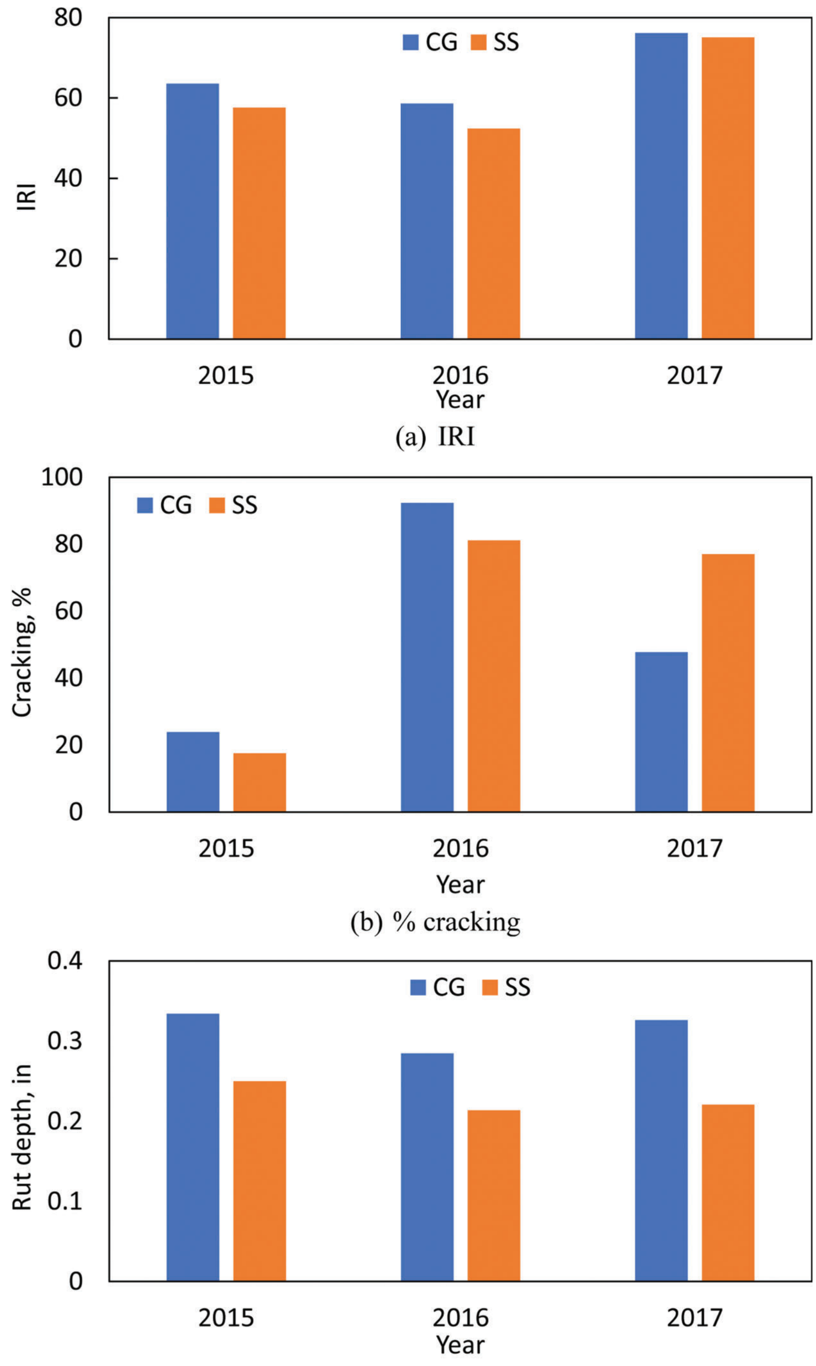
Hamburg Wheel Tracking Test. The Hamburg Wheel Tracking Test (HWTT) was performed according to AASHTO T 324 to evaluate the rutting resistance of the mixtures based on their aggregate combinations. Specimens were prepared to achieve an air void content of 7%, following an air void study for each mixture. The average air void content and rut depths of the test specimens are summarized in Table 4.7, with the rut depth progression shown in Figure 4.11.

The results demonstrated that, after 20,000 passes, the mixture S35D44, which contained the highest dolomite content, exhibited the greatest rut depth at 3.75 mm. However, this value was only 0.64 mm higher than that of S52D27, which had a minor rut depth. Despite the higher dolomite content in S35D44 failing to meet the degradation requirement in the aggregate degradation test, the HWTT results indicated no significant difference in rutting performance compared to the other mixtures.

4.4.3 Tests on Lab-Prepared Mixtures

4.4.3.1 Mixture designs for two extreme cases. Plant-produced mixes used steel slag and dolomite together, although in different proportions, so it is difficult to directly compare the performance differences according to the use of the two aggregates. Two extreme cases were designed to evaluate the performance impact of these materials. One mix utilized only steel slag and crushed gravel as coarse aggregates, excluding dolomite. The other mix was designed using dolomite and crushed gravel without steel slag. Both designs used the same fine aggregates and filler.

As detailed in Table 4.8, the two mix designs shared identical aggregate types and filler proportions, with the key difference being the consistent 48% substitution of steel slag for dolomite or vice versa. To ensure comparable gradation, particles smaller than sieve No. 4 were excluded from steel slag and dolomite. The target steel slag or dolomite proportion of 50% was based on



(a) IRI

(b) % cracking

(c) Rut depth

Figure 4.9 Change in each parameter by year: (a) IRI, (b) percent cracking, and (c) rut depth.

the maximum steel slag and dolomite levels observed in the investigated DMFs, with the final design proportion set at 48%.

Figure 4.12 illustrates the control points and the composite aggregate structure, confirming that the gradation meets the 9.5-mm SMA control limits.

Both mixtures were determined to have the optimal asphalt content (OAC) required to achieve a target air void of 4%. The binder contents for S48D00 and S00D48 were 5.8% and 6.3%, respectively. Despite having the same aggregate structure, this difference in OAC is due to the difference in bulk-specific gravity between steel slag and dolomite.

Therefore, although the binder content, which is the weight ratio, differed between the two mixtures, the effective asphalt content did not show a large difference, at 5.76% and 5.63%. Both mixtures met the minimum void in mineral aggregate (VMA) requirement of 17.0%. Table 4.9 shows the properties according to the mix design results of the two mixtures.

Figure 4.10 INDOT HWTT setup.

4.4.3.2 Lab tests on lab-prepared mixtures

Degradation Test. Degradation tests were conducted using the same procedure with plant-produced samples on two mixtures. The degradation loss of S48D00 was 1.71%, which satisfies the maximum allowable limit of 3.0%. In contrast, the degradation loss of S00D48 was 5.47%, exceeding the requirement due to dolomite's insufficient durability.

Hamburg Wheel Tracking Test. HWTT was performed on two extreme cases to evaluate rutting resistance. The average air voids in the S48D00 and S00D48 specimens were 7.01% and 7.10%, respectively. Despite the notable difference in degradation loss between the two mixtures, this disparity did not significantly influence their rutting performance. As shown in Figure 4.13, the rut depths after 20,000 passes were 4.24 mm for S48D00 and 4.82 mm for S00D48, suggesting that S48D00 exhibited slightly better rutting resistance. However, the difference in rutting performance between the two mixtures was insignificant. Figure 4.10 shows INDOT HWTT setup.

Indirect Tensile Asphalt Cracking Test. IDEAL-CT tests were conducted to assess the cracking performance of the two mixtures. Figure 4.14 presents the loading-displacement curves, while Table 4.10 summarizes the IDEAL-CT results. The steel slag SMA (S48D00) demonstrated a higher peak load than the dolomite SMA (S00D48). However, after reaching the peak load, the steel slag SMA failed more abruptly, attributed to its higher strength. Consequently, the fracture energy of S48D00 was greater than that of S00D48.

In contrast, S00D48 exhibited a gentler slope beyond the peak load, resulting in a slower progression to fracture. As a result, the CTIndex was higher for S00D48 than for S48D00. This suggests that S00D48 had better resistance to cracking despite its lower fracture energy. However, it is essential to note that the IDEAL-CT test has limitations in evaluating cracking performance. Additional research and testing are necessary to assess the cracking resistance of SMA mixtures more accurately.

4.4.4 Correlation Between Performance and Aggregate Types

The test results from both plant-produced and lab-prepared mixtures were analyzed to determine whether there was a correlation between aggregate type and either degradation or rutting performance.

4.4.4.1 Correlation with steel slag. Figure 4.15 illustrates the relationships between steel slag content and degradation and rut depth. As the proportion of steel slag increased, both degradation and rut depth decreased slightly. However, the low R^2 value suggests no significant correlation between steel slag content and the observed performance metrics.

TABLE 4.6
Collected plant-produced mixtures

Design ID	233xxxxxx	192xxx	196xxx
Sample ID	S35D44	S52D27	S00D00
NMAS	9.5-mm	9.5-mm	9.5-mm
PG	76-22	76-22	76-22
% Binder	6.2%	6.0%	6.6%
Dolomite	43.7%	27.0%	0.0%
Steel Slag	35.0%	52.0%	0.0%

TABLE 4.7
Air voids and rut depth of HWTT specimens

Mixture	Average Air Void, %	Rut Depth, mm
S52D27	7.02	3.11
S00D00	7.00	3.26
S35D44	7.06	3.75

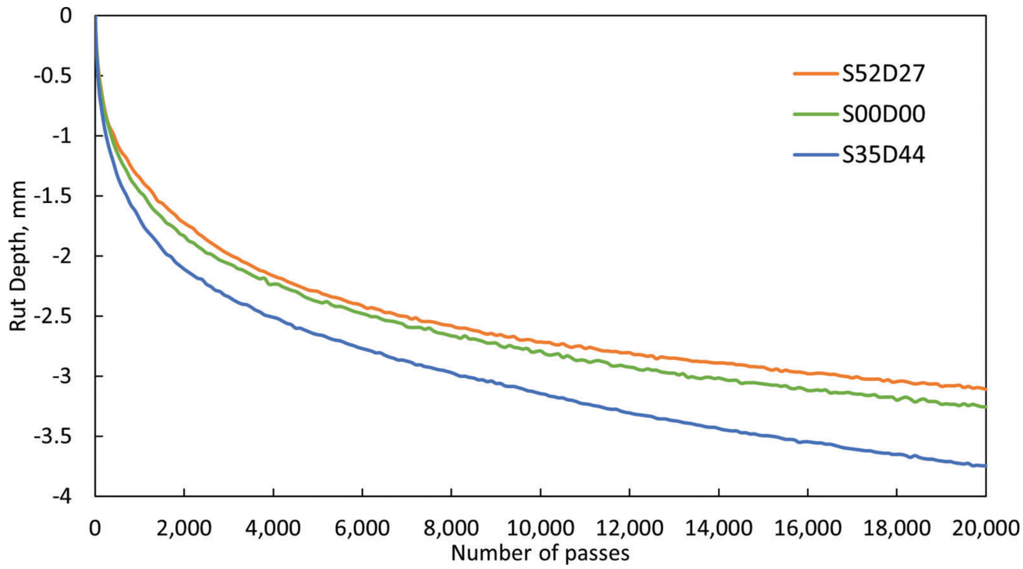


Figure 4.11 HWTT results.

4.4.4.2 Correlation with dolomite. Figure 4.16 depicts the correlation between dolomite content and degradation and between dolomite content and rut depth. A strong correlation was observed between dolomite content and degradation, with an R^2 value of 0.9294, indicating that higher dolomite content significantly increases degradation. Conversely, while rut depth also tended to increase with dolomite content, the correlation was much weaker, with an R^2 value of 0.1328.

4.4.4.3 Recommendations. Based on the test results, dolomites satisfying the LA abrasion loss or Micro-Deval abrasion loss requirements can be used in SMA without proportion restrictions, but the maximum allowable degradation loss limit of 3.0% may limit the proportion of dolomite to 25%. However, even with higher dolomite proportions, the impact on rutting performance appears to be minimal.

4.5 Summary

Field performance and laboratory tests were analyzed to understand better the aggregates used in the Indiana SMA mixtures. The findings are summarized as follows.

Field Performance Evaluation

- A demonstration project comparing the performance of steel slag and crushed gravel SMA revealed no significant difference in the International Roughness Index (IRI).
- While statistical differences in cracking and rutting were observed between steel slag and crushed gravel SMA, these differences were minor.
- Overall, there was no significant correlation between steel slag or dolomite content and field performance.

As the dolomite content increased, the friction number tended to decrease. Notably, a project with the highest dolomite content (47%) in this study was predicted to fail in pavement friction by the 10th year after construction.

Laboratory Tests

- A strong positive correlation was observed between dolomite content and degradation loss; higher dolomite content led to increased degradation.
- No significant correlation was found between dolomite content and performance.
- Steel slag had minimal impact on both degradation loss and performance.
- SMA containing only crushed gravel exhibited low degradation loss and good performance, making it a viable alternative to steel slag.

Key Findings and Recommendations

Chapter 4 provides important insights into coarse aggregate selection for Indiana SMA mixtures. INDOT has strict coarse aggregate requirements, reflecting its commitment to quality. Historically, steel slag and dolomite have been the main choices, but the study showed that crushed gravel can perform similarly to steel slag, expanding options for aggregate selection. Although increasing dolomite content to replace steel slag is possible in terms of the SMA performances, it would require careful consideration of the aggregate toughness (degradation loss) requirements.

TABLE 4.8
The proportions and gradations of each aggregate

Mix Design		Steel Slag or Dolomite	Cr. Gravel	Dolo Sand	QA 16 Filler	Composite	Control Limits	
Proportion, %		**48.0**	**30.0**	**10.0**	**12.0**	**100.0**	**Lower**	**Upper**
Sieve Size	3/4"	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	1/2"	100.0	100.0	100.0	100.0	100.0	99.0	100.0
	3/8"	81.0	94.0	100.0	100.0	89.1	70.0	95.0
	#4	20.0	23.0	97.3	100.0	38.2	30.0	50.0
	#8	0.0	3.2	72.1	100.0	20.2	20.0	30.0
	#16	0.0	1.8	40.3	100.0	16.6	–	21.0
	#30	0.0	1.5	21.7	100.0	14.6	–	18.0
	#50	0.0	1.2	10.3	99.4	13.3	–	15.0
	#100	0.0	1.0	4.4	96.8	12.4	–	–
	#200	0.0	0.8	1.5	67.3	8.5	8.0	12.0

TABLE 4.9
Properties of two mixtures

Design ID		G_{sb}	P_b	P_{be}	G_{mb}	G_{mm}	AV (%)	VMA (%)
S48D00	A	2.977	5.8%	5.53%	2.570	2.686	4.31	18.1
	B	2.977	5.8%	5.53%	2.577	2.686	4.04	17.9
	Ave	–	–	–	–	–	4.18	18.0
S00D48	A	2.721	6.3%	5.63%	2.411	2.506	3.81	17.0
	B	2.721	6.3%	5.63%	2.396	2.506	4.38	17.5
	Ave	–	–	–	–	–	4.09	17.3

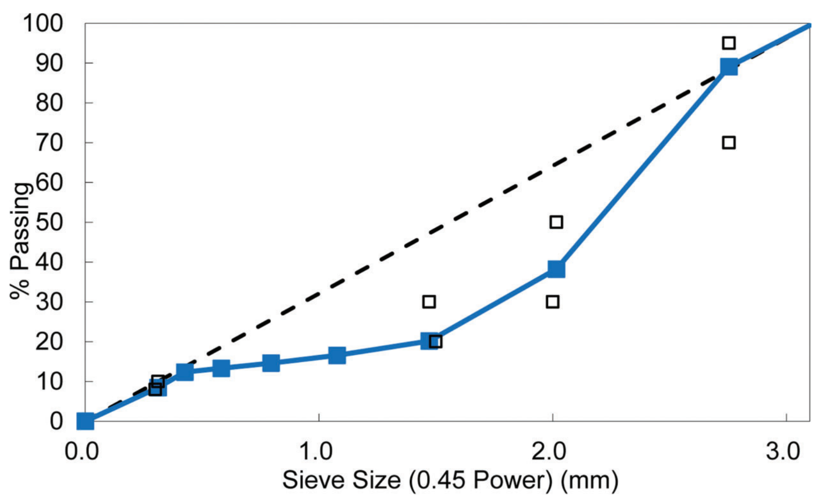


Figure 4.12 Composite aggregate structure of mix design.

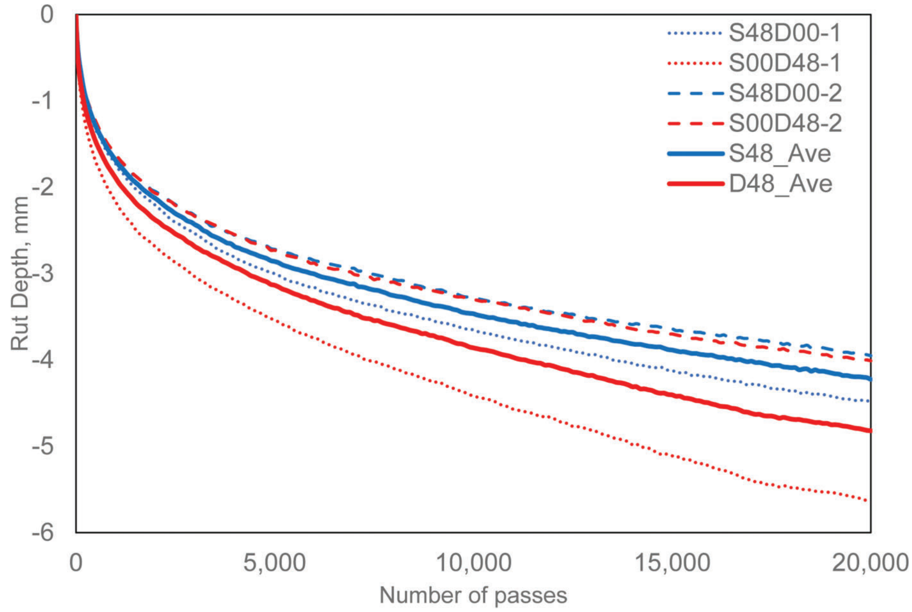


Figure 4.13 HWTT results of two extreme cases.

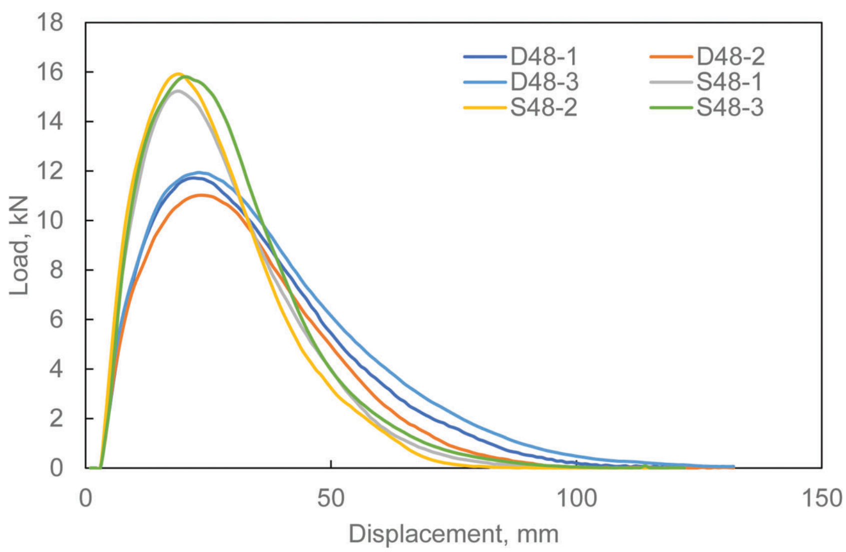


Figure 4.14 Load-displacement curves of IDEAL-CT.

TABLE 4.10
IDEAL-CT results

Mixture							
Mix	**ID**	**Air Voids (%)**	**Tensile Strength (kPa)**	**Displacement (L), mm**	**Fracture Energy (Gf)**	**Slope (S)**	**CTIndex**
S48D00	#1	7.24	1,042.82	2.4	4,610.91	5.96	12.39
	#2	7.37	1,090.19	2.3	4,582.64	6.61	10.72
	#3	6.27	1,081.50	2.6	4,966.35	6.91	12.31
	Ave.	*6.96*	*1,071.51*	*2.4*	*4,719.96*	*6.49*	*11.81*
S00D48	#1	7.33	801.80	3.0	4,599.27	3.35	27.28
	#2	7.30	753.88	3.0	4,106.92	3.69	22.13
	#3	6.49	817.00	3.2	5,085.56	3.40	31.46
	Ave.	*7.04*	*790.89*	*3.0*	*4,597.25*	*3.48*	*26.96*

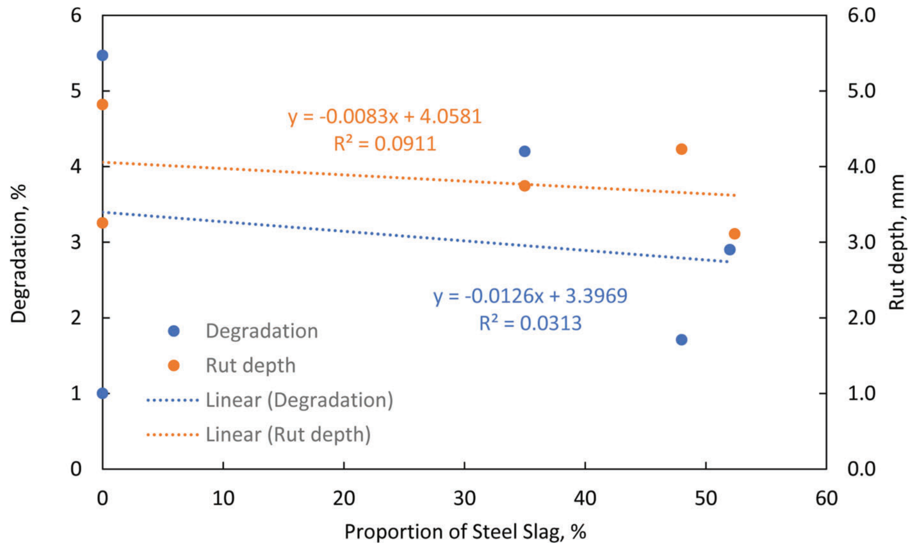


Figure 4.15 Correlation between performance and steel slag.

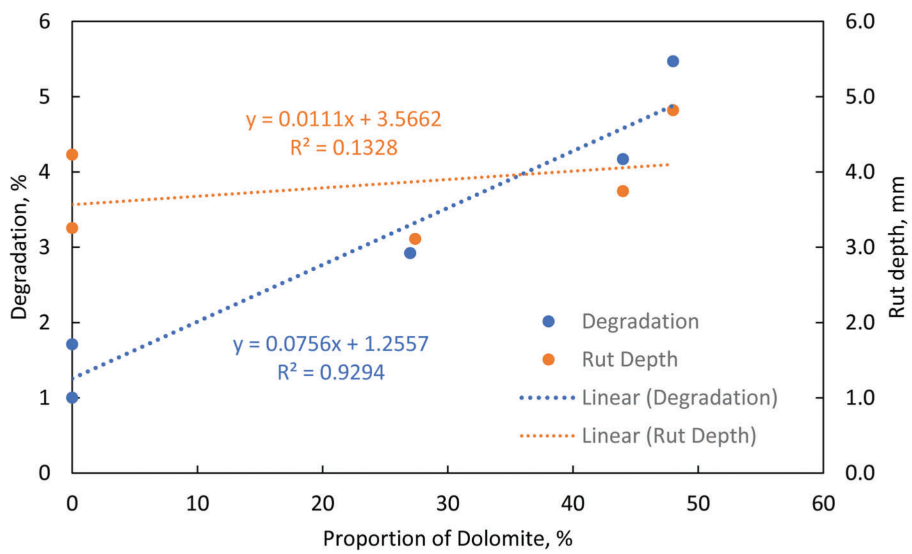


Figure 4.16 Correlation between performance and dolomite.

5. CONCLUSION

This study aimed to evaluate the performance and cost-effectiveness of SMA pavements compared to conventional HMA pavements in Indiana. The research provides insights into optimizing pavement maintenance and rehabilitation strategies by analyzing performance metrics such as the IRI, cracking, and rutting, and conducting a detailed life-cycle cost analysis. The study also aimed at identifying alternative aggregates to reduce reliance on steel slag, a primary material used in Indiana's SMA. The following conclusions were drawn from this study.

5.1 Conclusions

5.1.1 SMA Performance and Cost-Effectiveness Study

- The performance evaluation highlights the superior performance of SMA over HMA on U.S. highways. The significant percentage differences in IRI and cracking demonstrate SMA's enhanced durability and ability to resist deformation and cracking.
- On interstates, the differences are less pronounced but still favor SMA, especially regarding rutting resistance. However, there are instances where SMA demonstrates performance comparable to HMA.

- LCCA results for U.S. highways demonstrate that, despite higher initial construction costs, SMA overlays exhibit superior long-term cost performance relative to HMA. The NPV for SMA was calculated as $112,448 per lane mile, compared to $128,898 per lane mile for HMA, reflecting a 12.58% reduction in lifecycle costs.
- The ROI analysis revealed that SMA overlays yielded a 14.63% ROI over the 29-year analysis period. This economic advantage is primarily attributed to the extended service life of SMA, which delays the need for costly rehabilitation activities, thereby reducing total maintenance expenditures.

5.1.2 SMA Coarse Aggregate Study

- A demonstration project comparing the performance of steel slag and crushed gravel SMA revealed no significant difference in the IRI. While statistical differences in cracking and rutting were observed between steel slag and crushed gravel SMA, these differences were minor.
- Overall, there was no significant correlation between steel slag or dolomite content and field performance. However, the friction number tended to decrease as the dolomite content increased. Notably, a project with the highest dolomite content (47%) in this study was predicted to fail in pavement friction by the 10th year after construction.
- A strong positive correlation was observed between dolomite content and degradation loss; higher dolomite content led to increased degradation. However, no significant correlation was found between dolomite content and performance.
- SMA containing only crushed gravel exhibited low degradation loss and good performance, making it a viable alternative to steel slag

5.2 Recommendations

Based on the results of the studies, recommendations for Indiana SMA are as follows.

- The findings from field performance evaluation underscore the importance of selecting the appropriate material based on road type, traffic conditions, and performance expectations.
- It is recommended that future studies employ probabilistic approaches to complement the deterministic analysis conducted in this research. By incorporating stochastic modeling, future studies can better capture the inherent uncertainties in cost estimates, service life predictions, and traffic demand variations
- Further investigation into the long-term performance of SMA overlays through field validation and performance monitoring is essential.
- Through field performance evaluations and lab validation tests, crushed gravel has been evaluated as a viable replacement for steel slag.
- Although increasing dolomite content to replace steel slag is possible regarding the SMA performances, it would require careful consideration of the degradation requirements. Additionally, further research on the effect of dolomite content on friction is necessary to increase dolomite usage.

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On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

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