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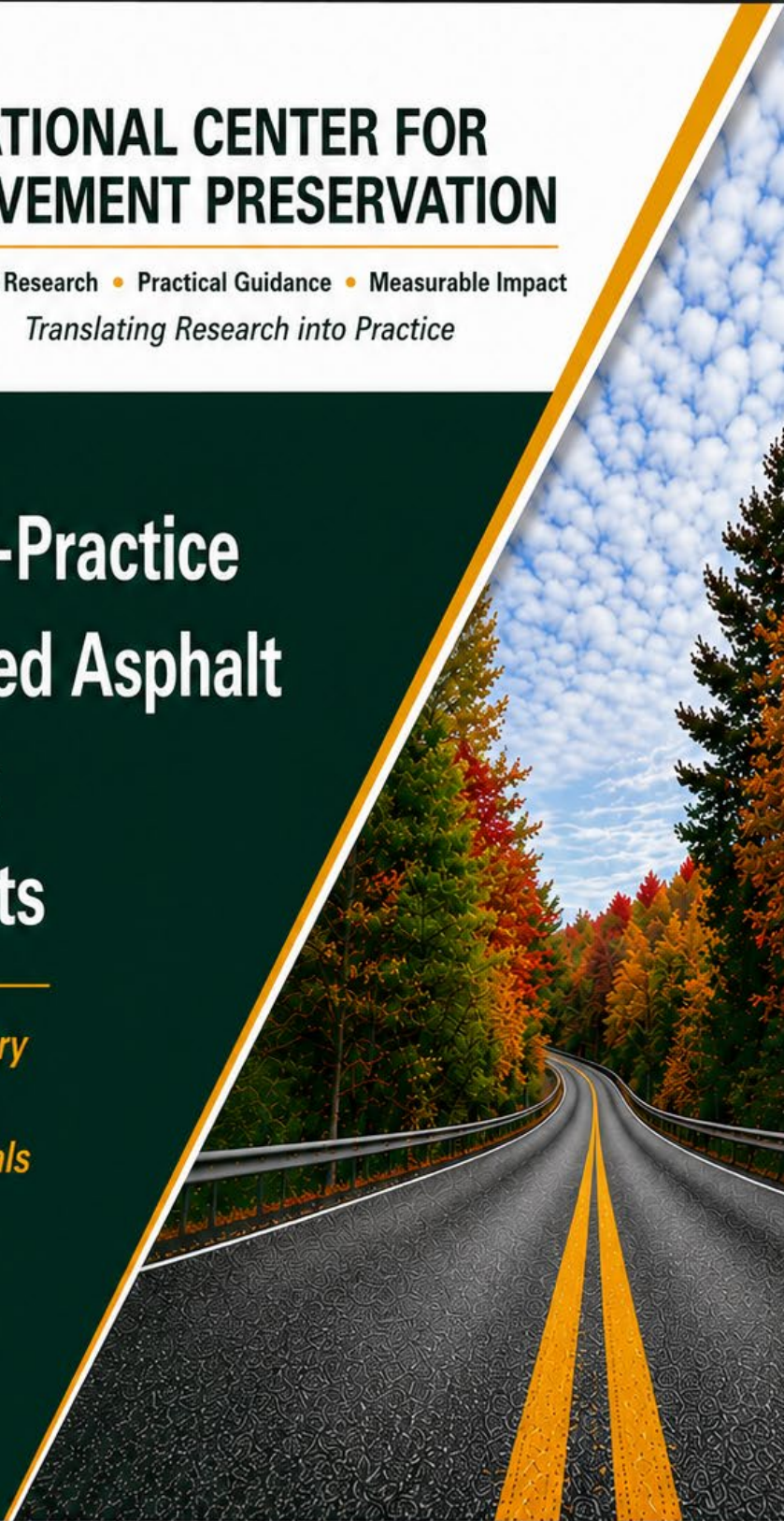
*Translating Research into Practice*

## Economic and State-of-Practice Assessment of Reclaimed Asphalt Pavement in Pavement Preservation Treatments

*A nationwide survey of agency and industry practices combined with a performance-neutral life-cycle cost analysis for chip seals and micro surfacing treatments*



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National Center for Pavement Preservation Report

NCPP Report No. 01-05-26

May 2026



MICHIGAN STATE UNIVERSITY

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## List of Abbreviations and Acronyms

AASHTO.....	American Association of State Highway and Transportation Officials
DOTs.....	State Departments of Transportation
FHWA.....	Federal Highway Administration
HMA.....	Hot Mix Asphalt
LCCA.....	Life-Cycle Cost Analysis
NAPA.....	National Asphalt Pavement Association
NCPP.....	National Center for Pavement Preservation
NCHRP.....	National Cooperative Highway Research Program
NPV.....	Net Present Value
MSU.....	Michigan State University
PI.....	Principal Investigator
RAP.....	Reclaimed Asphalt Pavement
SHRP.....	Strategic Highway Research Program
TRB.....	Transportation Research Board

## Executive Summary

Transportation agencies face increasing pressure to preserve roadway networks under constrained budgets while advancing sustainability, resource-efficiency, and asset-management goals. Reclaimed asphalt pavement (RAP), one of the most widely recycled construction materials, offers a significant opportunity to support these objectives. Although widely used in hot-mix asphalt (HMA), its application in pavement preservation treatments remains limited and inconsistent despite widespread availability and demonstrated technical feasibility.

This study evaluates the implementation status, economic viability, and adoption readiness of RAP in pavement preservation through a nationwide state-of-practice assessment combined with a life-cycle cost analysis (LCCA). Two structured surveys of transportation agencies and industry practitioners were conducted to document current practices, implementation barriers, quality-control procedures, and perceptions regarding RAP use in preservation treatments. Survey findings indicate that RAP implementation remains localized despite favorable practitioner experience, demonstrated technical feasibility, and abundant material availability. Institutional barriers, including limited specification development, concerns regarding material variability, quality-control requirements, and uncertainty regarding long-term performance, were identified as the primary constraints to broader adoption. The findings further indicate that RAP preservation applications have reached a level of technical maturity sufficient to support broader implementation, although institutional frameworks have not evolved at the same pace.

To quantify RAP's economic contribution independent of performance uncertainty, RAP-based and virgin-material treatments were assumed to provide equivalent service life and functional performance. Results indicate that RAP incorporation can reduce life-cycle costs by approximately 6 to 14%, depending on treatment type, with savings driven primarily by aggregate substitution and accumulation across repeated preservation cycles. Sensitivity analysis further demonstrates that RAP maintains its economic advantage unless service-life reductions exceed approximately 16.7%.

Collectively, the findings demonstrate that RAP is a technically feasible and economically advantageous resource for pavement preservation. Broader implementation depends primarily on overcoming institutional rather than technical barriers. In this context, the study provides a conservative and defensible basis for agencies to expand RAP use while improving cost-effectiveness, resource efficiency, and long-term sustainability of pavement preservation programs.

## Practical Applications

The findings provide transportation agencies with a defensible basis for incorporating reclaimed asphalt pavement (RAP) into pavement preservation programs. By isolating the economic effects of material substitution under performance-neutral assumptions, the study demonstrates that cost savings can be achieved without reliance on assumed performance improvements. The results

support specification development, pilot projects, and program-level decision-making for chip seal and micro surfacing applications where aggregate substitution is most applicable. The study also identifies institutional barriers, including specification limitations, quality-control concerns, and limited agency familiarity, as the primary obstacles to broader implementation. Addressing these barriers through targeted guidance, training, and standardized quality-control procedures can facilitate more consistent adoption.

At the network level, the demonstrated cost savings and resilience to performance uncertainty indicate that RAP can improve the efficiency of pavement preservation programs and reduce dependence on virgin aggregates. The findings also suggest that agencies can pursue implementation incrementally through pilot projects and specification refinement while continuing to collect long-term performance data.

**Keywords:** Reclaimed Asphalt Pavement; Pavement Preservation; Life-Cycle Cost Analysis; Chip Seal; Micro Surfacing; Sustainability.

# 1. Introduction

Transportation agencies are increasingly challenged to preserve roadway networks under constrained funding conditions while simultaneously advancing sustainability, resiliency, and resource-efficiency objectives. Rising construction costs, aging infrastructure, and expanding system demands have intensified the need for preservation strategies that maximize infrastructure value and extend pavement service life. Consequently, agencies continue to seek innovative approaches that improve cost-effectiveness and support long-term asset management goals.

Among recycled transportation materials, reclaimed asphalt pavement (RAP) has emerged as one of the most valuable and widely used resources in the pavement industry (*FHWA, 2023*). RAP consists primarily of aggregates coated with aged asphalt binder and is generated through pavement milling, rehabilitation, and reconstruction activities. National estimates indicate that approximately 95 to 101 million tons of RAP are reused annually in the United States, making it one of the most extensively recycled construction materials in the transportation sector (*NAPA, 2023*). Its widespread use has reduced dependence on virgin aggregates and asphalt binder, providing significant economic and environmental benefits (*FHWA, 2023*).

The technical and economic advantages of RAP in hot-mix asphalt (HMA) are well established. Numerous studies have demonstrated that RAP can be incorporated into asphalt mixtures at substantial contents while maintaining acceptable performance when proper processing, mix design, and quality-control procedures are applied (*NCHRP, 2014*). As a result, many transportation agencies have developed specifications and standard practices that support routine RAP use in asphalt paving operations.

In contrast, RAP use in pavement preservation treatments remains comparatively limited. Preservation treatments, such as chip seals and micro surfacing, differ fundamentally from structural HMA layers. They are designed to maintain pavement condition, slow deterioration, and extend service life rather than increasing structural capacity. Because these treatments contain a significant proportion of aggregate and are applied repeatedly throughout a pavement's life cycle, they present a strong opportunity for RAP utilization.

In pavement preservation, RAP functions primarily as a coated aggregate rather than as a significant source of usable asphalt binder (*Copeland, 2011*). Thus, in these instances, its

economic value derives primarily from replacing virgin aggregate and reducing associated materials acquisition and transportation costs. Because preservation treatments are applied several times over the life of a pavement network, even modest reductions in application costs may generate substantial savings over time.

Previous studies demonstrated the technical feasibility of RAP incorporation in preservation treatments and reported satisfactory field performance when appropriate processing and quality control are applied (*Duncan et al., 2020; Rada et al., 2018; Sayeh et al., 2023*). Comparatively, however, little research has focused on quantifying RAP's direct economic contribution independent of performance assumptions. Furthermore, limited information exists regarding nationwide implementation practices, institutional readiness, and barriers affecting broader adoption.

The contrast between widespread RAP availability and limited use in preservation treatments presents a significant opportunity for transportation agencies to improve both resource utilization and program-level cost efficiency. Understanding both the economic implications and implementation challenges associated with RAP incorporation is essential for supporting informed decision-making and wider adoption. Accordingly, this study combines a nationwide state-of-practice assessment with a performance-neutral life-cycle cost analysis (LCCA) to evaluate RAP use in pavement preservation treatments. Specifically, the objectives are to:

- Document current RAP implementation practices in pavement preservation treatments;
- Identify barriers and opportunities influencing adoption;
- Quantify the economic impacts of RAP incorporation under controlled assumptions;
- Evaluate sensitivity to potential service-life reductions; and
- Assess implications for broader implementation and program integration.

Unlike previous studies that primarily focus on technical feasibility and field performance, this study integrates a nationwide state-of-practice assessment with a performance-neutral life-cycle cost framework to isolate RAP's direct economic contribution and evaluate implementation readiness. As such, the study provides a comprehensive assessment of RAP use in pavement preservation programs and establishes a framework for understanding not only whether RAP can be used successfully, but also what factors continue to limit broader

implementation. This distinction is important because the principal challenge appears to be institutional adoption rather than technical feasibility.

## 2. Background

### 2.1 Generation and Processing of RAP

The properties, consistency, and performance of RAP are strongly influenced by how the material is generated, processed, and managed.

RAP is typically produced through milling operations (cold planing), pavement rehabilitation activities, and roadway reconstruction projects. The material consists primarily of aggregates coated with aged asphalt binder and has become an integral component of modern pavement engineering practice.

After removal, RAP is transported to stockpile locations where it undergoes processing. Processing activities may include crushing, screening, fractionation, contaminant removal, moisture control, and stockpile management. These procedures improve material consistency and facilitate compliance with project specifications.

Crushing reduces oversized particles and improves uniformity. Screening separates RAP into controlled size ranges. Fractionation further enhances gradation control by dividing material into multiple stockpiles. These steps are particularly important for applications where consistent aggregate properties are required.

Material consistency is especially critical for preservation treatments, which often require tighter gradation control than conventional HMA mixtures. Effective processing and quality control procedures are essential. Moisture management is also important. Excess moisture affects hauling, handling, and mixture performance. Proper stockpile management practices are therefore necessary to maintain material uniformity and minimize variability.

Because RAP originates from materials that previously satisfied agency specifications, its aggregate element is often of relatively high quality and suitable for reuse in various transportation applications.

### 2.2 RAP in Transportation Infrastructure

Increased RAP utilization aligns with broader transportation industry objectives related to sustainability, resource conservation, and life-cycle asset management. Transportation agencies

are increasingly tasked with maximizing infrastructure durability while minimizing environmental impacts. Recycling reclaimed pavement materials has, therefore, become an essential strategy for achieving these goals.

RAP offers several advantages. Its aggregate component is typically of high quality because it originates from materials that previously satisfied agency specifications. In HMA applications, the residual binder also contributes to mixture performance. These characteristics have contributed to RAP's widespread adoption in asphalt mixtures.

Despite its widespread availability and demonstrated feasibility, RAP use in pavement preservation treatments remains comparatively limited (*Duncan et al., 2020; Sayeh et al., 2023*). This contrast highlights a gap between material supply and practical implementation.

## 2.3 National RAP Availability

RAP is widely available across the United States and continues to accumulate. Ongoing pavement rehabilitation activities generate large quantities each year (NAPA, 2023). In many regions, production exceeds immediate reuse, resulting in substantial stockpiles. Industry surveys indicate that nearly all RAP generated through pavement rehabilitation activities is either reused or retained for future use, with millions of tons remaining in stockpiles nationwide (*NAPA, 2023*). This confirms that material availability is generally not a limiting factor for expanded preservation-treatment applications.

RAP stockpiles are typically located near asphalt plants, contractor facilities, and major transportation corridors. This proximity reduces hauling distances and transportation costs while improving supply-chain resilience. RAP provides a readily available alternative to virgin aggregates in regions where supply is limited or aggregate costs are high.

For preservation treatments, where aggregate represents a significant portion of total cost, RAP availability creates opportunities for cost reduction.

## 2.4 Sustainability Considerations

Although environmental benefits are not incorporated into the economic analysis presented in this study, they provide important context for understanding broader agency interest in RAP utilization. RAP supports transportation-agency sustainability objectives by promoting resource conservation, material reuse, and waste reduction. It also reduces demand for virgin

aggregate production and associated environmental impacts. Additional benefits include reduced land disturbance, lower energy consumption, decreased transportation-related emissions, and improved material-use efficiency. Furthermore, RAP supports circular-economy principles by returning previously used materials to productive applications rather than requiring disposal or long-term stockpiling. Beyond potential cost savings, RAP can contribute to agency goals related to greenhouse-gas reduction, responsible resource stewardship, and sustainable infrastructure management. These benefits further support consideration of RAP as a viable material for pavement preservation applications.

## 2.5 RAP in Hot-Mix Asphalt Applications

In hot-mix asphalt (HMA), RAP functions as both an aggregate and a source of residual binder. Research and field experience show that it can be incorporated at significant levels while maintaining acceptable performance when appropriate mix design and quality-control procedures are applied (*NCHRP, 2014*).

The development of specifications and standardized practices has enabled widespread use across the asphalt industry. However, preservation treatments differ from HMA in both function and material behavior. Therefore, findings from HMA cannot be directly applied without adjustment.

## 2.6 RAP in Pavement Preservation Treatments

As previously stated, pavement preservation treatments are designed to maintain pavement condition, extend service life, and delay more costly rehabilitation or reconstruction activities. Unlike structural overlays, preservation treatments do not substantially increase pavement structural capacity. Instead, they protect the existing pavement, improve surface characteristics, and slow deterioration processes.

In preservation applications, RAP serves primarily as an aggregate replacement material. Unlike HMA mixtures, where RAP contributes both aggregate and residual binder value, preservation treatments derive most RAP-related benefits from aggregate substitution. Consequently, aggregate quality, gradation consistency, cleanliness, and compatibility with binder systems become primary considerations for successful implementation.

Previous investigations have demonstrated that RAP can be successfully incorporated into various preservation treatments when appropriate processing and quality-control procedures are employed (*Duncan et al. 2020; Sayeh et al. 2023*). Reported benefits include satisfactory constructability, acceptable field performance, and reductions in material costs. Nevertheless, implementation remains relatively limited across transportation agencies.

Several factors may contribute to this limited adoption. Concerns regarding material variability, specification development, quality-control requirements, and long-term performance continue to influence agency decision-making. Additionally, many agencies have accumulated extensive experience using RAP in HMA but possess comparatively limited experience with preservation-treatment applications.

The resulting gap between demonstrated feasibility and routine implementation highlights the need for a more comprehensive understanding of current practices, barriers, and economic implications.

## 2.7 Summary of Previous Research

Previous research has examined RAP use in preservation treatments from technical and practical perspectives. Early work by Copeland (2011) documented material characteristics and national practices. Subsequent studies demonstrated feasibility across multiple treatments (*Duncan et al., 2020*) and highlighted preservation effectiveness (*Rada et al., 2018*). More recent work reports favorable field performance under controlled conditions (*Sayeh et al., 2023*).

Collectively, these studies demonstrate that RAP can be successfully incorporated into pavement preservation treatments when appropriate processing and quality-control procedures are employed. However, key gaps remain. Few studies isolate economic impacts independent of performance assumptions, and limited data exist on nationwide implementation practices.

## 2.8 Research Need and Study Context

Existing research has largely focused on the technical feasibility and performance characteristics of RAP in preservation treatments. Previous studies have documented successful implementation, satisfactory constructability, and favorable field performance under controlled conditions (*Copeland 2011; Duncan et al. 2020; Sayeh et al. 2023*), establishing RAP as a technically viable material.

However, several knowledge gaps remain. First, relatively limited information exists regarding nationwide implementation practices, agency perceptions, and barriers influencing adoption. Second, few studies have isolated RAP's economic contribution independent of performance assumptions. As a result, agencies considering RAP implementation often lack a clear understanding of its direct economic value associated with aggregate substitution.

Furthermore, the contrast between widespread RAP availability and limited use in preservation treatments suggests that barriers may be institutional rather than technical. Survey findings indicate that RAP preservation applications are at an intermediate stage of implementation maturity. Technical feasibility has largely been demonstrated through agency experience, pilot projects, and previous research, whereas institutional frameworks have not evolved at the same pace as those supporting RAP use in HMA. This imbalance explains why implementation remains localized despite favorable economic and operational outcomes. Better understanding the relative importance of economic, operational, and organizational factors is therefore essential for supporting broader adoption.

To address these gaps, the present study combines a nationwide state-of-practice assessment with a performance-neutral life-cycle cost analysis. The survey component documents current practices, barriers, and implementation readiness, while the economic analysis isolates RAP's direct contribution by holding performance constant. Together, these components provide a comprehensive framework for evaluating RAP use in pavement preservation programs.

## 2.9 Background Summary

The literature and industry experience reviewed in this chapter indicate that RAP is a technically viable material for pavement preservation applications and is widely available throughout North America. Despite demonstrated feasibility and potential economic benefits, implementation remains limited and inconsistent across agencies. Existing research has focused primarily on material performance and constructability, while comparatively little attention has been given to economic impacts and implementation readiness.

To address these gaps, the following chapters present a nationwide state-of-practice assessment and a performance-neutral life-cycle cost analysis designed to evaluate both the implementation status and economic viability of RAP in pavement preservation programs.

### 3. Description of Pavement Preservation Treatments

Pavement preservation treatments are applied to extend pavement service life, maintain acceptable surface condition, and delay the need for more costly rehabilitation or reconstruction activities. Unlike structural overlays, these treatments are not intended to increase structural capacity. Instead, they protect the underlying pavement, improve surface characteristics, and slow the rate of deterioration. Because they are applied at relatively frequent intervals, their cost-effectiveness depends on both unit cost and consistent performance over time.

Several preservation treatments are available for roadway systems. However, this study focuses on chip seals and micro surfacing. They are among the most widely used preservation techniques and are promising candidates for evaluating RAP incorporation due to their reliance on aggregate properties.

#### 3.1 Chip Seal

Chip sealing is a surface treatment that consists of applying an asphalt emulsion followed by the placement of a uniform layer of crushed aggregate. The process begins with preparation of the existing pavement surface, including cleaning and removal of debris. An emulsified asphalt binder is applied using a distributor truck, followed immediately by the placement of a uniform layer of crushed aggregate. The aggregate, typically with a nominal maximum size of approximately 3/8 inch, is then embedded into the binder using rubber-tired rollers. After curing, excess aggregate is removed by sweeping.

Chip seals provide a protective wearing surface that reduces water infiltration, minimizes oxidation, and protects the pavement from environmental exposure. They also seal existing cracks and improve surface durability (*Choubane et al., 2024*). An additional benefit is improved skid resistance, which enhances roadway safety. Field evaluations have shown that chip seals provide immediate improvement in surface friction characteristics while maintaining stable performance over time when properly applied (*FHWA, 2012*). Figure 1 illustrates a typical chip seal wearing surface.



**Figure 1.** Photographic illustration of a chip seal wearing surface

### 3.2 Micro Surfacing

Micro surfacing is a pavement preservation treatment used to address surface distresses such as raveling, rutting, and cracking (*Choubane et al., 2024*). It can also function as a leveling course. The treatment consists of a mixture of polymer-modified asphalt emulsion, crushed aggregate, mineral filler, water, and additives.

The mixture is produced and placed using specialized equipment that continuously blends and applies the material in a thin, uniform layer. Micro surfacing improves ride quality, restores skid resistance, and corrects minor surface irregularities. It can also be applied in multiple lifts when needed. Figure 2 shows a micro surfacing wearing surface applied to an existing pavement surface.

Compared with chip seals, micro surfacing involves a more complex mixture design and higher material costs due to the use of polymer-modified binders and additives. However, it also provides greater functional improvement in surface characteristics.



**Figure 2.** Photographic illustration of a micro surfacing layer

### 3.3 Relevance to Recycled Materials

Both chip seals and micro surfacing rely heavily on aggregate properties to achieve desired performance. Thus, the use of recycled materials, such as RAP, depends primarily on meeting requirements related to gradation, cleanliness, and compatibility with the binder system.

The characteristics of these treatments make them particularly suitable for evaluating RAP incorporation. When properly processed and controlled, RAP can serve as an effective alternative aggregate source, providing potential economic and logistical advantages without compromising performance. Consequently, because aggregate quality is a primary determinant in treatment performance, chip seals and micro surfacing provide particularly appropriate case studies for evaluating RAP as an aggregate replacement material.

## 4. Nationwide State-of-Practice Assessment

### 4.1 Survey Methodology

To assess the nationwide state of practice for RAP use in pavement preservation treatments, two structured online surveys were developed and distributed. One survey targeted public transportation agencies, including state departments of transportation (DOTs), territorial and provincial agencies, and local governments. The second survey targeted industry

stakeholders, including contractors, suppliers, consultants, and other practitioners involved in pavement preservation activities.

The surveys were designed to collect information on RAP usage, specification requirements, material processing procedures, quality-control practices, implementation drivers, perceived barriers, and overall experience with RAP preservation treatments. Both surveys consisted primarily of structured multiple-choice and categorical-response questions, with optional open-ended responses to capture additional qualitative insights.

The agency-focused survey addressed topics such as RAP specification limits, regional applicability, processing and fractionation requirements, quality control and testing procedures, implementation drivers, and perceived barriers. The industry-focused survey emphasized RAP usage practices, processing procedures, contractor experience, implementation challenges, and satisfaction with project outcomes.

Survey responses were collected electronically and compiled into a centralized database for analysis. Descriptive statistical methods were used to summarize quantitative responses, while qualitative responses were reviewed to identify recurring themes and implementation trends.

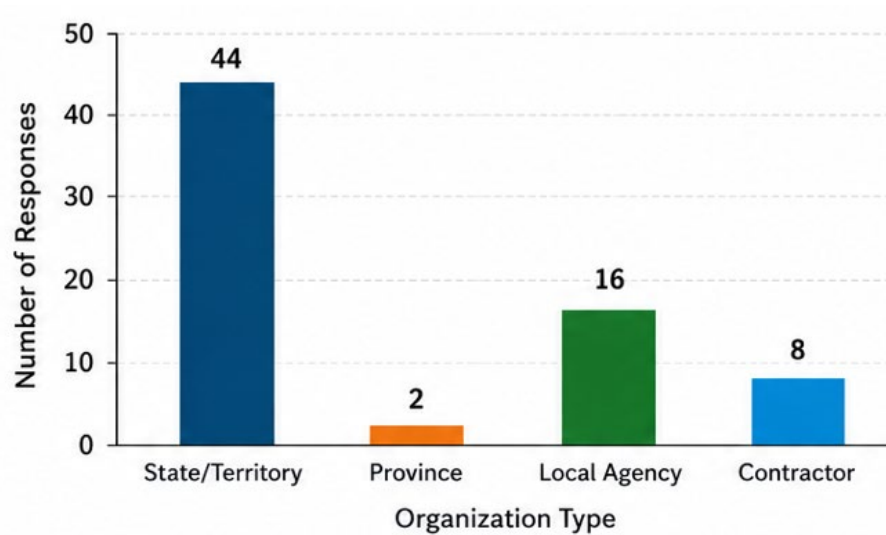
A total of 70 valid responses, representing a broad cross-section of transportation stakeholders, were received and included in the analysis. Although the survey was not intended to establish statistically representative national adoption rates, it provides valuable insight into prevailing practices, implementation challenges, and emerging trends associated with RAP preservation applications.

## 4.2 Survey Respondent Distribution

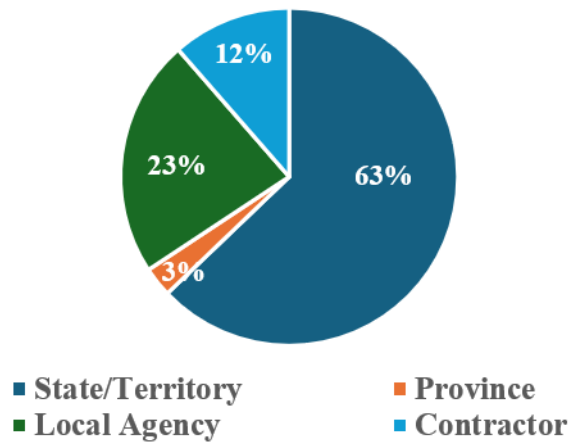
The 70 responses represented a diverse range of transportation organizations across North America. Respondents included state and territorial agencies, provincial agencies, local governments, contractors, and suppliers involved in pavement preservation activities.

State and territorial agencies accounted for the majority of responses, reflecting their central role in specification development and policy implementation. Local agencies constituted the second-largest respondent group, while contractors and suppliers provided important insights on construction practices and field implementation. State agencies typically establish specifications and policy direction, whereas local agencies and contractors often act as early

adopters of innovative practices. Together, these responses capture the perspectives of both policymakers and field practitioners. Figure 3 summarizes the distribution of respondents by organizational category, while Figure 4 illustrates the corresponding percentage distribution.



**Figure 3.** Number of survey responses by organization type (N = 70)



**Figure 4.** Percentage distribution of survey responses by organization type (N = 70)

The geographic distribution of respondents encompassed multiple climatic regions, aggregate supply conditions, and organizational environments. This diversity enhances the applicability of the findings by capturing a broad range of operational contexts. Figure 5 illustrates the geographic distribution of respondents across the United States. Although



Contractor responses supported these observations. Many industry participants reported that RAP preservation projects were initiated by local governments rather than state agencies and that implementation often depended upon agency willingness to consider nontraditional materials.

These findings suggest that adoption remains driven primarily by local innovation and operational flexibility rather than by statewide policy. The pattern is consistent with early stages of technology adoption, where implementation often begins through localized experience before broader institutional acceptance develops. In this regard, RAP preservation applications appear to be following an implementation pathway similar to that observed historically for RAP use in HMA, where local experimentation preceded broader specification acceptance.

Overall, RAP preservation applications remain significantly less mature than RAP use in HMA. While technical feasibility has been demonstrated through field experience and research, institutional acceptance and specification development have not progressed at the same pace.

#### 4.4 Usage Characteristics

Among agencies and contractors currently using RAP in preservation treatments, implementation practices vary but exhibit several common characteristics and trends.

High RAP content was frequently reported for chip seal applications, with several agencies allowing complete replacement of virgin aggregate. Micro surfacing applications demonstrated somewhat greater variability, with agencies reporting both full RAP replacement and blended RAP–virgin aggregate mixtures depending on project requirements and material availability.

Specification requirements generally focused on aggregate quality rather than residual binder characteristics. This finding is consistent with RAP's functional role in preservation treatments, where the material serves primarily as an aggregate substitute.

Requirements for material processing also varied among agencies. Fractionation and additional screening procedures were more commonly required for micro surfacing applications because of the tighter gradation tolerances associated with those mixtures. Chip seal applications generally allowed greater flexibility in processing requirements.

Industry responses indicated substantial variability in crushing, screening, stockpile management, and material-processing practices. This variability contributes directly to

differences in material consistency and may partially explain agency concerns regarding implementation.

Overall, the survey results indicate that RAP preservation practices continue to evolve and have not yet achieved the level of standardization commonly associated with HMA production. The absence of consistent national practices further underscores the need for standardized implementation guidance.

## 4.5 Quality Control and Testing

As expected, survey responses indicate that quality-control programs emphasize aggregate-related properties rather than residual binder characteristics. The most commonly reported quality-control activities include:

- Sieve analysis and gradation verification;
- Sand equivalent testing;
- Durability assessments;
- Soundness testing;
- Moisture monitoring; and
- Visual inspection of processed material.

Binder content testing was reported less frequently, reflecting RAP's limited binder contribution in preservation applications.

Respondents consistently identified material consistency as one of the most important factors affecting constructability and field performance. Moisture control, stockpile management, contamination prevention, and consistent processing procedures were frequently cited as essential implementation practices.

Importantly, survey responses suggest that many quality-control concerns are not attributable to RAP itself but rather to variability in material processing, stockpile management, and production practices. This distinction has important implications because it indicates that many implementation barriers may be addressed through improved specifications, processing requirements, and quality-control guidance rather than through changes in material technology.

## 4.6 Drivers and Constraints

Survey findings consistently indicated that material availability was not the factor limiting RAP implementation. Instead, adoption was influenced primarily by institutional and procedural considerations. The most frequently identified implementation barriers included:

- Lack of standardized specifications;
- Concerns regarding material variability;
- Limited institutional experience;
- Uncertainty regarding long-term performance;
- Quality-control requirements; and
- Limited implementation guidance.

Conversely, respondents identified several important drivers supporting RAP use:

- Cost savings;
- Reduced dependence on virgin aggregates;
- Environmental benefits;
- Material availability; and
- Resource-efficiency objectives.

The coexistence of strong implementation drivers and persistent barriers highlights a recurring theme throughout the survey results. The technical feasibility appears to be generally accepted among experienced users, while institutional acceptance remains comparatively more limited. This observation is particularly significant because it suggests that future implementation efforts should focus on specification development, training, demonstration projects, and knowledge transfer rather than on fundamental material-development research.

## 4.7 Industry Perspective

Industry responses provide an important complement to agency perspectives and offer insight into practical implementation experiences. Contractors and suppliers frequently reported more extensive experience with RAP preservation treatments than is reflected in many agency specifications.

Respondents with direct implementation experience generally reported favorable constructability and satisfactory field performance. Key observations include:

- Construction operations become comparable to conventional treatments once processing and quality-control procedures are established
- Reported challenges relate primarily to material consistency rather than constructability
- Local agencies play a central role in initiating RAP projects and pilot evaluations

Contractors also indicated that local agencies are often more willing than state agencies to evaluate alternative materials and implement pilot projects.

Overall, industry responses were predominantly positive. Reported concerns focused on specification variability, material consistency, and quality-control requirements rather than performance deficiencies. This distinction reinforces the conclusion that institutional barriers represent a greater constraint to implementation than technical feasibility.

## 4.8 Key Survey Findings and Implications

Several important conclusions emerge from the nationwide assessment.

First, RAP preservation applications appear to be at an intermediate stage of implementation maturity. Technical feasibility has largely been demonstrated through agency experience, pilot projects, and previous research. However, institutional frameworks have not evolved to the same extent as those supporting RAP use in HMA. This imbalance helps explain why implementation remains localized despite favorable operational and economic outcomes. In effect, the challenge is no longer determining whether RAP can be used successfully; rather, it is developing the specifications, guidance, quality-control procedures, and institutional confidence necessary for routine implementation.

Second, the findings indicate that broader adoption will depend less on additional proof of constructability and more on improving organizational readiness. Specification refinement, quality-control guidance, training programs, and knowledge transfer appear likely to have a greater influence on future implementation than further demonstrations of technical feasibility.

Finally, the survey results suggest that economic considerations remain a primary motivator for adoption. Quantifying RAP's direct economic contribution therefore represents an essential step toward supporting broader implementation. Accordingly, the following sections present a performance-neutral economic evaluation designed to isolate RAP's economic value independent of performance assumptions.

## 4.9 Survey Limitations

Although the survey provides valuable nationwide insight, several limitations should be considered when interpreting the findings.

- Participation was voluntary and may introduce response bias. Agencies and contractors with RAP experience may have been more likely to participate than those without such experience.
- RAP implementation remains relatively limited, meaning that some responses reflect pilot projects or localized experience rather than mature, long-term programs.
- The number of contractor responses was smaller than the number of agency responses, potentially limiting representation of industry perspectives.
- Implementation practices, specifications, and agency policies continue to evolve as organizations gain experience with RAP preservation treatments.

Despite these limitations, the survey represents one of the most comprehensive assessments currently available regarding RAP use in pavement preservation. The findings identify consistent trends across multiple stakeholder groups and provide valuable insight into implementation practices, barriers, and opportunities. Most importantly, the survey indicates that the principal barriers to broader RAP implementation are institutional rather than technical in nature. This conclusion establishes the context for the economic evaluation presented in the following chapters and provides a foundation for the policy and implementation recommendations developed later in this report.

While the survey findings provide important insight into current implementation practices, barriers, and perceptions regarding RAP preservation treatments, they do not quantify the economic implications of RAP incorporation. To address this gap, the following chapter presents a performance-neutral life-cycle cost analysis designed to isolate the direct economic effects of RAP utilization under a consistent set of assumptions.

## 5. Economic Evaluation Methodology

This study evaluates the economic implications of using RAP in pavement preservation treatments through a performance-neutral LCCA. The primary objective is to isolate the direct

economic effects associated with RAP incorporation while minimizing the influence of performance-related uncertainty.

Life-cycle cost analysis is widely recognized as a systematic framework for comparing competing investment alternatives over a defined analysis period. FHWA guidance recommends LCCA as a decision-support tool for evaluating transportation investments because it accounts for the timing of future expenditures and provides a consistent basis for comparing alternatives (FHWA, 1998). In pavement management applications, LCCA is commonly used to compare treatment strategies, rehabilitation alternatives, and preservation programs.

In the context of RAP preservation treatments, LCCA provides a useful framework for evaluating whether material substitution produces measurable economic benefits. Because long-term field performance data remain limited in many regions, a performance-neutral approach was selected to isolate RAP's direct economic contribution independent of assumptions regarding future pavement performance.

## 5.1 Analytical Framework

A performance-neutral LCCA framework was adopted to evaluate the direct economic contribution of RAP incorporation in pavement preservation treatments. The framework was specifically designed to isolate material-substitution effects while minimizing uncertainty associated with long-term performance variability.

Under the performance-neutral framework, RAP-based and virgin-aggregate treatments were assumed to provide equivalent service life, treatment timing, maintenance requirements, and functional performance. Hence, any observed differences in life-cycle cost are attributable solely to differences in treatment cost. As such, this framework provides a consistent basis for evaluating economic performance across treatment categories. This approach was selected for three primary reasons.

First, available research generally indicates that RAP can be incorporated successfully into pavement preservation treatments when appropriate processing and quality-control procedures are applied (*Duncan et al., 2020; Sayeh et al., 2023*). However, the long-term performance data remain limited relative to traditional pavement materials.

Second, agencies often hesitate to adopt emerging practices when economic benefits depend upon uncertain performance assumptions. A performance-neutral framework avoids this concern by evaluating RAP solely on the basis of measurable cost differences.

Third, the approach provides a conservative estimate of RAP’s economic value. Any future performance improvements associated with RAP would increase the economic benefit beyond the values reported herein.

The analysis focuses on two commonly used pavement preservation treatments: (1) Chip seals and (2) Micro surfacing. These treatments were selected because they represent mature preservation technologies, rely heavily on aggregate materials, and have received the greatest attention in previous RAP preservation research.

For each treatment type, costs were compared between conventional treatments using virgin aggregates and alternative treatments incorporating RAP.

Net present value (NPV) was used as the primary economic evaluation metric, consistent with FHWA LCCA guidance (*FHWA, 1998*). It converts all future treatment costs into present-day values and sums them, allowing consistent comparison of alternatives over the analysis period.

The general NPV formulation for preservation treatments is given by:

$$NPV = \sum_{t=0}^n \frac{C_{pres,t} + C_{maint,t}}{(1 + r)^t} \quad (1)$$

where:

- $C_{pres,t}$  = preservation treatment costs at year  $t$
- $C_{maint,t}$  = maintenance costs at year  $t$
- $r$  = discount rate
- $t$  = analysis year
- $n$  = analysis period

Under the performance-neutral assumption, RAP and virgin-aggregate alternatives are assumed to have identical maintenance requirements, service lives, treatment schedules, and residual values. As such, maintenance-related cost differences are eliminated, allowing the analysis to focus exclusively on preservation-treatment costs.

Under the performance-neutral assumption, Equation (1) simplifies to:

$$NPV = \sum_{t=0}^n \frac{C_{pres,t}}{(1+r)^t} \quad (2)$$

The life-cycle cost differential between virgin-aggregate and RAP-based treatments is therefore expressed as:

$$\Delta NPV = (C_{init}^V - C_{init}^R) \sum_{t=0}^n \frac{1}{(1+r)^t} \quad (3)$$

where:

- $C_{init}^V$  = initial treatment cost using virgin aggregate
- $C_{init}^R$  = initial treatment cost using RAP aggregate

Equation (3) isolates RAP's direct economic contribution by focusing exclusively on treatment-cost differences and avoiding uncertainty associated with performance modeling. Consequently, it provides a conservative lower-bound estimate of RAP's economic value in pavement preservation applications.

## 5.2 Cost Components

The economic evaluation considered the principal cost components associated with RAP use in pavement preservation treatments. These costs were grouped into three categories:

1. **Material-Related Costs:** These costs include activities necessary to prepare RAP for use and deliver it to the project site. These activities include:
  - Crushing;
  - Screening;
  - Fractionation;
  - Stockpile management;
  - Moisture control;
  - Transportation; and
  - Quality-control testing.

Because RAP functions primarily as an aggregate replacement in preservation treatments, these costs represent the most significant sources of economic differentiation between RAP and conventional alternatives.

**2. Production-Related Costs:** These costs may include:

- Mix-design modifications;
- Plant operational adjustments;
- Additives or rejuvenators;
- Additional energy consumption; and
- Material handling requirements.

These costs vary considerably among facilities and geographic regions.

**3. Construction-Related Costs:** These costs may include:

- Workability adjustments;
- Additional rolling operations;
- Inspection requirements;
- Contractor learning-curve effects; and
- Operational modifications during placement.

These costs are often project-specific and may vary substantially based on contractor experience and local conditions.

Although numerous cost categories were identified, only those with reliable and quantifiable cost differences were incorporated into the LCCA. Production- and construction-related costs exhibit considerable variability and lack sufficient nationally representative data for consistent quantification. Including highly uncertain values could introduce analytical bias and reduce transparency. Consequently, the analysis focuses on cost components that can be reasonably estimated and consistently applied across treatment types. This approach is consistent with FHWA guidance emphasizing treatment-specific cost differences and transparent analytical assumptions (*FHWA, 1998*). The resulting methodology intentionally produces conservative estimates of RAP-related savings.

### 5.3 Aggregate Cost Assumptions

Contractor interviews, agency discussions, and published preservation-treatment cost breakdowns indicate that virgin aggregate typically represents a substantial component of total treatment cost in both chip seal and micro surfacing applications. Based on the available information, the aggregate component was conservatively estimated to represent approximately 20% of total treatment cost for both chip seal and micro surfacing applications. Although

aggregate cost shares can vary among agencies and regions, sensitivity reviews conducted during the development of this analysis indicated that reasonable variations in aggregate cost proportion primarily affect the magnitude of savings rather than the direction of the economic results. Consequently, the selected value provides a practical and sufficiently robust basis for comparative evaluation.

Because RAP functions primarily as an aggregate substitute in pavement preservation treatments, aggregate-related costs represent the principal driver of the economic advantage identified in this study. Consequently, variations in the aggregate cost share would influence the magnitude of the resulting cost savings. However, such variations would not alter the overall direction of the results, whereby RAP-based treatments consistently exhibit lower life-cycle costs under the assumptions considered.

The magnitude of potential savings is influenced by several interrelated factors, including aggregate market prices, RAP processing costs, hauling distance, material availability, and stockpile location. In particular, regions with high aggregate costs or limited local supply are more likely to experience greater economic benefits from RAP incorporation, while regions with abundant and inexpensive aggregate resources may observe comparatively smaller cost differentials.

These factors were incorporated into the economic analysis through representative assumptions developed from agency input, contractor experience, and available industry data. The resulting framework provides a transparent and conservative basis for evaluating the economic implications of RAP use while maintaining applicability across a broad range of pavement preservation conditions.

## 5.4 Key Assumptions and Input Parameters

The analysis is conducted over a defined evaluation period reflecting typical pavement preservation planning horizons. Treatments are applied at regular intervals based on assumed service life and the number of applications is a key factor influencing cumulative cost. By maintaining consistent service-life assumptions between RAP-based and conventional treatments, cost comparisons isolate differences in initial and recurring treatment costs.

The assumptions reflect typical pavement preservation programs, with the analysis period allowing multiple treatment cycles at intervals based on commonly reported service lives.

Table 1 summarizes the key assumptions and input parameters used throughout the life-cycle cost analysis. These values establish the baseline conditions used for comparing RAP-based and conventional preservation treatments and provide the foundation for the economic results presented in Chapter 6. They were selected to reflect typical pavement preservation practice and were reviewed through discussions with contractors and agency personnel experienced in RAP chip seal and micro surfacing applications.

**Table 1.** Summary of key economic analysis assumptions and input parameters

Parameter	Value / Description
Analysis Period	20 years
Discount Rate	4%
Micro Surfacing Treatment Interval	8 years
Chip Seal Treatment Interval	6 years
Aggregate Application Rate	20 lb/yd <sup>2</sup> (for both treatments)
Average RAP Hauling Distance	30 miles
RAP Processing Cost	\$0.10/yd <sup>2</sup>
Aggregate Share of Total Cost	20%
Amount of Aggregate Replacement	100% (equivalent volumetric basis)
RAP Binder Contribution Assumption	None
Performance Assumption	Equal

The assumption of full aggregate replacement was selected to isolate RAP’s maximum practical contribution as an aggregate substitute and does not imply universal feasibility across all agency specifications or project conditions. No binder credit was assigned because RAP contributes minimal effective binder value in preservation-treatment applications.

The equal-performance assumption ensures that differences in life-cycle cost are attributable solely to economic factors rather than uncertainties associated with treatment performance.

## 5.5 Sensitivity Analysis

Because long-term field performance remains an important consideration for agencies evaluating RAP implementation, a sensitivity analysis was conducted to assess the effect of reduced service life on economic outcomes. The objective was to identify the threshold at which RAP-based treatments would lose their economic advantage. This approach evaluates economic

resilience rather than attempting to predict future performance. Specifically, the sensitivity analysis examines:

- Incremental reductions in service life;
- Additional treatment-cycle requirements; and
- Break-even conditions under adverse performance assumptions.

The sensitivity analysis methodology is presented in detail in Chapter 7. The analysis evaluates the degree of service-life reduction required to eliminate the economic advantage associated with RAP incorporation and provides an indication of the robustness of the life-cycle cost results under less favorable performance assumptions.

## 5.6 Relationship to Survey Findings

The economic analysis was developed in conjunction with the survey findings presented in Section 4. Survey responses identified cost savings as a primary motivation for RAP implementation while also highlighting uncertainty related to specifications, material variability, and long-term performance.

The performance-neutral LCCA addresses performance-related uncertainty by evaluating RAP under controlled assumptions that eliminate variability, allowing economic effects to be assessed independently of implementation challenges.

The survey characterizes current practices, implementation barriers, and institutional readiness, while the LCCA quantifies the economic effects of RAP incorporation. Together, they provide complementary perspectives on the opportunities and constraints associated with broader RAP utilization in pavement preservation programs.

## 5.7 Methodological Considerations

The performance-neutral life-cycle cost analysis (LCCA) framework adopted in this study was intentionally designed to isolate the direct economic effects associated with RAP incorporation in pavement preservation treatments. By holding service life, maintenance requirements, treatment timing, and functional performance constant between RAP-based and conventional alternatives, the analysis focuses exclusively on measurable differences in treatment costs. This approach minimizes uncertainty associated with long-term performance prediction and provides a transparent basis for evaluating RAP's economic contribution.

Several methodological considerations define the scope and interpretation of the economic analysis.

First, the analysis evaluates RAP primarily as an aggregate replacement material and does not assign economic value to potential residual binder contributions. This assumption is consistent with the functional role of RAP in chip seal and micro surfacing applications and results in a conservative estimate of economic benefit.

Second, the cost assumptions used in the analysis were developed to represent typical pavement preservation conditions and were informed by agency input, contractor experience, and published industry information. Actual project costs may vary according to local aggregate availability, hauling distances, processing requirements, labor rates, market conditions, and agency specifications. Consequently, the results should be interpreted as representative rather than universally applicable to all jurisdictions.

Third, several potentially relevant cost factors were not explicitly quantified due to limited availability of consistent nationwide data. These include contractor learning-curve effects, facility-specific production adjustments, regional operational efficiencies, and project-specific constructability considerations. Excluding these factors improves analytical transparency and reproducibility while avoiding the introduction of highly uncertain cost estimates.

Finally, the analysis does not monetize environmental or sustainability benefits associated with RAP utilization. Potential reductions in virgin aggregate consumption, energy use, material transportation, greenhouse-gas emissions, and resource depletion may provide additional value beyond the direct economic benefits quantified in this study. As a result, the reported life-cycle savings should be viewed as conservative estimates that reflect only the direct economic impacts associated with material substitution.

These methodological considerations do not diminish the value of the analysis. Together, they establish the analytical boundaries of the study while maintaining transparency, reproducibility, and consistency with the objective of isolating RAP's direct economic contribution to pavement preservation treatments. Broader study limitations, including survey-related considerations and long-term performance uncertainties, are discussed in Section 10.

## 5.8 Economic Evaluation Methodology Summary

This chapter presented the economic evaluation methodology used to assess the direct economic implications of RAP incorporation in pavement preservation treatments. A performance-neutral life-cycle cost analysis framework was adopted to isolate material-related cost effects while minimizing uncertainty associated with long-term performance variability. Key assumptions, cost components, and analytical parameters were defined, and the relationship between the economic evaluation and survey findings was established. The resulting framework provides the analytical foundation for the life-cycle cost results presented in Chapter 6 and the service-life sensitivity analysis presented in Chapter 7.

## 6. Economic Analysis Results

### 6.1 Overview

LCCA quantifies the economic implications of incorporating RAP into pavement preservation treatments. Under the performance-neutral framework described in Section 5, RAP-based and conventional treatments are assumed to provide equivalent service life and functional performance. Accordingly, all cost differences identified in the analysis are attributable solely to material-related cost factors rather than differences in treatment effectiveness or longevity.

The analysis focused on chip seal and micro surfacing because these treatments represent two of the most widely implemented pavement preservation strategies and depend heavily on aggregate materials. Since aggregate constitutes a significant portion of treatment cost, these applications provide an appropriate basis for evaluating the economic effects of RAP substitution.

The methodology evaluates RAP under a range of reasonable assumptions and intentionally excludes potential environmental benefits, network-level sustainability impacts, and speculative performance enhancements. Therefore, the resulting savings represent conservative estimates of RAP's economic value and establish a lower-bound assessment of potential financial benefits.

Results for chip seal and micro surfacing applications are presented separately and then synthesized to identify broader economic implications for pavement preservation programs.

## 6.2 Economic Analysis Results for Chip Seals

Replacing virgin aggregate with RAP reduces dependence on newly produced aggregate materials and lowers aggregate acquisition costs. Because chip seals are applied relatively frequently throughout a pavement's life cycle, even modest reductions in treatment cost can generate meaningful cumulative savings.

Conventional chip seals were evaluated using an assumed unit cost of approximately \$3.00/yd<sup>2</sup>. For a standard 12-foot-wide lane-mile, this corresponds to an initial treatment cost of approximately \$21,120. Assuming a six-year treatment interval over a 20-year analysis period and applying a 4% discount rate, the resulting NPV is approximately \$61,438 per lane-mile (Equation 2).

For RAP-based chip seals, replacing the virgin aggregate component (approximately 20% of total cost) reduces the base treatment cost from about \$3.00/yd<sup>2</sup> to \$2.40/yd<sup>2</sup>. Additional costs include approximately \$0.10/yd<sup>2</sup> for processing and crushing and about \$0.069/yd<sup>2</sup> for hauling (based on a unit hauling cost of \$0.23/ton-mile and an average hauling distance of 30 miles), resulting in a total treatment cost of about \$2.57/yd<sup>2</sup>. Table 2 summarizes RAP cost adjustments for chip seal.

**Table 2.** Summary of RAP cost adjustments for chip seal

<b>Cost Component</b>	<b>Estimated Cost (per yd<sup>2</sup>)</b>
Base treatment cost after aggregate replacement	\$2.40
RAP processing	\$0.10
RAP hauling	\$0.069
Additional field adjustments	minimal
<b>Total RAP treatment cost</b>	<b>\$2.57</b>

This corresponds to an initial treatment cost of approximately \$18,086 per lane-mile and an NPV of approximately \$52,611 per lane-mile over the analysis period. The subsequent life-cycle savings are approximately \$8,827 per lane-mile, representing a 14.4% reduction relative to conventional chip seals. Because treatment intervals remain unchanged under the performance-neutral framework, these savings happen during each treatment cycle. Consequently, the

economic benefits accumulate throughout the analysis period without requiring modifications to preservation schedules or asset-management strategies.

The findings indicate that RAP can significantly improve the economic efficiency of chip seal programs while maintaining equivalent treatment frequency and expected performance.

### 6.3 Economic Analysis Results for Micro Surfacing

Micro surfacing involves a more complex material system than chip seals because it incorporates polymer-modified emulsions, mineral fillers, additives, and specialized mixture-design requirements. These additional components increase overall treatment cost and reduce the relative influence of aggregate costs. Nevertheless, aggregate remains a meaningful cost component and therefore presents opportunities for cost reduction through RAP incorporation.

Conventional micro surfacing was evaluated using an assumed cost of approximately \$5.00/yd<sup>2</sup>. This corresponds to an initial treatment cost of approximately \$35,200 per lane-mile for a typical 12-ft-wide lane. Under an eight-year treatment interval and a 20-year analysis period, the resulting NPV is approximately \$79,728 per lane-mile.

For RAP-based micro surfacing, virgin aggregate substitution reduces the base treatment cost to approximately \$4.00/yd<sup>2</sup>. Additional RAP-related costs include processing and crushing costs of approximately \$0.10/yd<sup>2</sup>, hauling of approximately \$0.069/yd<sup>2</sup>, and field adjustment (consisting mainly of additional roller compaction) costs estimated at approximately \$0.50/yd<sup>2</sup>. Incorporating these components yields a total unit cost of approximately \$4.67/yd<sup>2</sup>. Table 3 summarizes RAP cost adjustments for micro surfacing.

**Table 3.** Summary of RAP cost adjustments for micro surfacing

<b>Cost Component</b>	<b>Estimated Cost (per yd<sup>2</sup>)</b>
Base treatment cost after aggregate replacement	\$4.00
RAP processing	\$0.10
RAP hauling	\$0.069
Additional field adjustments	\$0.50
<b>Total RAP treatment cost</b>	<b>\$4.67</b>

This unit cost results in an initial treatment cost of approximately \$32,870 per lane-mile and an NPV of approximately \$74,450 per lane-mile. The life-cycle savings are estimated to be

approximately \$5,278 per lane-mile, representing a 6.6% reduction relative to conventional micro surfacing.

Although percentage savings are lower than those observed for chip seals, the overall fundamental trend remains: RAP incorporation reduces treatment costs while preserving the existing treatment schedule and level of performance.

These findings indicate that the economic advantages of RAP are not limited to a single preservation treatment type but extend across multiple categories of preservation applications. RAP incorporation therefore represents a viable cost-reduction strategy.

## 6.4 Summary of LCCA Results

Table 4 summarizes life-cycle costs and savings associated with RAP incorporation for both preservation treatments.

**Table 4.** Summary of LCCA economic analysis results

Aggregate Type	Micro Surfacing			Chip Seal		
	NPV, per Lane-Mile	Savings, \$	Savings, %	NPV, per Lane-Mile	Savings, \$	Savings, %
Virgin	\$79,728.00	\$5,278	6.6	\$61,438	\$8,827	14.4
RAP	\$74,450.00			\$52,611		

The results demonstrate that RAP incorporation consistently reduces life-cycle costs across both preservation treatments evaluated. Under the performance-neutral framework, RAP-based alternatives produce lower net present values while maintaining identical treatment schedules and service-life assumptions. Consequently, the observed savings are attributable solely to material-related cost reductions rather than assumed performance improvements.

The magnitude of savings varies between treatment types. Chip seals exhibit larger percentage savings because aggregate represents a larger share of total treatment cost and because treatments occur more frequently over the analysis period. Micro surfacing exhibits smaller percentage reductions because treatment costs are distributed across additional components, including polymer-modified emulsions, mineral fillers, and additives. Nevertheless, both treatments demonstrate meaningful reductions in life-cycle cost.

The consistency of these findings across two distinct preservation treatments strengthens confidence in the conclusion that RAP can improve the economic efficiency of pavement

preservation programs. More importantly, because service life and treatment intervals are held constant throughout the analysis, the economic benefits identified herein reflect direct cost reductions associated with aggregate substitution rather than assumptions regarding enhanced performance.

## 6.5 Interpretation of LCCA Results

The LCCA shows that RAP generates measurable cost savings independent of performance assumptions. Because service life and treatment effectiveness are held constant throughout the analysis, observed cost differences arise solely from material-related factors.

This approach isolates RAP's economic contribution and provides a conservative baseline for evaluation. Savings result solely from replacing virgin aggregate with recycled material, independent of performance assumptions.

Unlike previous studies that primarily emphasize constructability and performance, the present analysis demonstrates that RAP provides value even when performance is assumed to be equivalent. This distinction is important because it allows agencies to evaluate RAP based on material substitution alone, independent of performance uncertainty.

Because preservation treatments are applied cyclically, modest cost reductions accumulate over time. Accordingly, the reported savings should be viewed as conservative, lower-bound estimates of RAP's economic contribution. Any future performance benefits, operational efficiencies, or environmental advantages associated with RAP utilization would further improve its overall value proposition.

## 6.6 Sources of Economic Benefits

The economic benefits associated with RAP incorporation are driven primarily by aggregate substitution and the resulting reduction in material acquisition costs. Several related factors contribute to these savings, including:

- Reduced demand for virgin aggregate;
- Utilization of existing RAP stockpiles;
- Lower aggregate acquisition costs;
- Potential reductions in transportation requirements; and
- Increased reliance on locally available materials.

These factors are consistent with previous research identifying aggregate substitution as the main driver of RAP-related economic value in pavement preservation (*Copeland, 2011; Duncan et al., 2020*).

Unlike HMA applications, where RAP contributes both aggregate and residual binder value, pavement preservation treatments derive most economic benefits from aggregate replacement. Consequently, local aggregate prices, RAP availability, and transportation logistics are likely to be significant determinants of project-level outcomes.

Survey findings presented in Section 4 support this conclusion, with agencies consistently identifying cost savings and material availability as primary motivations for RAP implementation. The alignment between survey responses and analytical results reinforces confidence in the economic relationships identified through the LCCA.

## 6.7 Program-Level Implications

Although project-level savings may appear modest on a per-lane-mile basis, preservation programs frequently encompass hundreds or thousands of lane-miles over extended planning horizons. As a result, relatively small reductions in treatment costs can accumulate into substantial long-term savings at program-level.

Agencies managing extensive chip seal or micro surfacing networks may realize significant cumulative benefits over a 20-year planning period. These savings can be reinvested in additional preservation activities, used to address deferred maintenance needs, or allocated to other asset-management priorities.

For agencies operating under constrained budgets, improved cost efficiency increases the number of lane-miles that can be treated using available funding. Expanded preservation coverage may, in turn, delay more costly rehabilitation or reconstruction activities and improve overall network condition.

From an asset-management perspective, RAP incorporation provides benefits that extend beyond individual projects by improving network-level cost efficiency, expanding preservation coverage, and supporting more effective allocation of limited transportation resources.

## 6.8 Comparison of LCCA Results with Survey Findings

The economic analysis was developed in conjunction with the survey findings presented in Section 4. Survey responses identified cost savings as a primary motivation for RAP implementation while also highlighting concerns regarding specifications, material variability, and long-term performance.

The performance-neutral LCCA addresses these concerns by evaluating RAP under controlled assumptions that remove performance-related uncertainty, allowing economic effects to be assessed independently of implementation challenges.

The survey characterizes current practices, implementation barriers, and institutional readiness, whereas the LCCA quantifies the economic consequences of RAP incorporation. Together, they provide a more comprehensive assessment of the opportunities and constraints associated with broader RAP use in pavement preservation programs.

The combined findings reveal a noteworthy disconnect between economic potential and current implementation practice. Agencies and contractors frequently identified cost savings as a primary motivation for RAP use, yet implementation remains relatively limited. The LCCA demonstrates that these perceived economic benefits are supported by quantifiable life-cycle savings under conservative assumptions. This agreement between practitioner experience and analytical results increases confidence in RAP's economic viability and suggests that uncertainty regarding economic performance is largely unwarranted.

Importantly, the LCCA confirms that RAP can provide measurable economic benefits under conservative assumptions. Consequently, the principal barriers to broader implementation appear to be institutional rather than economic in nature. These barriers include specification development, quality-control procedures, implementation guidance, and agency familiarity with RAP preservation applications.

## 6.9 Summary of Key Findings

The LCCA yields several important findings:

- RAP incorporation reduces life-cycle costs for both chip seal and micro surfacing applications.
- Cost savings are achieved without assuming improved performance or extended service life.

- Aggregate substitution is the primary driver of economic benefit.
- Program-level savings can become substantial when applied across large preservation networks.
- Economic findings align closely with practitioner perceptions reported in the survey.

Collectively, these findings demonstrate that RAP can improve economic efficiency while supporting more effective utilization of available preservation funding.

## 6.10 Economic Analysis Summary

The economic analysis demonstrates that RAP incorporation reduces life-cycle costs for both chip seal and micro surfacing treatments under a range of reasonable assumptions. Because service life and treatment performance were held constant throughout the analysis, the observed savings are attributable solely to material-related cost reductions associated with aggregate substitution.

The findings indicate that RAP can improve economic efficiency at both the project and program levels while maintaining existing preservation schedules. When considered alongside the survey results, the analysis suggests that economic feasibility is not a primary constraint to broader implementation. Instead, the principal barriers appear to be institutional and operational in nature.

While the LCCA establishes the economic viability of RAP under equal-performance assumptions, uncertainty regarding long-term treatment performance remains an important consideration for agencies. Therefore, the following chapter evaluates the sensitivity of the economic results to reductions in service life and other performance-related uncertainties.

## 7. Service-Life Sensitivity Analysis

The performance-neutral life-cycle cost analysis (LCCA) presented in Chapter 6 demonstrated a clear economic advantage associated with the incorporation of reclaimed asphalt pavement (RAP) into pavement preservation treatments. However, transportation agencies frequently express concerns regarding potential differences in long-term field performance, including treatment durability, service life, and variability in RAP material characteristics. These concerns remain among the primary barriers to broader implementation.

To address this uncertainty, a sensitivity analysis was conducted to evaluate the degree of service-life reduction required to eliminate this economic advantage. Rather than assuming perfect performance equivalence, the analysis identifies the threshold at which reduced service life necessitates additional treatment applications within the 20-year analysis period, thereby offsetting the cost savings identified in the LCCA. This approach provides a practical measure of the robustness of the economic findings and supports agency decision-making under conditions of performance uncertainty.

## 7.1 Analytical Approach

The sensitivity analysis adopts a threshold-based framework focused primarily on treatment-cycle timing rather than detailed deterioration modeling. Under this framework, the principal evaluation is conducted by determining whether reduced service life results in an additional treatment cycle within the 20-year analysis period. Because the economic advantage of RAP is derived from reduced treatment costs under equivalent performance assumptions, this advantage is maintained unless reduced service life necessitates an additional treatment application within the analysis period. Accordingly, the cycle-based threshold condition serves as the primary measure of economic resilience and forms the basis of the sensitivity analysis presented in this chapter.

To complement this approach, a simplified economic relationship is introduced to provide secondary validation of the threshold results. Under this formulation, RAP remains economically advantageous as long as the present value of its cost savings exceeds the discounted cost of any additional treatment required due to reduced service life. The governing economic threshold condition is expressed as:

$$\frac{C_R}{(1+r)^t} = \Delta NPV \quad (4)$$

where:

- $C_R$  = cost of an additional RAP treatment
- $r$  = discount rate
- $t$  = timing of the additional RAP treatment
- $\Delta NPV$  = life-cycle savings under equal-performance assumptions

This relationship defines the point at which the cost of an additional treatment cycle offsets the economic advantage associated with RAP. In parallel, a treatment-cycle threshold analysis is used to determine whether an additional RAP treatment would occur within the 20-year analysis period. Together, these approaches provide complementary measures of economic resilience and allow the robustness of RAP-related cost savings to be evaluated under progressively less favorable performance assumptions.

## 7.2 Micro Surfacing Sensitivity

Under the baseline analysis, conventional micro surfacing treatments are applied at Years 0, 8, and 16 within the 20-year analysis period. Under the equal-performance assumption, RAP-based micro surfacing follows the same treatment schedule as the conventional alternative. The economic advantage of RAP would be diminished only if a shorter service life caused an additional treatment application to be required before the end of the analysis period.

Let  $L_{RAP}$  represent the service life of the RAP-based micro surfacing treatment. The condition for an additional RAP treatment cycle within the 20-year analysis period is given by:

$$3L_{RAP} < 20 \quad (5)$$

Solving for the threshold service life yields:

$$L_{RAP} < \frac{20}{3} \approx 6.7 \text{ years}$$

Relative to the conventional service life of 8 years, this corresponds to a service-life reduction of approximately 16.7%.

This threshold-based result indicates that RAP-based micro surfacing retains its economic advantage unless service life decreases by approximately 16.7%. Such a reduction exceeds most performance differences reported in the preservation-treatment literature and represents a substantial departure from the equal-performance assumption used in the LCCA. Therefore, moderate variations in field performance are unlikely to eliminate the economic benefits associated with RAP incorporation.

### 7.2.1 Economic Validation of Micro Surfacing Sensitivity

As an independent secondary validation of the cycle-based threshold analysis, the economic relationship introduced in Section 7.1 may be evaluated using the life-cycle cost values developed in Chapter 6.

Using:

$$C_R = \$32,870 \text{ per lane-mile}$$

$$r = 4.0\%$$

$$\Delta NPV = \$5,278 \text{ per lane-mile}$$

Substituting these values into Equation (4) gives:

$$\frac{32,870}{(1.04)^t} = 5,278$$

Solving for the timing  $t$  of the additional treatment yields:

$$t = \frac{\ln(32,870/5,278)}{\ln(1.04)} = 46.6 \text{ years}$$

Because the additional treatment would occur well beyond the 20-year analysis period, the economic advantage remains robust within the study horizon. This result confirms that moderate reductions in service life would not materially alter the favorable economic outcome identified for RAP-based micro surfacing.

### 7.3 Chip Seal Sensitivity

For conventional chip seals, treatments are assumed to occur at Years 0, 6, 12, and 18 within the 20-year analysis period. As with micro surfacing, RAP-based chip seals follow the same schedule under equal-performance conditions.

Under the threshold-based framework, RAP chip seals would lose their economic advantage only if reduced service life results in an additional treatment cycle within the analysis period.

Let  $L_{RAP}$  represent the RAP chip seal service life. The condition for an additional RAP treatment cycle within the analysis period is given by:

$$4L_{RAP} < 20 \quad (6)$$

Solving for the threshold service life yields:

$$L_{RAP} < \frac{20}{4} = 5.0 \text{ years}$$

Relative to the conventional six-year service life, this threshold corresponds to a service-life reduction of approximately 16.7%. This level of reduction is comparatively large relative to typical variations reported in practice, indicating that RAP-based treatments are likely to remain economically favorable under realistic field conditions.

### 7.3.1 Economic Validation of Chip Seal Sensitivity

As an independent secondary validation of the cycle-based threshold analysis, the economic relationship presented in Section 7.1 may be evaluated using the life-cycle cost values developed in Chapter 6.

Using:

$$C_R = \$18,086 \text{ per lane-mile}$$

$$r = 4.0\%$$

$$\Delta NPV = \$8,827 \text{ per lane-mile}$$

Substituting these values into Equation (4) yields:

$$\frac{18,086}{(1.04)^t} = 8,827$$

Solving for the timing  $t$  of the additional treatment yields:

$$t = \frac{\ln (18,086/8,827)}{\ln (1.04)} = 18.4 \text{ years}$$

This result indicates that an additional treatment occurring before approximately Year 18.4 would eliminate the economic advantage. Because the cycle-based threshold predicts an additional treatment only when service life falls below approximately 5 years, resulting in a treatment near Year 20, both approaches produce consistent conclusions regarding the robustness of RAP's economic advantage.

## 7.4 Interpretation of Sensitivity Analysis

The sensitivity analysis demonstrates that RAP incorporation remains economically favorable under realistic performance uncertainty when evaluated using the threshold-based framework. For both micro surfacing and chip seal treatments, service-life reductions of approximately 16.7% are required before the economic advantage is eliminated. These thresholds correspond to the point at which an additional treatment cycle would be required within the 20-year analysis period.

These thresholds exceed most performance differences reported in available literature and agency experience, indicating that the economic advantage associated with RAP does not depend on strict equivalence in service life. Even under moderately reduced performance conditions, RAP-based treatments remain economically favorable within the analysis period.

From an implementation perspective, these findings indicate that performance uncertainty alone is unlikely to eliminate RAP's economic advantage. Consequently, concerns regarding long-term performance should be evaluated within the context of RAP's demonstrated economic resilience rather than viewed as independent barriers to implementation.

Collectively, the findings indicate that the economic advantage identified in Chapter 6 is not highly sensitive to realistic reductions in treatment longevity and therefore provides a robust basis for evaluating RAP implementation in pavement preservation programs.

## 7.5 Additional Sensitivity Considerations

Although service life is the primary uncertainty evaluated, several additional factors may influence the economic performance of RAP preservation treatments:

- RAP hauling distance;
- Virgin aggregate price escalation;
- RAP processing costs;
- Discount rate variability;
- Regional material availability;
- Contractor experience and operational efficiency;
- Material quality and consistency; and
- Changes in construction market conditions.

Among these factors, aggregate pricing and hauling distance are expected to have the greatest influence on project-level economics. Regions with limited aggregate supply or high transportation costs may experience greater economic advantage from RAP incorporation because aggregate replacement represents the primary source of economic benefit identified in this study.

Similarly, contractor familiarity with RAP processing, stockpile management, and construction practices may influence production efficiency and implementation costs. As agency and contractor experience increases, operational efficiencies may improve, potentially enhancing the economic benefits reported herein.

Regional variations in material availability and processing infrastructure may also influence project-level outcomes. Areas with established RAP processing facilities and readily

available stockpiles may realize lower implementation costs than regions where RAP must be transported longer distances or undergo additional processing.

Future analyses incorporating regional cost variability, environmental life-cycle impacts, agency-specific cost structures, and long-term field-performance datasets would provide additional insight into the economic sensitivity of RAP preservation strategies under varying operating conditions. Such analyses would further strengthen understanding of how local conditions influence the magnitude of RAP-related economic advantages.

## 7.6 Service-Life Sensitivity Analysis Summary

The sensitivity analysis confirms that RAP-based preservation treatments maintain their economic advantage under a broad range of plausible performance scenarios. For both micro surfacing and chip seal applications, substantial reductions in service life, approximately 16.7%, are required before the economic advantage is eliminated.

These findings reinforce the conclusions of the LCCA and indicate that RAP represents a robust economic option for pavement preservation. When considered alongside the broader results of this study, the analysis suggests that performance uncertainty and economic risk are not primary barriers to implementation. More importantly, the results demonstrate that the economic benefits associated with RAP incorporation remain resilient even under adverse performance assumptions. This strengthens the overall conclusion that barriers to broader implementation are more likely institutional and organizational in nature than economic or technical. Consequently, future implementation efforts may be more effectively directed toward specification development, implementation guidance, quality-control standardization, demonstration projects, and agency education than toward additional studies focused solely on economic justification.

## 8. Discussion

The combined survey findings and economic analyses reveal a clear disconnect between RAP availability and its use in pavement preservation programs. Despite widespread availability, demonstrated technical feasibility, and measurable economic benefits, RAP remains underutilized across much of the transportation industry.

The survey results suggest that RAP preservation applications occupy an intermediate stage of implementation maturity. Technical feasibility has largely been demonstrated through research and field experience. However, institutional frameworks have not advanced at a comparable pace. This imbalance helps explain why implementation remains localized despite favorable economic and operational outcomes.

The findings suggest that the central question is no longer whether RAP can be used successfully in preservation treatments. Rather, the challenge lies in developing the specifications, guidance documents, quality-control procedures, and institutional confidence necessary for routine implementation.

The economic analysis reinforces this conclusion. Under conservative assumptions, RAP consistently reduces life-cycle costs across both treatment categories. Because the analysis excludes speculative performance benefits, the reported savings provide a defensible economic foundation for implementation.

The sensitivity analysis further strengthens the economic case. RAP remains economically advantageous even under scenarios involving moderate reductions in service life. This demonstrates that the observed benefits are not dependent on perfect performance equivalence and remain resilient under a broad range of realistic field conditions.

Taken together, the survey and economic findings indicate that future implementation efforts should focus less on demonstrating feasibility and more on facilitating institutional adoption. Priority areas include:

- Development of standardized specifications;
- Expanded agency guidance;
- Improved quality-control procedures;
- Demonstration projects;
- Knowledge transfer initiatives; and
- Long-term field performance monitoring.

Advancement in these areas would help bridge the gap between technical capability and routine implementation.

## 9. Policy and Implementation Implications

The findings of this study indicate that RAP can be incorporated into pavement preservation programs with relatively low economic risk under conservative assumptions. Because the analysis isolates material-related cost effects and excludes speculative performance benefits, the reported savings represent a robust baseline estimate. This provides agencies with a defensible economic foundation for considering broader RAP use.

From a policy perspective, expanding RAP implementation requires institutional adjustments. The results show that current constraints arise primarily from specification limitations, variability concerns, and uncertainty regarding long-term field performance. Addressing these barriers is essential to enabling wider adoption.

A key implication is the need for greater flexibility in specification development. Rigid or overly conservative specifications can limit the ability of agencies and contractors to incorporate RAP effectively. Performance-based or guidance-oriented specifications allow for controlled implementation while accommodating regional material variability and operational conditions.

Pilot and phased implementation strategies provide an effective pathway for adoption. These approaches allow agencies to evaluate RAP performance under local conditions. Over time, successful pilot applications can support the transition to standardized practices.

Training and knowledge transfer are also critical. Survey results indicate that limited familiarity contributes significantly to adoption barriers. Targeted training programs, technical guidance, and peer exchange can improve understanding of RAP behavior, quality-control requirements, and construction practices.

Agencies should also consider integrating RAP into broader pavement management and material resource planning strategies. Rather than treating RAP as a supplemental material, it can be incorporated systematically to improve resource efficiency, reduce dependence on virgin aggregates, and enhance long-term cost performance.

From an economic standpoint, the benefits of RAP increase at the network level due to repeated treatment cycles. Even modest reductions in unit costs can generate substantial cumulative savings across large roadway systems. This reinforces RAP's value as a strategic material within preservation program planning.

In addition to economic benefits, expanded RAP utilization supports broader sustainability objectives. These include reduced demand for virgin aggregates, lower transportation requirements, improved material efficiency, and diversion of recyclable materials from waste streams.

Overall, the findings indicate that the primary pathway to broader RAP adoption lies in addressing institutional constraints. By improving specifications, expanding training, supporting pilot projects, and integrating RAP into program-level planning, agencies can transition from limited use to more systematic and effective implementation in pavement preservation programs.

## 10. Study Limitations

As with any statewide or nationwide assessment, the findings of this study should be interpreted within the context of several limitations associated with data availability, analytical assumptions, and current implementation experience.

First, the economic analysis was intentionally developed using a performance-neutral framework that assumes equivalent service life, functional performance, and maintenance requirements for RAP-based and conventional preservation treatments. This assumption was adopted to isolate the direct economic effects of material substitution and eliminate uncertainty associated with long-term performance variability. Although this approach provides a conservative and transparent evaluation of RAP's economic contribution, actual field performance may vary depending on material characteristics, processing methods, climatic conditions, traffic loading, and construction quality. Consequently, project-specific economic outcomes may differ from those reported herein.

Second, the analysis focuses primarily on material-related cost factors and does not explicitly quantify variability associated with contractor experience, operational efficiency, constructability, production rates, or RAP material heterogeneity. These factors may influence both project costs and field performance and could contribute to regional differences in implementation outcomes.

Third, environmental and sustainability benefits were not monetized within the life-cycle cost framework. Potential benefits such as reductions in greenhouse-gas emissions, decreased aggregate extraction, lower energy consumption, reduced hauling requirements, and improved resource conservation were acknowledged qualitatively but were not incorporated into the

economic calculations. As a result, the reported cost savings likely underestimate the full societal value associated with RAP utilization.

Fourth, regional economic variability was not explicitly modeled. Aggregate prices, RAP availability, hauling distances, processing costs, labor rates, and market conditions can vary substantially across geographic regions. While the assumptions used in this study were selected to represent reasonable and broadly applicable conditions, agencies may experience economic outcomes that differ from those presented in the analysis.

Fifth, although the survey provides one of the most comprehensive assessments currently available regarding RAP use in pavement preservation treatments, participation was voluntary and therefore subject to potential response bias. Agencies and contractors with RAP experience may have been more likely to participate than organizations without such experience. In addition, some responses reflected pilot projects or localized implementation efforts rather than mature, long-term preservation programs. Accordingly, the survey findings should be interpreted as indicative of prevailing practices, perceptions, and trends rather than statistically representative measures of national adoption rates.

Finally, long-term field performance data for RAP preservation treatments remain relatively limited compared with the extensive body of knowledge available for RAP use in hot-mix asphalt applications. Although available research and practitioner experience generally report satisfactory performance, continued monitoring of field projects is needed to strengthen understanding of long-term durability, treatment effectiveness, and network-level impacts under diverse operating conditions.

Despite these limitations, the study provides a robust and conservative evaluation of RAP implementation in pavement preservation. By combining nationwide survey findings with a performance-neutral economic framework, the research establishes a defensible baseline for assessing RAP's economic value while identifying the institutional, operational, and policy factors that currently influence broader adoption. Future research incorporating long-term performance datasets, agency-specific cost structures, environmental life-cycle assessments, and regional implementation case studies would further strengthen the foundation for expanding RAP use in pavement preservation programs.

## 11. Conclusions

This study combined a nationwide state-of-practice assessment with a performance-neutral life-cycle cost analysis to evaluate the economic and implementation implications of RAP in pavement preservation treatments. The analysis provides a conservative basis for assessing RAP's cost-effectiveness and implementation potential while offering a comprehensive understanding of current practices, economic performance, and barriers to broader adoption.

Survey results indicate that RAP use in pavement preservation remains limited and uneven despite widespread availability and generally favorable practitioner experience. Adoption is more common at the local level, whereas relatively few state agencies have established formal specifications or standardized implementation procedures. These patterns reflect the absence of consistent institutional frameworks to support broader implementation.

The economic analysis demonstrates that RAP incorporation produces measurable life-cycle cost savings of approximately 6 to 14 percent. These savings arise primarily from aggregate substitution and accumulate through repeated treatment cycles. Because the analysis excludes speculative performance benefits, the results represent conservative estimates of RAP's economic value.

Sensitivity analysis further shows that RAP's economic advantages are robust. Substantial reductions in service life would be required before cost savings are eliminated, indicating that moderate performance uncertainty does not undermine the economic justification for RAP implementation.

The results indicate that RAP preservation applications have progressed beyond the proof-of-concept stage. Technical feasibility is well established through agency experience, field

implementation, and prior research. The remaining challenge lies in advancing institutional readiness, specifically through specification development, quality-control standardization, implementation guidance, and increased agency familiarity.

From a program-level perspective, RAP represents a strategic opportunity to improve the efficiency of pavement preservation systems. Because preservation treatments are applied repeatedly across large roadway networks, cost savings are amplified over time, enhancing both fiscal performance and resource utilization. Although not explicitly quantified, broader RAP utilization also supports sustainability objectives through reduced demand for virgin materials and improved material efficiency.

Overall, RAP is a technically feasible and economically advantageous resource for pavement preservation. Its limited use reflects institutional barriers rather than material limitations. Advancing specifications, expanding training, supporting pilot projects, and integrating RAP into preservation planning provide a practical pathway toward broader implementation. The findings demonstrate that expanding RAP use represents a low-risk, high-value opportunity to improve the cost-effectiveness, resource efficiency, and sustainability of pavement preservation programs.

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