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Integrating the Flexible Pavement Life Cycle

First Edition

NATIONAL ACADEMIES *Sciences Engineering Medicine*

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Integrating the Flexible Pavement Life Cycle

First Edition

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Introduction

Workshop 1009 on Integrating the Flexible Pavement Life Cycle was held at the 101st Annual Meeting of the Transportation Research Board (TRB) in January 2022. This e-circular was generated by the TRB Standing Committee on Design and Rehabilitation of Asphalt Pavements (AKP30), with contributions from the following committees in a supporting role:

- Standing Committee on Asphalt Materials Selection and Mix Design (AKM30);
- Standing Committee on Asphalt Mixture Evaluation and Performance (AKM40);
- Standing Committee on Pavement Preservation (AKT20);
- Standing Committee on Pavement Maintenance (AKT30); and
- Subcommittee on Sustainable and Resilient Pavements (AKP00).

Organization

This workshop was presented in four sections. The first section (Chapter 1: Background) provided an overview of the performance-engineered pavements (PEPs) and sustainable pavements initiatives supported by the Federal Highway Administration (FHWA). The next section (Chapter 2: Structural Design and Construction of Perpetual Asphalt Pavements) provided three presentations highlighting the various design stages in the life cycle of a flexible pavement: the material design stage, the structural design stage, and the management and use stage. The third section (Chapter 3: Materials Selection and Design for Long-Life Asphalt Pavements) included several questions that were posed to the live audience (and small virtual audience online) during a breakout session. The final portion of the workshop (Chapter 4: Life Stage: Preservation, Maintenance, Economics, and Environmental Impact) included a facilitated panel discussion from a group of experts invited to share their collective insight on how best to integrate design stages of the pavement life-cycle design processes. Comments documented from the interactive activities are recorded in the final section (Chapter 5: Current Activities and Readily Implementable Technologies and Processes).

In Chapter 6: Moving Forward, following a brief introduction by the session moderator that highlighted national initiatives and terms related to the flexible pavement life cycle, the first speaker, David Timm, presented the state of the practice in structural design, including construction. This was followed by presentations by Kevin Hall and Andrew Braham who highlighted different aspects of material selection (including production) and pavement preservation and maintenance [including life-cycle cost analysis (LCCA) and life-cycle assessment (LCA)], respectively. Participants in the workshop were divided into four groups (three in-person and one virtual) and provided with prompts to examine topics, such as current opportunities to better integrate stages of the pavement life cycle; types of practices or tools that can be immediately implemented for LCCA or LCA; identification of challenges in advancing more integrated LCCA or LCA practices in flexible pavements; and consensus on the major gaps and needs faced by pavement engineers in more holistically addressing flexible pavement life. A panel of five experts, Amy Epps-Martin, Dominique Pittenger, Silvia Caro, Barry Paye, and David Peshkin then provided their perspectives on aspects of the same topics and suggested paths forward for the pavement community at-large.

This e-circular provides a synopsis of the workshop by including key slides along with a synthesis of the points delivered by each of the three presenters, a summary of the breakout discussions, a summary of the panel discussion, and a final reflection by the authors of this e-circular. As mentioned above, comments and questions from attendees were collected and included. The material included in this e-circular provides a valuable reference and a reminder that there is value in understanding the hurdles in the wide-spread adoption or use of pavement LCA and how to overcome them through synthesizing research and activities in the pavement structural design, pavement material selection, and pavement service life areas.

The purpose of this publication is to provide a reference document for existing practices and ideas for furthering efforts of integrating the pavement life-cycle design stages for flexible pavements and fostering improved communications and organization among those who are involved in the overall flexible pavement community.

CHAPTER 1

Background

Traditionally, research and analysis of asphalt pavements have been siloed into pavement structural design, pavement material selection, and pavement service life. There has been relatively little discussion about the importance of synthesizing these three areas. However, the concept of perpetual pavements brings together the first two concepts by requiring very specific material behavior at different layers of the pavement structure. In addition, the pavement preservation and maintenance industry has long understood the importance of keeping the surface of a pavement structure at a high level of quality. In order to achieve a truly perpetual pavement and potentially minimize life-cycle economic costs and environmental impacts, the pavement structural design and material design must also be integrated with pavement preservation and maintenance decisions. We will refer to this as integrating the pavement life cycle.

Concept of Pavement Life Cycle

The concept of the life cycle, as defined for pavements, was the starting point for discussion in the workshop. One effective visual for describing the life cycle of pavements is captured in Figure 1.1 [University of California Pavement Research Center (UCPRC), 2010]. The challenge for the flexible pavement community is to overcome the barriers that separate each of the life-cycle stages, or the dashed lines as shown in Figure 1.1, to enable more holistic LCCA and LCA of flexible pavements.

Barriers to Applying the Life-Cycle Thinking in Pavements

There are current activities, technologies, and processes in practice that address both pre-installation (e.g., perpetual pavements) and post-installation (e.g., pavement preservation and maintenance) of flexible pavements, as seen in Figure 1.2. However, for the most part, these are treated as independent efforts in the majority of agency practice and research applications. It was discussed in the workshop that integration of these efforts will foster coordinated implementation of the pavement life cycle which can lead to improved pavement service lives. Specifically, when talking about pavement preservation, treatments can be sorted into two categories: treatments that address issues with the pavement surface and treatments that address issues with the pavement structure. In theory, a pavement’s service life can be extended significantly if surface treatments are applied at the proper timing in order to prevent additional structural issues.

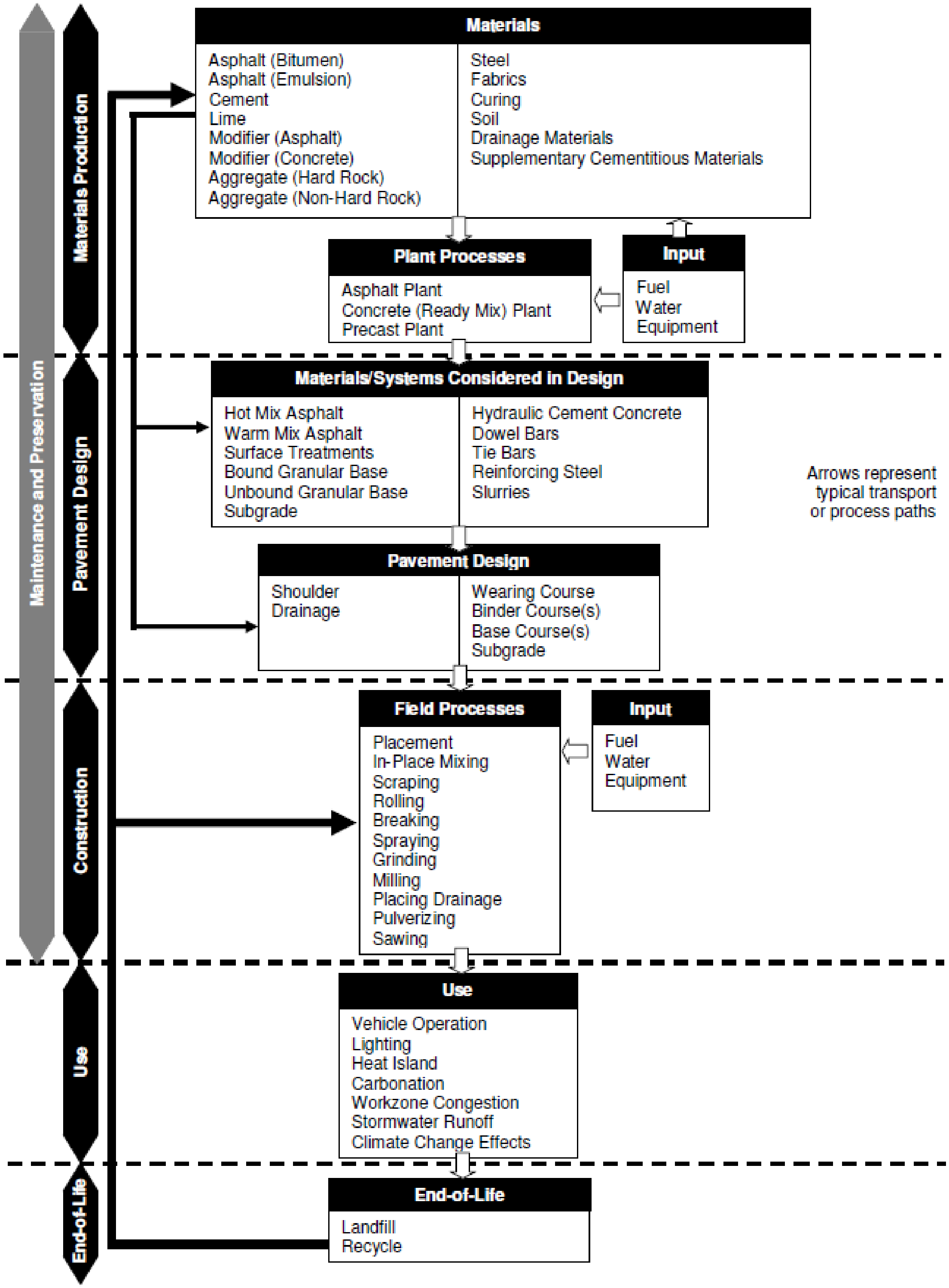

Figure 1.1 Pavement life-cycle stages (UCPRC, 2010).

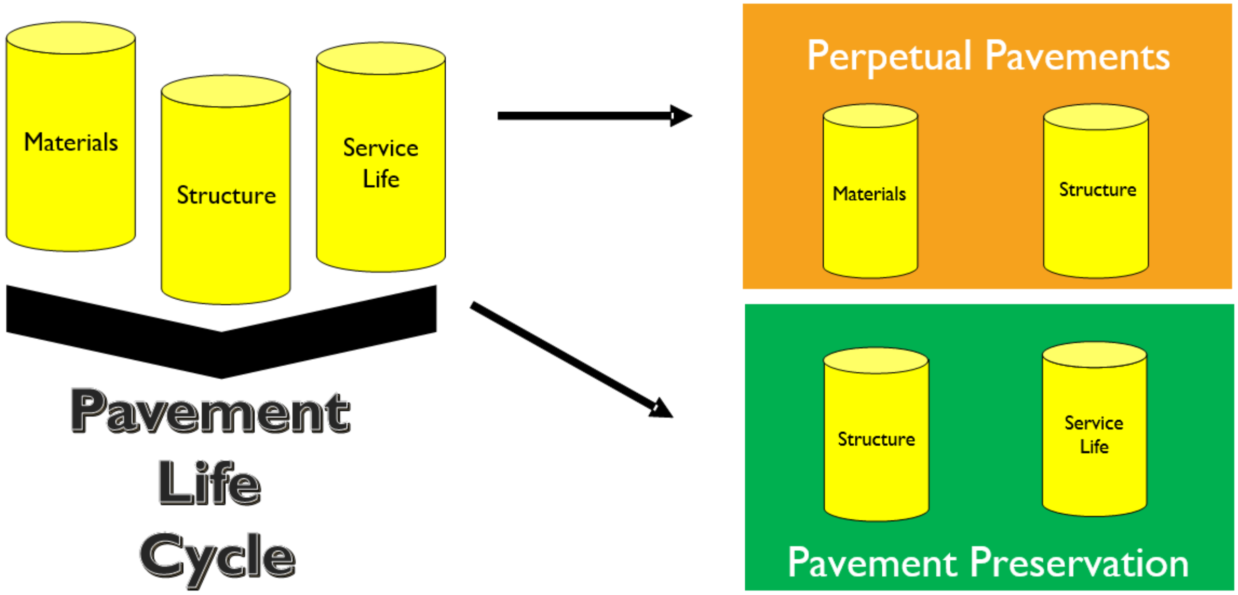

Figure 1.2 The pavement life cycle: bridging pre- and post-installation activities.

Performance-Engineered Pavements

It was discussed that the FHWA aims to improve pavement performance through the PEP initiative which seeks to unify various performance-focused programs under a single strategic vision (FHWA, 2019a). This vision seeks to incorporate the goal of long-term performance into the structural pavement design, construction, and materials acceptance of U.S. pavement infrastructure. As part of PEP, actions to achieve the desired pavement performance are integrated into each program area which relate to key agency's pavement life-cycle design/decision-making stages: design, materials, quality assurance (QA), construction, pavement management, and preservation and rehabilitation (FHWA, 2019b). Overall, the primary goal of PEP is to increase long-term durability, sustainability, and safety of pavements on all of the roadway network.

Furthermore, FHWA recently reorganized its pavements program to better reflect the integration of the various design and decision stages of pavement life in order to better align with the PEP approach. As previously mentioned, the organizational stovepipes that exist can also present challenges to successfully integrating the pavement life cycle. Figure 1.3 shows the various organizational barriers and how they can be centered around sustainable pavements.

Figure 1.3 The FHWA Pavement and Materials Program areas (image from FHWA).

Description of Workshop

A workshop was held at the 101st TRB Annual Meeting. This workshop provided a background on pavement structural design (including construction), pavement material selection (including production), and pavement service life (including initial construction, as well as activities during pavement maintenance (e.g., repair and rehabilitation). Tools and practices related to LCCA and LCA through the three stages of pavement life (the material design stage, the structural design stage, and the service life) were also discussed. Using all of these concepts, the workshop explored the opportunities and challenges that the flexible pavement community currently faces. This e-circular proposes parts of a framework that can better integrate these topics in a way that demonstrates the potential power of practices focused on optimizing the pavement life-cycle economic, environmental, and social impacts.

The workshop participants were divided into breakout groups to brainstorm ideas to address some of the following questions:

- What are some current opportunities to break down the silos and synthesize research and practices that integrate pavement structural design, pavement material selection, and pavement service life?
- Which practices or tools are already available to be immediately implemented for LCA or LCCA?

- What challenges exist to advancing LCCA or LCA practices more holistically in flexible pavement design, construction, and maintenance?
- What are the major gaps and needs faced by pavement engineers in overcoming existing and future challenges?
- What are current activities and readily implementable technologies and processes that can reduce the gaps and needs?
- What are specific next steps and practitioner/research groups that could begin working together more to advance efforts in this area?

The workshop concluded with a panel of five experts who provided their insight on the very same questions and suggested approaches to the next steps in developing a framework.

Objectives and Outcomes of Workshop

There are examples of properly integrated pavement structural design, materials selection, and maintenance techniques which culminate to provide longer pavement service lives. Likewise, there are research efforts underway that advance the integration of these principles in LCCA. There are also examples of initiatives at the federal and state levels to explore opportunities for the LCA of pavements. The objectives of the workshop then were to propose a framework for bringing these topics together and explore effective practices that optimize integration of the pavement life cycle.

References

FHWA. *Index-Based Tests for Performance Engineered Mixture Designs for Asphalt Pavements*. FHWA-HIF-19-103. FHWA, U.S. Department of Transportation, 2019a. https://www.fhwa.dot.gov/pavement/asphalt/pubs/hif19103.pdf.

FHWA. *Tech Brief: Performance Engineered Pavements*. FHWA-HIF-20-005. FHWA, U.S. Department of Transportation, 2019b. https://www.fhwa.dot.gov/pavement/materials/hif20005.pdf.

UCPRC. *Pavement Life Cycle Assessment Workshop*. UCPRC-TM-2010-03. University of California Pavement Research Center, Davis, Calif., 2010.

CHAPTER 2

Structural Design and Construction of Perpetual Asphalt Pavements

The structural design and construction process of perpetual pavements are two key components of the overall life cycle of sustainable pavements, as depicted in Figure 2.1. Successful integration of these components in the life cycle will ensure optimized flexible pavement cross sections that meet the needs of today and far into the future. This chapter will focus on design concepts related to perpetual pavements and key factors to their successful construction.

Structural Pavement Design and Perpetual Pavements

Regardless of the pavement type (e.g., flexible or rigid, perpetual or conventional), the designer must consider several important factors during the structural design stage. These include the existing soil or roadbed, climate conditions, traffic demands, performance expectations, and available materials and their respective properties. These factors come together in a design system used to determine the layer thicknesses needed to achieve performance expectations.

Figure 2.1 The pavement life cycle (image from FHWA).

Prior to the 1950s, the design system was essentially experience-based and with relatively low traffic demand, worked fairly well. The rise in automobile travel, trucking for commercial goods, and construction of Interstates from the 1950s into the 1960s created the demand for a more robust and scientific-based thickness design system. This led to the American Association of State Highway Officials (AASHO) Road Test (Highway Research Board, 1962) and subsequent empirically based design approach [American Association of State Highway and Transportation Officials (AASHTO), 1993] still used today by many states. The 1980s saw interest grow towards more mechanistic-based design systems and National Cooperative Highway Research Program (NCHRP) Project 1-26, "Calibrated Mechanistic Structural Analysis Procedure for Pavements" (National Academies, 1990, 1992) laid out many of the concepts related to mechanistic–empirical (M-E) pavement design. However, the computational power needed for such a design system was not yet available for implementation by practitioners. This began to change in the 1990s and NCHRP Project 1-37, "Development of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures" (ARA, 2004) worked towards the next AASHTO structural pavement design guide called the *Mechanistic–Empirical Pavement Design Guide* (MEPDG, 2008) and accompanying design software, AASHTOWare Pavement M-E Design. Today, many states are working toward implementing M-E design, though the older AASHTO 1993 design guide is still in use by many states.

While all these improvements and advances were going on, many miles of pavement were designed, constructed and far surpassed their performance expectations in the United States. In 2000, the Asphalt Pavement Alliance (APA) initiated an awards program to identify and highlight these "perpetual" pavements and began focusing attention on their structural and performance characteristics. Today, the APA (APA, 2022) has three categories of awards as follows:

- **Perpetual by Performance.** Existing pavements at least 35 years old with minimal structural improvements [<4 in. total increase in asphalt concrete (AC) thickness], infrequent resurfacing (at least 13-year intervals), and no deep structural distresses.
- **Perpetual by Design.** Newly designed and constructed pavements that meet perpetual pavement design criteria and are expected to perform according to the perpetual by performance criteria.
- **Perpetual by Conversion.** Existing pavements converted through rehabilitation from nonperpetual into perpetual using perpetual pavement design criteria and are expected to perform according to the perpetual by performance criteria.

Since the perpetual by design and by conversion are relatively new award programs, the focus of this discussion will be on perpetual by performance. Since 2000 (when the awards program began) through 2021, 164 pavements in 32 states have been

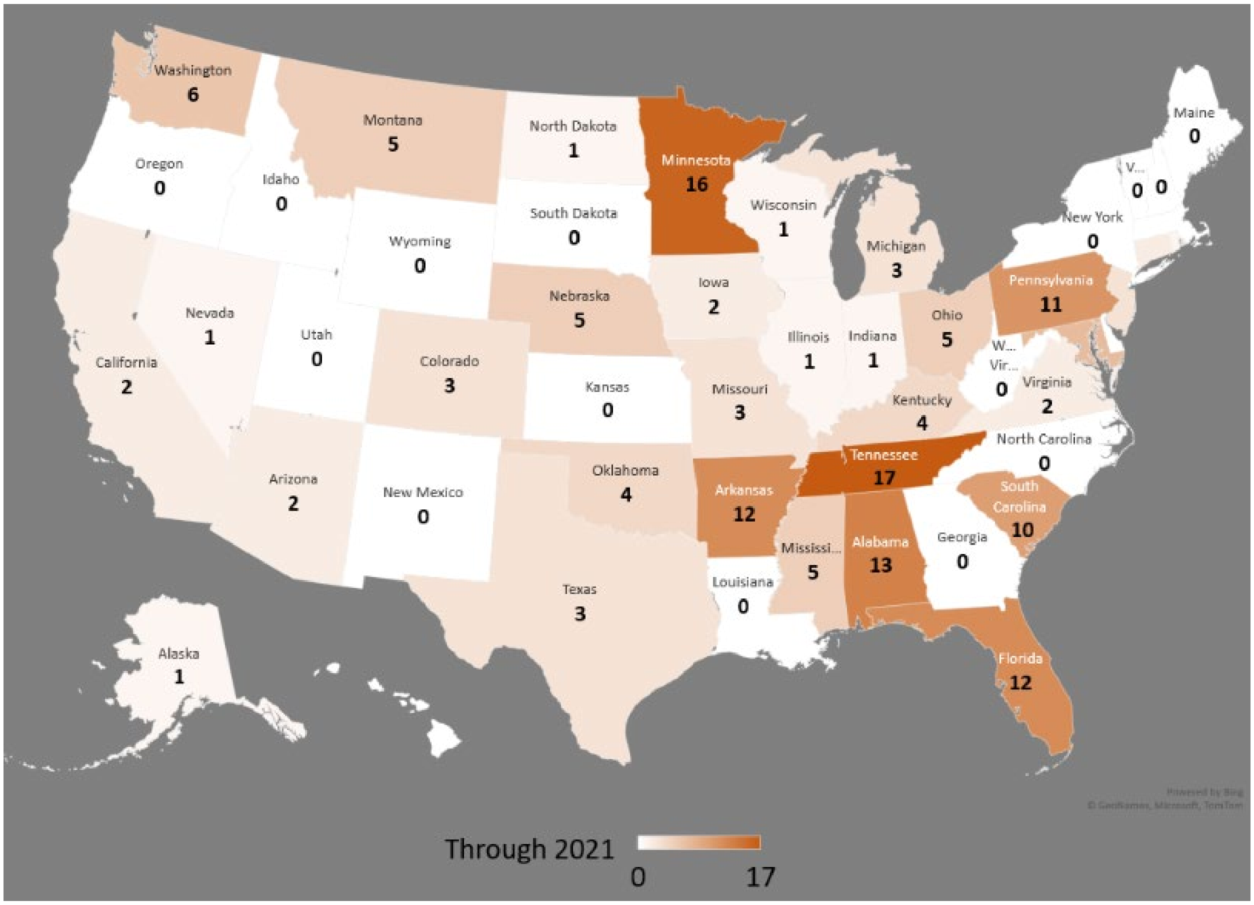

Figure 2.2 Number of Perpetual Pavement by Performance Awards through 2021.

identified, as shown in Figure 2.2. Tennessee (17 awards) and Minnesota (16 awards) currently lead the nation, but perpetual pavements are distributed across the entire United States covering every climate zone and traffic condition. The 13 most recent award winners from 2021 have an average age of 51 years with total traffic, expressed as equivalent single axle loads (ESALs), ranging from 290,000 to 60 million.

The design and construction of these perpetual pavement award winners, by definition, occurred at least 35 years ago following common practice at their respective times of design and construction. Since all of them predate modern concepts of perpetual pavement design, one can surmise that they were designed conservatively using older design systems and built to stand the test of time and traffic. Modern approaches to perpetual design are aimed at optimizing the cross section to achieve perpetual status. Under most high-traffic conditions, following perpetual pavement design criteria will result in the typical cross section depicted in Figure 2.3 (Newcomb et al., 2000). It should be noted that having a purposely design fatigue resistant layer in the bottom of the AC is not mandatory if the strain level at that location is below the endurance limit of the material. Total AC thicknesses, according to Figure 2.3, range from 8.5 to 14 in. which agrees well with perpetual pavement award cross sections.

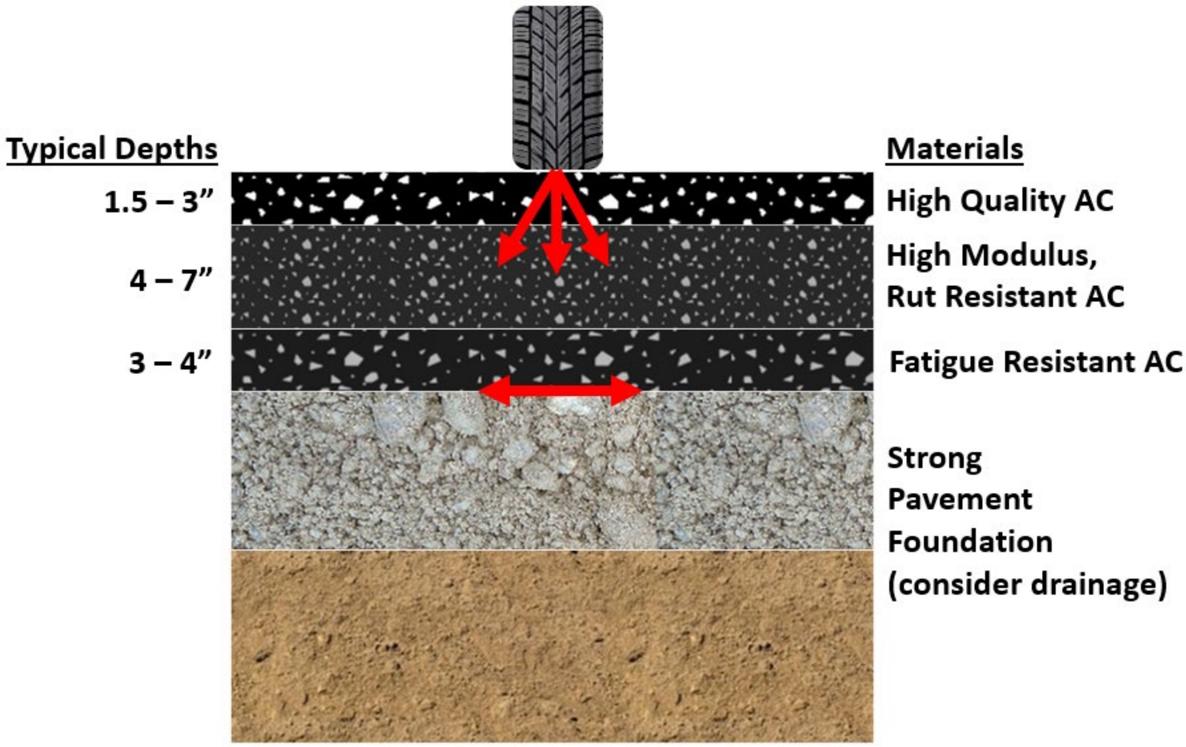

Figure 2.3 Typical perpetual pavement cross-section for high traffic conditions [image adapted from Newcomb et al. (2000)].

Figure 2.3 also identifies specific zones through the AC depth where various material types are more appropriately used. For example, near the pavement surface where high vertical compressive and shear stresses exist, it is important to have high-quality AC that will resist rutting and provide good weathering resistance. Intermediate layers can be high modulus materials and should also have good rut resistance. For the bottom AC layer, which will experience maximum horizontal tensile strain due to bending under tire loading, the fatigue resistance should be considered to prevent bottom-up fatigue cracking. The AC layers must be built on top of a strong pavement foundation which is outside of this discussion but an important consideration for perpetual pavements.

Material selection and mix design of the AC layers for perpetual pavements will be more fully explored in the next chapter, but from a thickness design perspective, it is important to consider the fatigue endurance limit of the base mix as it will directly impact the total thickness of the AC. The fatigue endurance limit is a threshold response below which fatigue damage does not occur. This idea is illustrated in Figure 2.4, representing sample test results from bending beam fatigue testing. Relatively high strain levels during the testing (i.e., exceeding 100 microstrain) result in a finite number of cycles to failure. However, once the strain level falls near or below the endurance limit of the

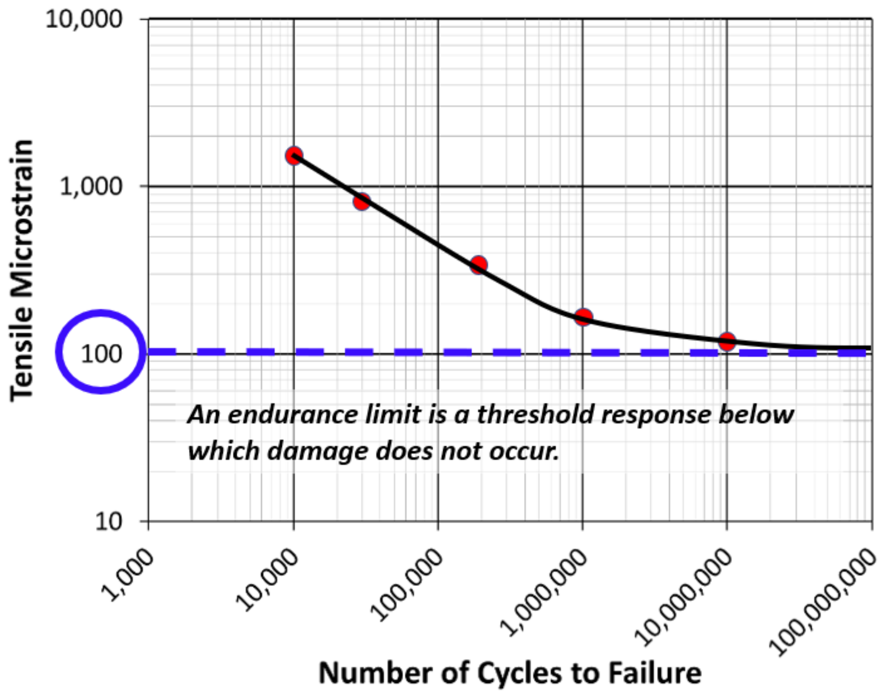

Figure 2.4 Example bending beam fatigue test results.

material, indefinite or infinite fatigue life is observed. The goal of structural design, then, is to determine the total AC thickness through mechanistic modeling needed to keep the tensile strain level at the bottom of the lowest AC layer below the endurance limit. Interested readers may refer to Prowell et al. (2010) for much more information concerning laboratory-determined fatigue endurance limits.

While fatigue endurance limits may be measured in the laboratory, other studies have examined distributions of strain measured in the field linked to perpetual and non-perpetual pavements. One such study by Willis and Timm (2009) at the National Center for Asphalt Technology (NCAT) Pavement Test Track found a limiting strain distribution that separated test sections based on whether they developed bottom-up fatigue cracking. Figure 2.5 shows that sections on or to the left of the blue "no fatigue" limiting distribution did not experience bottom-up cracking. All those sections on or to the right of the red "fatigue" distribution did experience bottom-up fatigue cracking. The clear separation above the 55th percentile provides a basis on which to design perpetual pavements (i.e., design such that the strain levels above the 55th percentile are less than those on the blue "no fatigue" distribution). It is also notable that the measured strain levels far exceeded their laboratory-determined endurance limits of approximately 150 microstrains which means a laboratory-determined value can be considered conservative for design purposes.

The "no fatigue" endurance limit distribution was adjusted for differences between measured and model-predicted strain levels by Robbins et al. (2015) and then tested

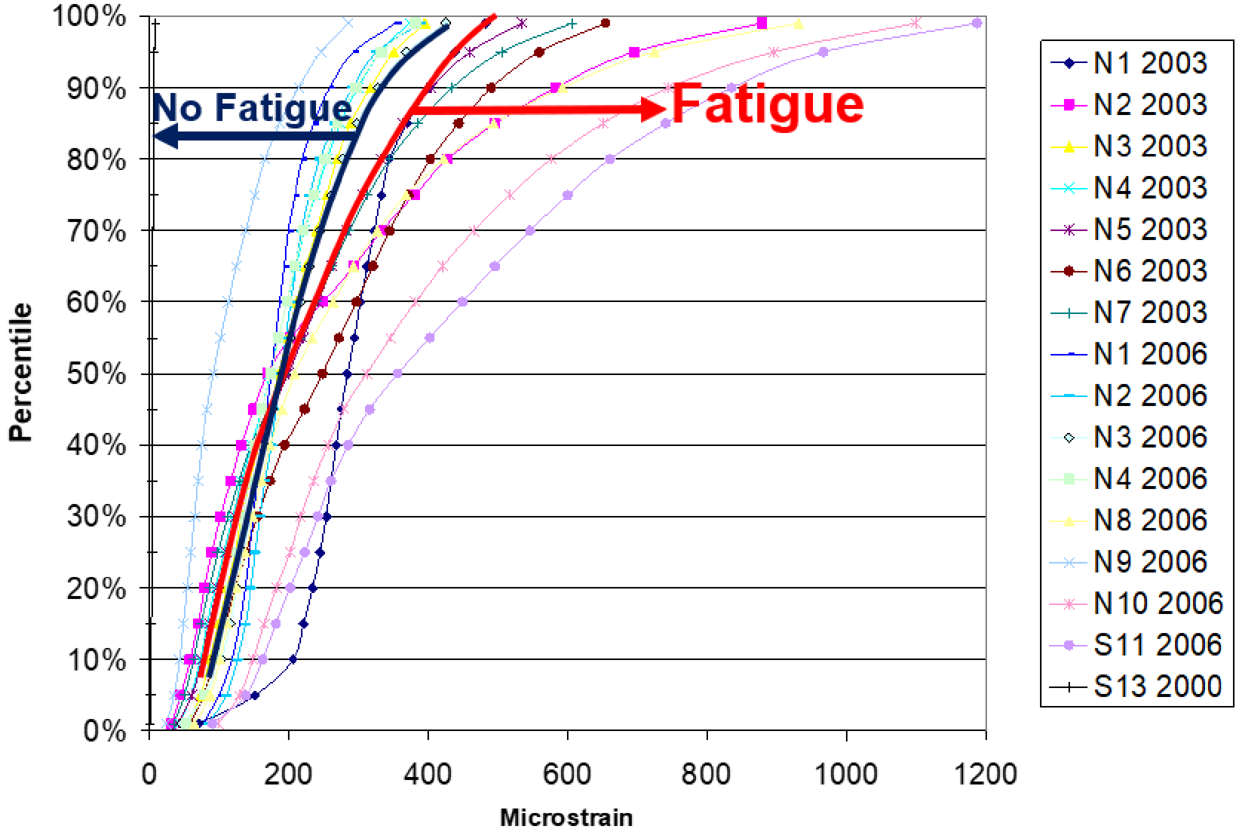

Figure 2.5 Cumulative strain data from NCAT Test Track (Willis and Timm, 2009).

against a number of perpetual pavement award winners in a separate study as described by Castro et al. (2017). The sections in the study by Castro et al. (2017) came from seven different states representing a wide range of pavement sections, as shown in Figure 2.6. It is important to note that the material types were local to each specific state but are shown with common legend symbols for simplicity. This figure is mainly intended to convey overall layer thicknesses with the red line indicating the bottom of the AC in each section. Total AC thicknesses ranged from 7.35 to 21.5 in. The predicted strain distributions from the sections in Figure 2.6 are illustrated in Figure 2.7 which shows that none exceeded the upper limit above the 60th percentile which validated using this approach for perpetual pavement design. As expected, the thinnest section (in Montana) was closest to the limit, while the thickest (in Iowa) was the most conservative. Moving forward, it is recommended that the strain distribution may be used to optimize the cross section by keeping the cumulative strain level just below the limiting distribution.

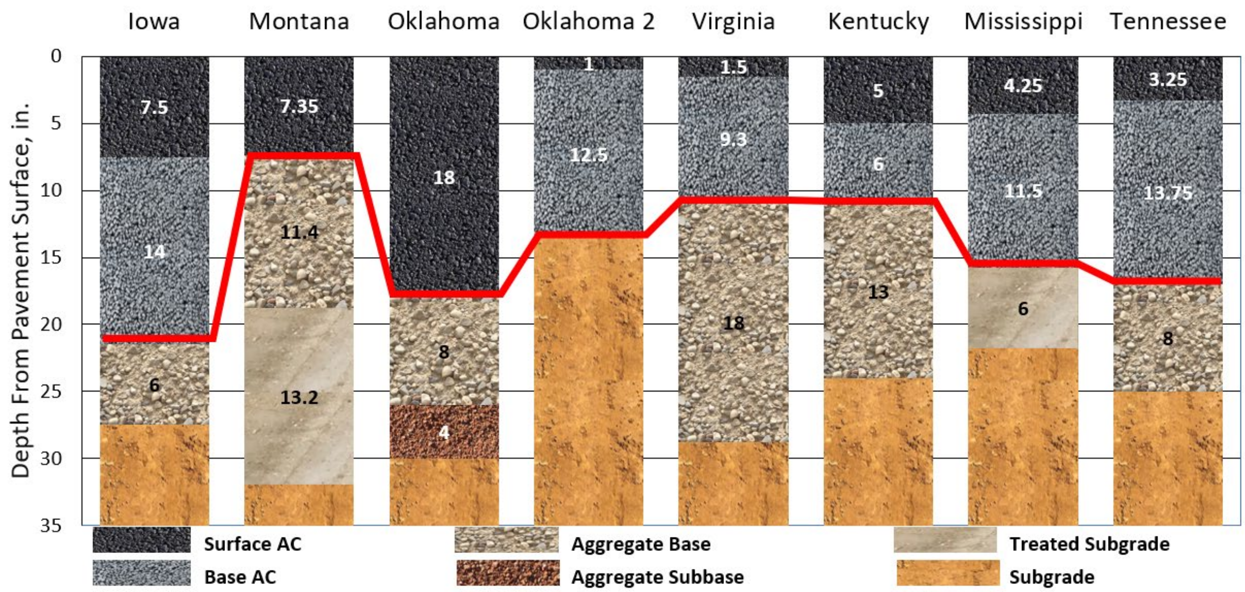

Figure 2.6 Perpetual pavement award winners used for strain distribution limit validation (Castro et al., 2017).

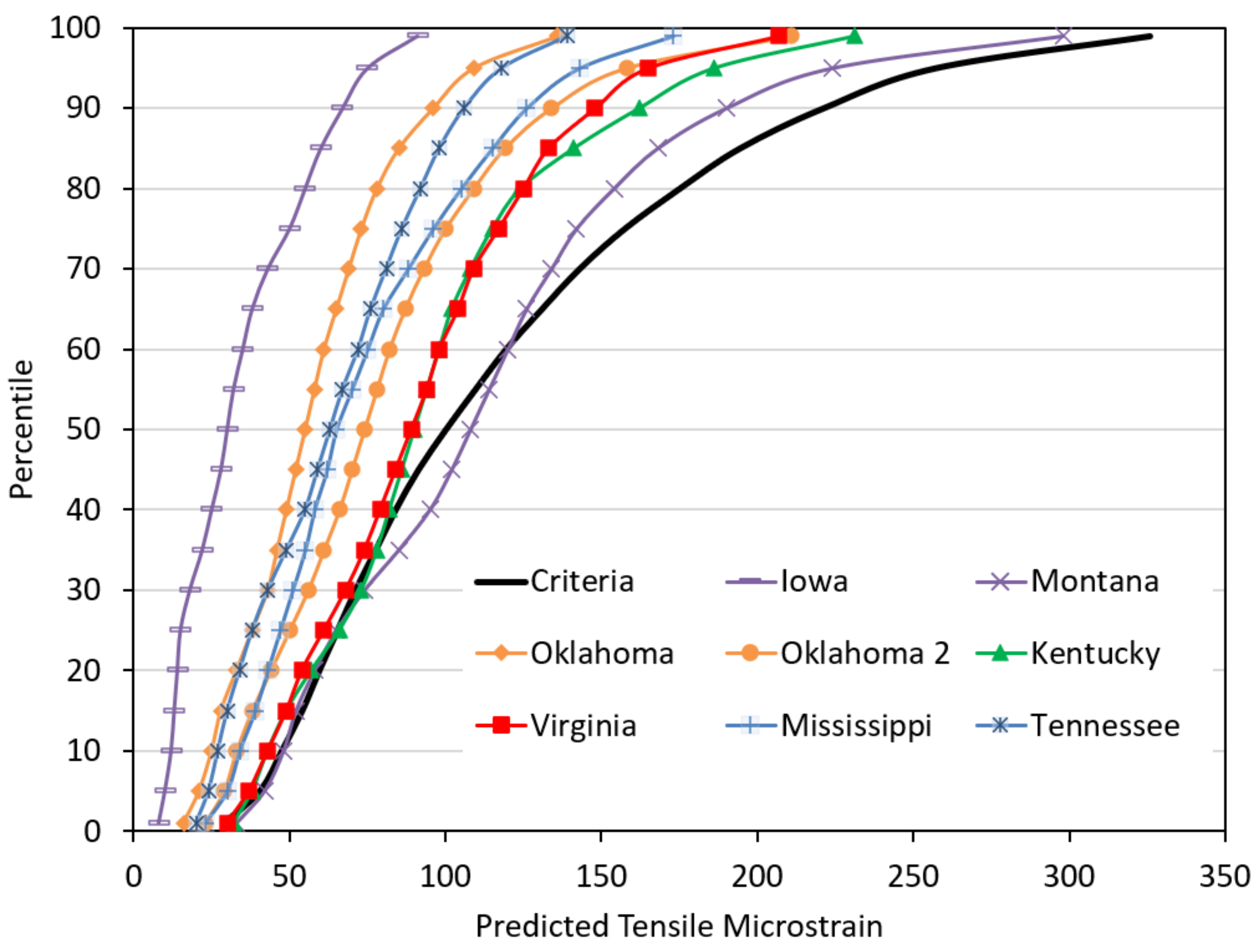

Figure 2.7 Validation of perpetual pavement limiting strain distribution (Castro et al., 2017).

In addition to bottom-up fatigue cracking, it is important to control the vertical compressive strain in the underlying layers to prevent deep structural rutting. The commonly accepted approach is to limit the compressive strain at the top of the subgrade layer to below 200 microstrain (Monismith et al., 2004; Walubita et al., 2008). Studies of NCAT Test Track sections, along with evaluation of perpetual pavement award winners, have validated this approach (Castro et al., 2017).

There are a number of resources available to execute perpetual pavement design. The computer programs PerRoad and PAVEXpress both use the limiting strain distribution approach described above. The AASHTOWare Pavement M-E software allows designers to input a single endurance limit value. Regardless of the program or approach, each requires very specific inputs to execute perpetual pavement design. Ideally, the designer would have detailed knowledge of what materials will be used in the cross section, but since the design is often executed months or years before construction, this can be difficult. Developing libraries of material properties and creating an understanding of how the properties affect overall thickness design, is critical.

Considerations for Constructing Perpetual Pavements

Like any conventional pavement, a perpetual pavement must meet or exceed rigorous specifications to ensure success. Achieving the target mix design during construction, proper placement, compaction, and smoothness are no different for perpetual pavements. Emphasis on placing adequate tack between successive AC lifts is important to ensure that the total design thickness is acting as a monolithic section. Slippage failure between lifts can cause higher tensile strain levels at shallower depths rendering the careful perpetual design ineffective. It is also important to carefully design and construct the pavement foundation layers. Though largely outside this overall discussion, having a well built and strong pavement foundation is important to prevent deep structural rutting and to achieve perpetual pavement status.

Questions, Challenges, and Opportunities for Perpetual Pavements

An area of keen interest for researchers and practitioners is the deployment of innovative and new materials into perpetual pavement cross sections. Like conventional pavements, proper use of unknown or innovative materials in a perpetual cross section requires sufficient material properties and performance characterization prior to implementation. This often can take years of study, including both laboratory and field investigations. Shortening this timeframe and overall cost of the evaluation is essential to more readily adopt and, in some cases, reject new or innovative materials for perpetual pavements.

Future maintenance and rehabilitation of perpetual pavements are also of concern in the life cycle of perpetual pavements. Covered in much greater detail later in this document, perpetual pavements should only require periodic surface treatments and shallow rehabilitation. How and when these treatments, milling, inlays, and overlays are done are critical to the long-term success of the perpetual pavement.

Not discussed in-depth in this chapter, but of importance is rehabilitating existing pavements into perpetual pavement structures. The so-called “perpetual by conversion” may take either nondistressed pavement and simply add thickness to make it perpetual or rehabilitate a pavement with existing distress into a perpetual pavement. The former is straightforward and would require analysis and design according to the principles described earlier in this chapter. The latter is more challenging as it requires first adequately mitigating existing distresses before paving. Existing cracking, whether in a flexible or rigid pavement must be accounted for in the design and construction process. There are currently no perpetual design criteria for reflection cracking, and this is an opportunity for future research. In the meantime, well established techniques to prevent cracks or joints from propagating through the newly placed AC may be used. These may include slab fracturing techniques to eliminate slab action, placing stress absorbing membrane interlayers, or simply removing distressed areas have been shown to be effective treatments. Again, though, this is an area for further research within the context of perpetual pavement design and construction.

References

AASHTO. *AASHTO Guide for Design of Pavement Structures*. Washington, D.C., 1993.

ARA, Inc., and ERES Consultants Division. *Guide for Mechanistic–Empirical Design of New and Rehabilitated Pavement Structures*. NCHRP Project 1-37A. Transportation Research Board of the National Academies, Washington, D.C., 2004.

APA. *Perpetual Pavement Awards*. https://www.driveasphalt.org/awards. Accessed June 2, 2022.

Highway Research Board. *The AASHO Road Test*. Report 5: Pavement Research. Special Report 61E. National Research Council, Washington, D.C., 1962.

NCHRP Project 1-26, “Calibrated Mechanistic Structural Analysis Procedure for Pavements,” Volume 1. TRB, National Research Council, Washington, D.C., 1990.

NCHRP Project 1-26, “Calibrated Mechanistic Structural Analysis Procedure for Pavements,” Volume 2. TRB, National Research Council, Washington, D.C., 1990.

NCHRP Project 1-26, “Calibrated Mechanistic Structural Analysis Procedure for Pavements,” Volume 1. TRB, National Research Council, Washington, D.C., 1992.

NCHRP Project 1-26, “Calibrated Mechanistic Structural Analysis Procedure for Pavements,” Volume 2. TRB, National Research Council, Washington, D.C., 1992.

Castro, A. J., N. Tran, M. M. Robbins, D. H. Timm, and C. Wagner. Further Evaluation of Limiting Strain Criteria for Perpetual Asphalt Pavement Design. *Transportation Research Record No. 2640*, Transportation Research Board, 2017, pp. 41–48.

Mechanistic–Empirical Pavement Design Guide, Interim Edition: A Manual of Practice. AASHTO, Washington, D.C., 2008.

Monismith, C., J. Harvey, T. Bressette, C. Suszko, and J. St. Martin. The I-710 Freeway Rehabilitation Project: Mix and Structural Section Design, Construction Considerations, and Lessons Learned. Presented at International Symposium on Design and Construction of Long-Lasting Asphalt Pavements, National Center for Asphalt Technology, Auburn, Ala., 2004, pp. 217–262.

Newcomb, D. E., M. Buncher, and I. J. Huddleston. Concepts of Perpetual Pavements. *Transportation Research Circular 503: Perpetual Bituminous Pavements*. Transportation Research Board, Washington, D.C., 2001, pp. 4–11.

Prowell, B., E. R. Brown, E. M. Anderson, J. S. Daniel, H. Von Quintus, S. Shen, S. Carpenter, S. Bhattacharjee, and S. Maghsoodloo. *NCHRP Report 646: Validating the Fatigue Endurance Limit for Hot Mix Asphalt*. Transportation Research Board of the National Academies, Washington, D.C., 2010.

Robbins, M. M., N. Tran, D. H. Timm and J. R. Willis. Adaptation and Validation of Stochastic Limiting Strain Distribution and Fatigue Ratio Concepts for Perpetual Pavement Design. *Journal of the Association of Asphalt Paving Technologists*, Vol. 84, 2015, pp. 181–217.

Walubita, L. F., W. Liu, T. Scullion and J. Leidy. Modeling Perpetual Pavements Using the Flexible Pavement System (FPS) Software. Presented at 87th Annual Meeting of the Transportation Research Board, Washington, D.C., 2008.

Willis, J. R., and D. H. Timm. *Field-Based Strain Thresholds for Flexible Perpetual Pavement Design*. Report No. 09-09. National Center for Asphalt Technology, Auburn University, Ala., 2009.

CHAPTER 3

Materials Selection and Design for Long-Life Asphalt Pavements

Introduction

Proper selection of materials, the subsequent design of asphalt mixes, and the production of those mixes are crucial components of the life cycle of long-life, sustainable asphalt pavements, as depicted in Figure 3.1. Ensuring these elements are successfully integrated into the pavement life cycle will help the pavement meet its objective of providing smooth, safe, and efficient operation of vehicles well into the future. This chapter will focus on concepts related to the materials used, the design procedures that seek to optimize the performance of those materials, the consistent production of those materials in the field, and the integration of data related to these processes into the pavement life cycle.

Figure 3.1 Pavement life cycle (image from FHWA.)

Before beginning the discussion, it is necessary to state what this chapter is not: (*a*) a compendium of all possible materials used in asphalt mixtures, with instructions on proper use; (*b*) a comprehensive listing of all possible laboratory and field tests of materials and mixes, with guidance on test selection and use; or (*c*) recommendations regarding best practices for operating an asphalt plant. There is a staggering amount of information available to the specifier, designer, and constructor for specifics in these areas.

Rather, this discussion explores three "Big Picture" questions.

1. What do we mean by pavement "life"?
2. (How often) Do we *intentionally* design an asphalt mixture for a <u>specific</u> purpose?
3. (When) Will robust data feedback loops become standard operating procedures?

Big Picture Question #1: What Do We Mean by Pavement "Life"?

In order to help the traveling public, understand the roads on which they drive, engineers typically discuss pavement "life" in terms of *years*. However, no structural design procedure or asphalt mixture design procedure uses "years" as a direct input into the various equations related to the design. Rather, the timespan concept used is typically *traffic*, e.g., the number of ESALs or load spectra applied to the pavement for a specified timeframe (or years). Ironically, there are numerous instances where a pavement is deemed to have failed "early," yet has withstood its specified/designed traffic loads, which (unfortunately) happened to have been reached ahead of schedule. A related question involves the definition of the *end-of-life* for a pavement structure or surface. In most cases, end-of-life is associated with a critical level of pavement distress (e.g., rutting, cracking, surface defects) or ride quality.

The end-of-life question becomes critical to the mix designer, who should be working in collaboration with the structural designer to ensure the asphalt mixes used in a given pavement structure exhibit the properties required by the design to provide the specified design "life." Here the mix designer faces a balancing act: the mix must resist mixture-related (and often premature) failure (excessive shear flow or compression leading to rutting, excessive brittleness leading to cracking, etc.)—and—must provide the stiffness properties (primarily) that are needed to contribute to the structural stability of the pavement system. This balance, unfortunately, reflects the traditional divide between pavement design and asphalt materials–mixture design—particularly in the present age of M-E pavement design. Rarely do common mixture design procedures and processes provide the *fundamental* material properties needed by M-E design systems. Thus, we often engage in two discussions related to pavement "life"—one from the structural designer and one from the mixture designer.

A continuing issue in the mix designer's balancing act involves mixture testing, namely *index* tests versus *fundamental* tests. Very broadly, an index test typically provides a measure of "performance" of a given mix, but from a perspective of acceptable-for-use versus not-acceptable-for-use. While some have a basis in engineering mechanics, their use is reasonably characterized as empirical—that is, the results of the test are matched (or calibrated or validated) against the field performance of the mix. Examples include wheel-tracking tests (for rutting) and indirect tension tests (for cracking). Fundamental mixture tests seek to provide a measure of some mechanical (or rheological) property of the mix—which can be subsequently used in mathematical models (mechanistic computations and related transfer functions) to estimate the performance of the mix or pavement system. Such tests typically require repeated compression, tension, and/or shear loading in a variety of configurations. Again, index tests tend to be faster, comparatively less complicated to perform, and require less expensive equipment than fundamental tests.

In context, then, the question of pavement life is a function of choices of tests to include in a mixture design system. A mixture design system, for example, with no performance tests (e.g., design is based strictly on the volumetric properties of the mix) relies on empirical relationships between the volumetric properties and the historic performance (hence *life*) of mixtures exhibiting those properties. Similarly, a mixture design system which features index-type performance tests defines the life of the mix/pavement as the historic performance of mixes and pavements exhibiting those index properties. In both cases, there is no real estimation of the *progression* of pavement distress/condition over time—life is only the end-state. Contrast this with design systems based on fundamental material/mix properties; in such systems, estimates are produced of the progression of pavement distress—e.g., rutting and cracking (and the associated ride quality), over time or the application of traffic loads. Candidly, these systems also rely on historic pavement performance to calibrate their distress estimation models (transfer functions).

Big Picture Question #1 leads us to conclude that asphalt materials selection and mixture design cannot exist in a bubble. The intricate connection between structural design and materials/mixture design requires an understanding of how pavement life is defined and estimated—and the materials-related data necessary for the process. There are two major items to be noted here:

1. Many agencies seeking to implement some form of M-E pavement design create catalogs of material properties for use in the M-E design procedure, obviating the need for ongoing, routine measurement of fundamental properties (particularly during the mix design process). The obvious risks here are that materials change over time, and new materials, additives, and (sometimes) waste products are

added to the mix design system. These changes cannot be fully captured with a somewhat static material property catalog.

2. Mixes designed in the laboratory must be produced in the field. Broadly, most fundamental material tests do not easily lend themselves to being performed during mixture production, *particularly* as part of the QA process. Indeed, to date, very few agencies routinely implement even *index*-type mixture performance tests as part of the QA system (although many are investigating this). A common approach for agencies seeking to implement M-E pavement design is to develop empirical relationships between common material properties (e.g., volumetric) and fundamental properties. Again, this approach risks being unable to efficiently capture the introduction of new materials and significant changes to existing materials.

Big Picture Question #2: (How Often) Do We Intentionally Design an Asphalt Mixture for a Specific Purpose?

It is universally recognized a given pavement structure which carries any appreciable amount of truck traffic (thus requiring a more substantial structure) will feature multiple asphalt mixtures. Generically, these layers may be referred to as a base layer, an intermediate layer, and a surface layer. Typical volumetric-based mixture design systems will include similar—if not identical—processes and techniques for designing these different mixtures. The mixtures will differ primarily in aggregate size and specification limits on certain volumetric properties, as well as possible adjustments in binder grade, the allowance of certain materials [e.g., reclaimed asphalt pavement (RAP), shingles], and possibly, variations in laboratory performance testing. Such systems are somewhat experience-based; that is, specific limits on volumetrics and materials to be used are based on past field performance of the mix.

However, at the intersection of materials–mixture design and structural design lies Big Picture Question #2. Each layer in the asphalt structure of a pavement system has a very specific role to play in the overall performance of that structure—there is a *purpose* for that layer. But is this (or *how often* is this) purpose *intentionally* addressed when designing the asphalt mix? Chapter 2 provides insight into the question of the purpose of various asphalt layers and the properties needed to fulfill that purpose. For convenience, we will repeat part of that discussion here. Newcomb and his colleagues (2000) identified specific zones within the asphalt layers where asphalt mixtures should be designed with specific purposes in mind (see Figure 2.3). Expanding on that concept, Figure 3.2 suggests both the purpose of asphalt layers and the material characteristics needed in the asphalt mixtures comprising those layers.

As shown in Figure 3.2, the surface layer(s) of an asphalt pavement require mixes that are resistant to both rutting (due to shear flow or excessive compression) and cracking

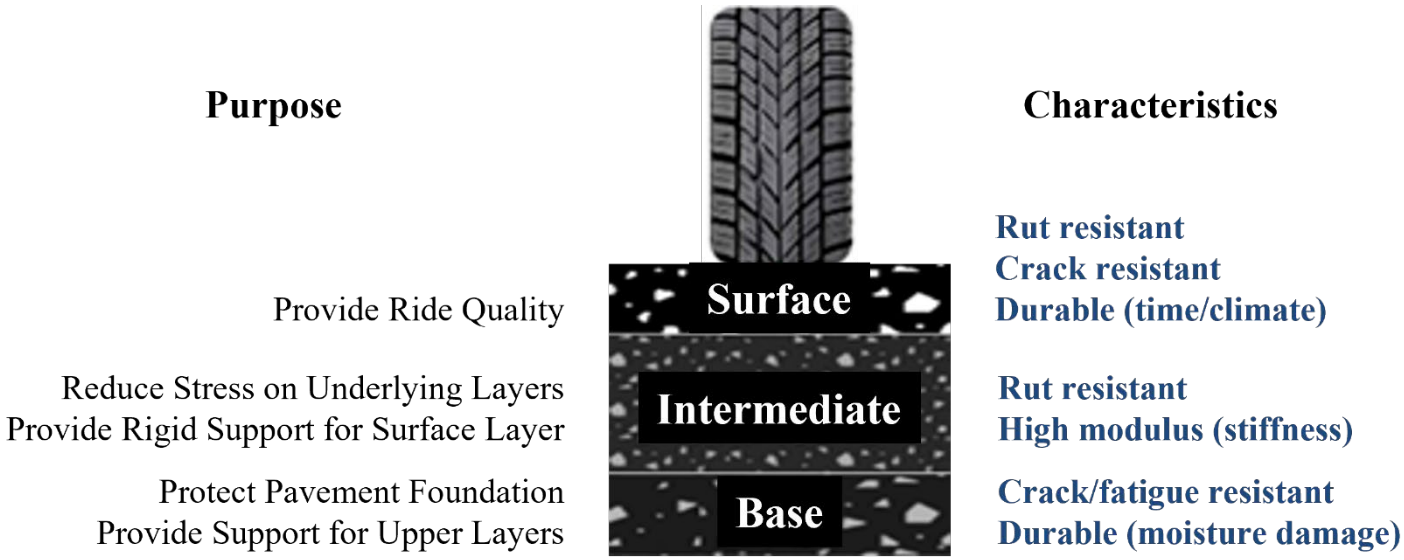

Figure 3.2 Purpose of asphalt pavement layers and associated mixture characteristics.

(primarily top-down). These mixes should also be highly durable, providing resistance to excessive oxidation and weathering. Intermediate layers function to help both the surface and base layers—to *support* the surface layer in resisting rutting and to *protect* the base layer by distributing traffic-related applied stresses (which relates to the stiffness of the mix), thereby reducing the risk of bottom-up fatigue cracking. Base layers should be highly fatigue resistant (see the discussion in Chapter 2 regarding endurance limit) and, due to their contact with underlying foundation layers, durable/resistant to moisture damage. It is noted that all flexible pavements do not contain each of these general 'layers' of asphalt; however, the principles discussed here remain valid.

Ideally, each mix in the asphalt pavement should be designed for its specific purpose and consider its associated characteristics as the driving design criteria. For **surface mixes**, we seek resistance to rutting and cracking, plus durability from a weathering/surface characteristics perspective. Structurally, maximizing the rutting resistance of a surface mix may lead to issues related to cracking; conversely, maximizing the cracking resistance of a mix may lead to issues related to rutting. Thus, many agencies are moving to the use of a balanced mix design (BMD) procedure to simultaneously address both common failure/distress mechanisms. The BMD concept is relatively straightforward, as illustrated in Figure 3.3. In general, as binder content is increased, a mixture's resistance to cracking (or durability) increases—but its resistance to rutting (or stability) decreases (and vice versa). There is, however, a zone or range of binder content at which both mixture durability and stability are improved (but not necessarily maximized). The key for a given mix is to develop the stability–durability versus binder content curves, to identify an appropriate balanced binder

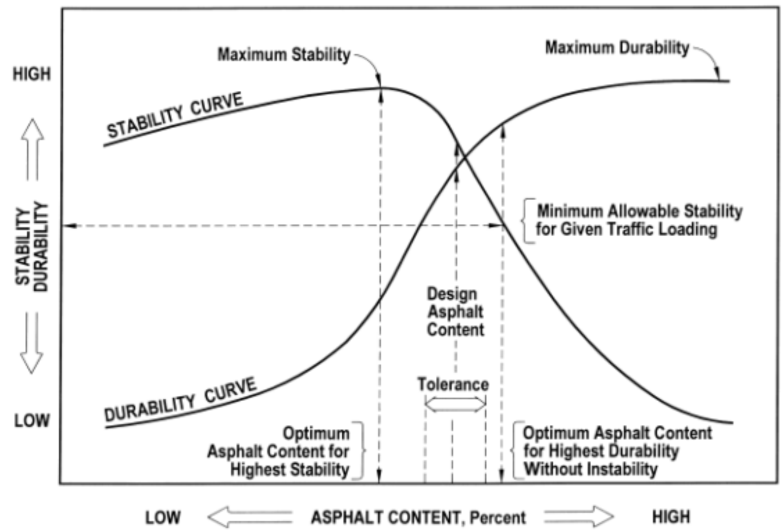

Figure 3.3 Concept of the durability–stability relationship of asphalt mixtures (FAA, 2013).

content range. Many states have implemented, or are in the process of implementing, performance-related tests (as discussed previously) that could prove useful to this task. Chkaiban, Hajj, and Hand (2022) provide an example of using various approaches to BMD in the mixture and pavement design process. Additional resources regarding BMD include the Final Report for NCHRP Project 20-07/Task 406, "Development of a Framework for Balanced Asphalt Mixture Design" (2018) and the *Balanced Mix Design Resource Guide* (IS-143) published by National Asphalt Pavement Association (NAPA) (2021).

A key characteristic for intermediate mixtures is mixture stiffness. A high-stiffness intermediate layer adds support to the surface layer while protecting the underlying/base layers of the pavement system. Increasing mixture stiffness may be accomplished in a variety of ways. From a materials-selection perspective, increasing binder stiffness is an option—bumping up a grade, polymer (or other) modification, etc. Increasing the use of RAP in the mix may also effectively increase mixture stiffness, as well as adjustments to the aggregate structure (gradation). Direct measurement of mixture stiffness (or modulus) typically requires more sophisticated testing than the index-type performance tests favored by many agencies; however, for intentionally designing asphalt mixes for this specific role, it might prove necessary and effective.

Base mixes in an intentionally designed pavement structure are required to be highly fatigue resistant. As discussed in Chapter 2, one criterion that may be used is the fatigue endurance limit—the bending strain level experienced in the mixture, below which no fatigue damage occurs. From a mixture design perspective, contributing factors to increase the fatigue resistance may include disallowing the use of RAP, adjusting the aggregate structure, and increasing the binder content of the mix [which, in many cases, is termed a rich-bottom mix (Hajj et al., 2011)]. As with stiffness testing for intermediate mixes, the laboratory testing program required to establish the fatigue endurance limit of a given asphalt mix can be substantial. As discussed in Chapter 2, however, there are other approaches to consider in long-life (perpetual) pavement design.

The overall concept here is not revolutionary: in terms of material selection and mixture design for the various asphalt mixes and layers present in a pavement structure, one size does NOT fit all. Pavement and mix designers should be aware of the specific properties required of the mixture being developed and intentionally design to optimize those properties.

Big Picture Question #3: (When) Will Robust Data Feedback Loops Become Standard Operating Procedure?

Engineering the pavement life cycle requires firm connections between the various stages of the pavement's life. Those connections are facilitated by data. Data—in many cases a substantial amount of data—are generated at each stage of the life cycle. Pavement designers, particularly when using some form of M-E design, require data on every aspect of the pavement system: climate, traffic, materials, structure, performance, etc. Material characteristics, mixture design data, and construction QA related data are all vital to producing the roadway. Pavement management activities generate pavement performance data over the 'use phase' of the pavement, which feeds decisions regarding preservation and maintenance activities. Rehabilitation requires pavement condition data to guide the selection of processes and products to be used. Figure 3.4 illustrates the concept. It has been pointed out numerous times in numerous venues that a typical agency with responsibility for roadways tends to separate all of these functions, which leads to a breakdown in *high-quality* data being *readily* available to all who need it.

Focusing on materials and mix design, we will illustrate the concept with two idealized examples. The first is the relationship between structural design and asphalt mixture design. For traditional projects, the structural design is completed well before material selection and mixture design occur. It is noted that alternate-delivery projects, such as design–build, may not apply here. However, the structural designer must make decisions regarding asphalt mixture materials and properties. In many cases, the designer consults a listing or catalog of average/typical values—particularly for M-E design, which requires substantially more mixture-related data than empirical design procedures. Key questions emerge:

1. How dynamic is the materials catalog—in other words, how often are the

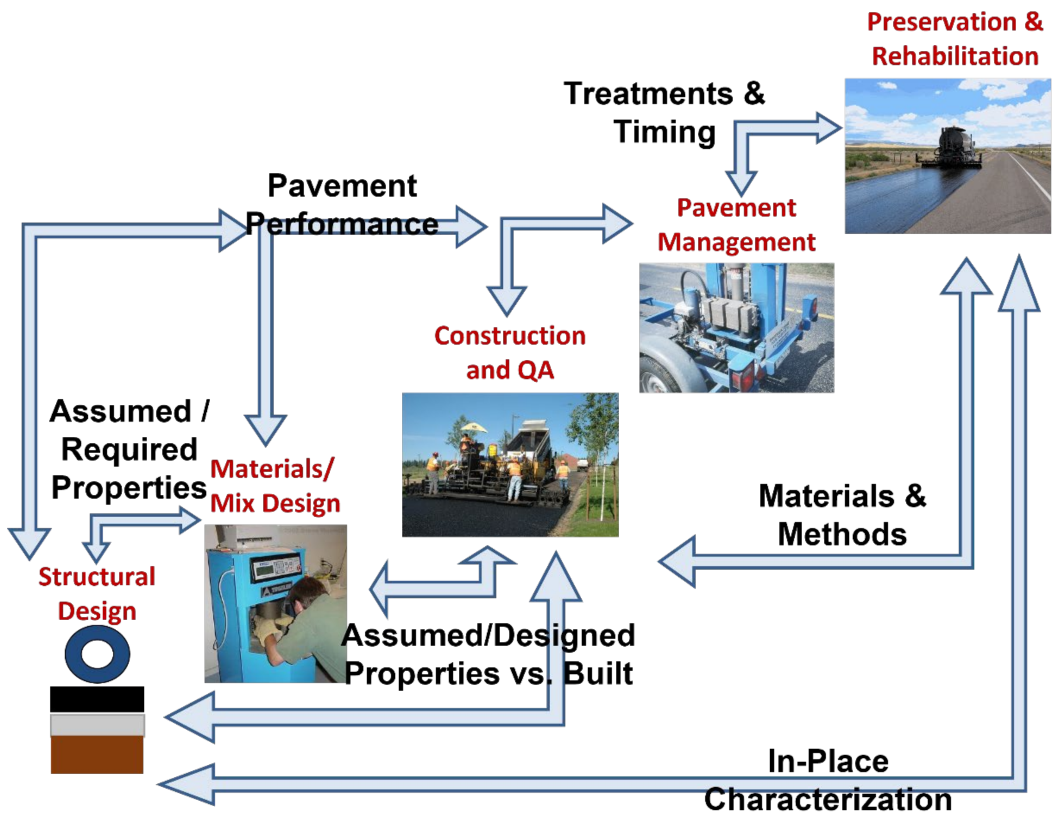

Figure 3.4 Conceptualizing data loops in the pavement life cycle.

materials data updated as new materials and mixture design methods continue to be introduced?

2. How often does the pavement designer inform the materials and mixture designer what property values were *assumed* in the structural design—so that the materials designer can *ensure* the mixture(s) designed for that particular project exhibit those values?
3. How often does the materials designer inform the structural designer what property values were obtained in the mix—so that the effect(s) of any discrepancy in property values might be estimated for the design? Obviously, some type of data feedback loop is needed to truly connect the structural design and materials design for a given project.

A second idealized example is the connection between the materials/mixture design (e.g., in the laboratory) and the mixture(s) produced in the field during construction. In many cases in roadway agencies, this connection is more well-realized than most in the pavement life cycle. The mixture design (or job mix formula) can reasonably be considered the trial design of the mix. Inevitably, certain adjustments are made at the hot-mix asphalt (HMA) plant to produce the mix consistently. In addition, producers periodically measure mixture properties as part of their quality control process, and owner/agencies verify mixture properties through their QA process. Again, key questions emerge: (1) what is the scale of the difference between designed and as-built properties of the mixtures—and are the differences substantial enough to affect the ultimate performance of the pavement? (2) Is there any direct relationship between the field data collected and the data used to design the mixture and the pavement structure? Question 1 actually traces back to the pavement designer to help determine if as-built properties are sufficiently close to the material properties assumed during the structural design to ensure the expected pavement performance is not substantially affected. Question 2 takes us back to the *basis* for design (for both the structure and the mix); currently, the most common field mixture tests are binder content and volumetric properties—not laboratory performance tests (which may be used in BMD, for example) and/or fundamental property tests (e.g., mixture stiffness, which may be used in an M-E structural design).

As with Big Picture Question #2, the concept here for Big Picture Question #3 is not revolutionary. Significant amounts of data are generated (and needed) at each stage of the pavement life cycle. These data are interconnected across life-cycle stages. It is imperative that systems are put in place to ensure the data are appropriate, useful, and readily or easily available to the users who need it.

Final Thoughts

In many ways, material selection, mixture design, and materials/mixture characterization lie at the heart of the performance of long-life asphalt pavements. The period from 2005–2022 has witnessed significant advances in materials, asphalt mixture design, and pavement design. Many state departments of transportation (DOTs) at the turn of the century were transitioning from a mixture design procedure (Marshall) that had been in place for more than 50 years (in some cases) to a new volumetric-based system called Superpave, and then on to the addition of performance-related laboratory tests for mixes. Many of these same DOTs are now also transitioning from a structural design procedure (AASHTO) that had been in place for more than 30 years to M-E procedures. These transitions provide the opportunity to intentionally design asphalt mixtures to play specific roles in the pavement structure to enhance the longevity of the pavement system.

These transitions also provide an opportunity to embrace the concept of considering the entire pavement life cycle, the role(s) of each of the major stages, and the interconnectedness of the stages of the life cycle. This chapter clearly demonstrates the absolute lock between pavement structural design and materials/mixture design. As with most discussions, one clear conclusion is the need for *communication*—including inter-agency, cross-agencies, and data platforms.

References

Federal Aviation Administration. Hot-Mix Asphalt Paving Handbook. Advisory Circular 150/5370-14B. 2013.

Chkaiban, R., E. Hajj, and A. Hand. Influence of Balanced Mix Design Approaches on Pavement Design Making Through an Illustrative Example. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2676, No. 10, 2022, pp. 495–506.

Hajj, E., A. Ulloa, P. Sebaaly, and G. Bazi. Impact of Rich-Bottom Design in Asphalt Pavements. *International Journal of Pavement Research and Technology*, Vol. 4, No. 6, 2011, pp. 313–323.

Newcomb, D. E., M. Buncher, and I. J. Huddleston. Concepts of Perpetual Pavements. *Transportation Research Circular No. 503: Perpetual Bituminous Pavements*. Transportation Research Board. Washington, D.C., 2000, pp. 4–11.

West, R., C. Rodenzo, F. Leiva, and F. Yin. NCHRP Project 20-07/Task 406, “Development of a Framework for Balanced Mix Design.” National Academies of Sciences, Engineering, and Medicine, 2018.

Yin, F., and R. West. *Balanced Mix Design Resource Guide.* Information Series IS-143. NAPA, Greenbelt, Md., 2021.

CHAPTER 4

Life Stage

Preservation, Maintenance, Economics, and Environmental Impact

Background

After an AC pavement is designed, the materials are selected, and the pavement is constructed, it then moves into its use stage. This is also referred to as its life stage. There are many different facets of the life stage, which include evaluating roadways, relating observed distresses to either surface or structural issues in the pavement, tying distresses to appropriate treatments, quantifying the economic impact of treatments, and capturing the environmental impacts of such treatments. Each of these steps is discussed in more detail throughout this chapter. Using the FHWA figure that has already been shown in Figure 2.1, the life stage can be defined by combining the pavement management stage and the pavement preservation and rehabilitation stage shown in Figure 4.1. The life stage image shown in Figure 4.1 shows a combination of the pavement management phase and the pavement preservation/rehabilitation stage.

The use stage of an AC pavement is crucial. In 2020, the United States boasted approximately 2.9 million miles of paved roads, at which time almost 94% were surfaced with AC [Bureau of Transportation Statistics (BTS), 2021]. It was estimated within that

Figure 4.1 The FHWA Pavement and Materials Program areas (image from FHWA.)

same year that all U.S. roads combined were worth a total of $4.0 trillion (in U.S. dollars) [Bureau of Economic Analysis (BEA), 2021]. There is therefore a significant amount of AC necessary to keep these essential roads in serviceable condition. Proper management of this vital, multifaceted network is key.

Pavement owners rely on four general steps for pavement management:

1. Assess,
2. Justify,
3. Identify, and
4. Estimate.

Assessing pavement consists of quantifying the current pavement condition and attempting to predict future pavement conditions. Once the network is assessed, the amount of necessary funding is determined in order to achieve the final overall network target condition. And, of course, this funding must be justified. The third step, which is to identify, consists of reviewing potential maintenance and rehabilitation treatments while optimizing available funding. Finally, the owner must estimate the consequences of the monetary investment along with the performance of the chosen treatment.

The most basic method for evaluating a pavement condition is done through a visual survey. The two most common visual surveys are ASTM D6433 (ASTM, 2020) and the FHWA Distress Identification Manual (Miller and Bellinger, 2014). While these visual surveys provide an overview of general pavement characteristics, there are other manual methods which evaluate specific roadway characteristics.

For example, the macro texture of pavements is highly correlated to surface friction. This macro texture can be measured either by using volumetric methods, such as the sand patch test found in ASTM E965 (ASTM, 2019), or using portable lasers. Alternatively, structural characteristics can be evaluated with nuclear density gauges found in ASTM D6938 (ASTM, 2021a), nonnuclear density gauges found in ASTM D7830 (ASTM, 2021b), portable seismic pavement analyzers, or rut depth measurements found in ASTM E1703 (ASTM, 2016). However, these manual methods are relatively inefficient, as they require an individual to take all necessary measurements by hand. Thus, many vehicle-based systems have been utilized to expedite the process. Table 4.1 summarizes five properties and their associated standards that use vehicle-based systems to collect pavement data.

Regardless of whether pavement characteristics are measured visually or by vehicle-based systems, it is important to relate specific distresses to their respective locations, whether on the actual pavement surface or within the pavement structure. If found on the surface, the distress is most likely only within the pavement's top half-inch (12.5 mm). These surface distresses include oxidation, minor raveling, non-load-related cracks, bleeding, polished aggregate, and high-quality patching. Figure 4.2 shows an oxidized/raveled road and a road with bleeding.

Table 4.1 Properties and Standards for Pavement Characteristics Using Vehicle-Based Systems

Property	Standard(s)
Skid resistance	ASTM E274, E1274, E1337, E1856
Roughness	ASTM E1082
Profiler	ASTM D950
Deflection	ASTM D4694, D4695
Layer thickness	ASTM D4748

Figure 4.2 Oxidation and raveling (left), and bleeding (right) on asphalt concrete roads. (Image credit: RoadResource.org.)

Structural distresses form due to the environmental and traffic loads exceeding the pavement's capacity. These distresses are found deeper than the pavement's top half-inch (12.5 mm) and can originate from either the top or bottom of the pavement structure. They can also originate in the unbound material underneath the AC material itself. Resulting distresses from these environmental and traffic loads include load-related cracks, severe raveling, poor patches, potholes, rutting, shoving, and water bleeding or pumping. Figure 4.3 shows a road with load-related cracking and a road with rutting.

Regardless of whether the distress is found on the pavement's surface or within its structure, properly identifying the type of distress is vital. Only after its correct identification can the appropriate treatment be selected, as treatment options are dependent upon which distress is found. This ultimately results in an extended pavement life span.

Figure 4.3 Load-related cracking (left) and rutting (right) on asphalt concrete roads. (Image credit: RoadResource.org.)

Tying Distresses to Treatments

There are five general categories of treatments to address distresses: three categories which address surface distresses, and two which address structural distresses. Surface treatments can increase skid resistance, restore surface characteristics, and protect the surface from further oxidation and moisture intrusion. Structural treatments either restore or enhance the load-carrying capability of the pavement. These five treatment categories can be summarized as follows and are discussed in further detail below:

1. Surface treatments, liquid-only: fog seals, rejuvenating fog seals, and crack seals;
2. Surface treatments, liquid plus fine aggregate: chip seals, scrub seals, slurry seals, micro surfacing, and cape seals;
3. Surface treatments, AC-based: ultra-thin bonded wearing courses (UTBWCs), thin overlays (<1.5 in., <38.1 mm), and mill and fills (<1.5 in., <38.1 mm);
4. Structural treatments, AC-based: overlays (≥1.5 in., ≥38.1 mm), mill and fills (≥1.5 in., ≥38.1 mm), and complete removal and replacement of the AC layer; and
5. Structural treatments, in-place recycling: hot in-place recycling (HIR), cold in-place recycling (CIR), and full-depth reclamation (FDR).

Among the first category, liquid-only surface treatments, are fog seals, rejuvenating fog seals, and crack seals. Fog seal and rejuvenating fog seal treatments can be placed on roads with minor surface cracks, oxidation, and raveling due to segregation or poor compaction. Rejuvenating fog seals are generally placed on roads with higher levels of oxidation than standard fog seals. Care needs to be taken when applying fog seals and rejuvenating fog seals, as immediately after application they may reduce surface friction. Crack seals include two different types: crack filling and crack sealing. Crack filling is used on nonworking cracks, which have horizontal movement of less than 1/8 in. (3.2 mm) over a yearly cycle. Crack sealing, however, is used on working cracks, which have movement greater than 1/8 in. (3.2 mm) over a yearly cycle. Regardless of whether the crack is working or not, crack sealing is appropriate for the following types of cracks: block, longitudinal, thermal, edge, reflective, and transverse. Figure 4.4 shows both a rejuvenating fog seal and crack sealing.

The second category, liquid plus fine aggregate surface treatments, includes chip seals, scrub seals, slurry seals, microsurfacing, and cape seals. Chip seals and slurry seals can be placed on roads with minor cracking of less than 1/4 in. (6.4 mm), raveling, oxidation, and polished aggregates. Chip seals tend to provide higher surface friction after placement, while slurry seals can also be placed on roads with bleeding. Micro surfacing can also be used on roads with the same distresses as chip seals and slurry seals but is often used when a quick return to traffic is desired. In addition, micro surfacing can provide structural capacity, so it can be utilized to even surface profiles or fill-in static ruts. Scrub seals are like chip seals, except they can be used on roads with larger cracks (including fatigue, longitudinal, and transverse) and on roads with higher levels of oxidation. The polymer-modified rejuvenating emulsion in a scrub seal not only coats the surface of the road, but also fills in cracks. Finally, a cape seal is either a chip seal or scrub seal, followed by either a slurry seal or microsurfacing, which creates four distinct combinations. Cape seals are used on roads with moderate cracking, polished aggregate, bleeding, oxidation, and raveling. The images shown in Figure 4.5 portray a slurry seal and scrub seal.

AC-based surface treatments, the third treatment category, includes UTBWC, thin overlays (<1.5 in., <38.1 mm), and mill and fills (<1.5 in., <38.1 mm). UTBWC is a

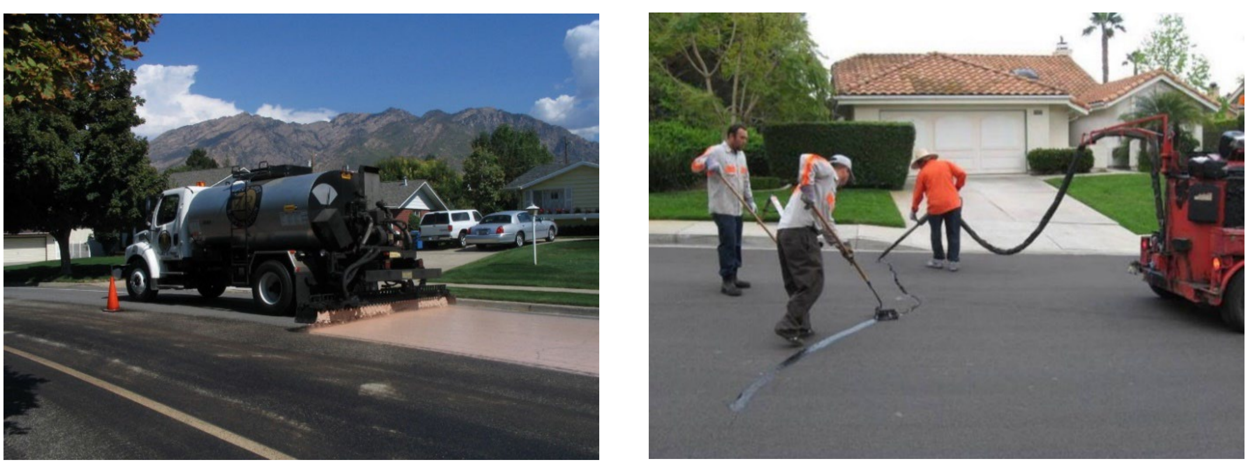

Figure 4.4 Application of a rejuvenating fog seal (left) and crack sealing (right) on AC roads. (Image from RoadResource.org.)

Figure 4.5 Application of a slurry seal (left) and scrub seal (right) on AC roads (image from RoadResource.org.)

combination of polymer-modified emulsified asphalt and open-graded AC. Ultra-thin bonded overlays seal the existing pavement surface, mitigate light cracking, bleeding, polished aggregate and raveling, and prevent further pavement oxidation. The emulsified asphalt creates a strong bond between the existing pavement surface and the newly placed overlay that does not delaminate or bleed when applied correctly. In addition, the gap-graded aggregate structure allows water to flow through the surface and out the side (lateral drainage on the shoulder), while the strong aggregate skeleton resists rutting in the overlay. Thin overlays and mill and fills less than 1.5 in. (<38.1 mm) completely restore the pavement surface to a new AC surface. However, this third category is limited to less than 1.5 in. (<38.1 mm) because it only addresses surface issues, not adding any structural capacity. Thin overlays are generally used when existing roadway geometry does not need to be maintained and when overhead clearance is not an issue. If these two areas are a concern, a mill and fill is preferred. Figure 4.6 shows images of both a UTBWC and a thin overlay.

The fourth treatment category, AC structural treatments, includes overlays ≥1.5 in., ≥38.1 mm), mill and fills ≥1.5 in., ≥38.1 mm), and complete removal and replacement of the AC layer. These treatment options are able to address many types of pavement distress within the thickness of the treatment. Similar to the third category, the end result is a completely restored flexible pavement surface. However, since more than 1.5 in. (≥38.1 mm) is placed in the overlays and mill and fill, structural capacity is added to the roadway. Regarding mill and fill, if more than 1.5 in. (≥38.1 mm) needs to be removed, it is implied that the existing pavement structure is not sound to the depth being replaced, therefore, structural capacity is added to the existing pavement. Of course, the complete removal and replacement of AC layer will completely remove all distresses but is also the most expensive treatment of all treatments discussed.

Figure 4.6 Application of a UTBWC (left) (Image credit: A. Braham) and a thin overlay (right) on AC roads (image from RoadResource.org).

Figure 4.7 shows images of both a mill and fill and a complete removal and replacement.

Finally, the fifth treatment category is in-place recycling structural treatments. Like the fourth category, these treatments address types of pavement distresses within the thickness of the treatment. HIR is generally placed less than 3.0 in. (76 mm), whereas CIR recycles anywhere between 2.5 to 6.0 in. (64 to 152 mm). Both HIR and CIR are designed to only recycle fully bound AC material. On the other hand, FDR can reclaim between 6.0 to 18.0 in. (152 to 457 mm) of in-place material. The potential reclaimable material with FDR includes not only fully bound AC material but also engineered unbound material such as crushed base courses and even in-place soil. Figure 4.8 shows images of both the HIR and FDR processes.

It should be noted that many references can be found for the aforementioned

Figure 4.7 Application of a mill and fill (left) and a complete removal and replacement (right) on AC roads (image from A. Braham.)

Figure 4.8 Application of HIR (left) and FDR (right)
(image from RoadResource.org.)

treatments; however, for a broad overview, three helpful sources of information include the application certificate run by the University of Arkansas (Braham, 2017), RoadResource.org (PPRA, 2022), and *NCHRP Report 523: Optimal Timing of Pavement Preventive Maintenance Treatment Applications* (Peshkin et al., 2004). All three resources can provide further details on each previously described treatment. In addition to mapping the existing pavement distresses to potential treatments, two other motivations for choosing specific treatments are economic and environmental impacts.

Economic Impact of Treatments

Several factors can impact the LCCA, of pavement preservation treatments. One of the most contentious topics of LCCA is the agency cost used for each treatment. References for the treatment costs include national level reports, journal articles, and state data. Three resources to begin exploring treatment costs at a national level are RoadResource.org (PPRA, 2022), *NCHRP Report 523*, and Strategic Highway Research Program (SHRP) 2 Report S2-R26-RR-2: Guidelines for the Preservation of High-Traffic-Volume Roadways (Peshkin et al., 2011). However, a word of caution is given when looking at published reports. First, it is important to know from where specific cost numbers are derived. For example, the costs shown on RoadResource.org are an average of costs from around the United States from approximately 2017. For a crack seal, RoadResource.org provides a cost of \$0.48/yd^2 (PPRA, 2022). Conversely, Peshkin et al. (2011) provides the cost of crack seal from \$0.10 to \$1.20/ft. Here, two immediate differences appear: each source uses different units, and one source gives an exact number while the other gives a cost range. In addition, these costs are up to 10 years old, and infrastructure material cost has generally increased over that time period. Therefore, it is not only crucial to be aware that such cost variances exist, but it is also important to look at many sources to get a more accurate perspective of treatment costs from a national level.

Another source for treatment cost is journal articles. Hajj et al. (2010) looked at multiple treatments in Nevada, which included chip seals, sand seals, scrub seals, fog/flush, crack filling, maintenance overlay cold mix, and machine patching paver. In one single Nevada district, the price of chip seals varied between $4,501/lane mile and $5,959/lane mile. However, the price of a chip seal on RoadResource.org calculates a cost of $14,502/lane mile. Between these differing costs is the range provided by Peshkin et al. (2011), which estimates the cost of a chip seal to be from $10,560/lane mile to $14,080/lane mile. Therefore, it is important to carefully analyze and cite any assumptions and sources when exploring cost estimation.

A third method is to explore weighted average prices within specific states. This method is most accurate for regional LCCA exercises. For example, weighted average prices for Arkansas in 2021 estimated the cost of a fog seal to be between $2.97 to $5.88/gal (Arkansas DOT, 2021). If 0.10 gal/yd^2 is placed, the price of a fog seal is between $2,091/lane mile and $4,140/lane mile within the state. The price of a fog seal on RoadResource.org is $4,013/lane mile, just under the maximum cost estimated in Arkansas, whereas the cost of a fog seal is $3,168/lane mile in *NCHRP Report 523* (Peshkin et al., 2004). By leveraging the weighted average for states, the cost structure compared the price of chip seals to 2-in. overlays, mill and fill, remove and replace, and FDR using 2014 weighted average prices in Arkansas (Braham, 2016). In this exercise, a chip seal was estimated to cost $11,990 USD/lane mile, which falls within the range that Peshkin et al. (2011) described above. Table 4.2 provides a cost summary for different treatments based upon their sources of data.

In addition, other factors influence the LCCA. This can include analysis period, performance period of treatment, terminal values of treatments, discount rates, and user costs. A similar exercise can be performed with each of these factors as was performed with agency costs above, and an excellent summary of these factors can be found in NCAT Report 19-03 (Gu and Tran 2019). In addition, an entire report, NCAT Report 20-05, is dedicated solely to pavement end-of-life considerations (Musselman and West, 2020).

Since differing conclusions regarding an LCCA can be made depending on what assumptions or resources are used, there are major benefits to utilizing more than one resource, fully acknowledging that the costs from one source of data may not be completely representative of costs from other data sources. One example of such an analysis was performed by Kiihnl and Braham (2021). This research was done as an off-shoot of an in-class project that explored the impact of different pavement maintenance and rehabilitation treatments within a network. Students enrolled in a required senior-level course were broken into groups, and each group was assigned one maintenance treatment and one rehabilitation treatment. Each group used the

Table 4.2 Summary of Agency Costs for Specific Treatments from Various Sources

Treatment	Cost	Source Reference
Crack seal	$0.48/yd^2	PPRA, 2022
	$0.10 to $1.20/ft	Peshkin et al., 2011
Chip seal	$4,501/lane mile to $5,959/lane mile	Hajj et al., 2010
	$14,502/lane mile	PPRA, 2022
	$10,560/lane mile to $14,080/lane mile	Peshkin et al., 2011
	$11,990/lane mile	Braham, 2016
Fog seal	$2,091/lane mile to $4,140/lane mile	Arkansas DOT, 2021
	$4,013/lane mile	PPRA, 2022
	$3,168/lane mile	Peshkin et al., 2004

Arkansas DOT network length (over 37,000 lane-miles across freeways, multilane highways, and two-lane highways), Arkansas DOT traffic (annual average daily traffic on each highway type), Arkansas DOT network pavement condition (pavement condition index (PCI) grades A through F of the three highway types, where “A” is excellent and “F” is poor), and the 2018 Arkansas DOT pavement preservation, rehabilitation, and reconstruction budget (approximately $236 million). Armed with this data from Arkansas DOT, each group entered their one maintenance treatment and one rehabilitation treatment into the following four calculations on RoadResource.org: 1) equivalent annualized cost, 2) life-cycle cost, 3) remaining service life, and 4) cost–benefit value. Figure 4.9 shows the cost of placing each treatment throughout the entire Arkansas DOT network over a 50-year analysis period, assuming no salvage value for any of the treatments. The same treatment was placed cycle after cycled on the entire network (note, this is not recommended for any network, but does a good job of

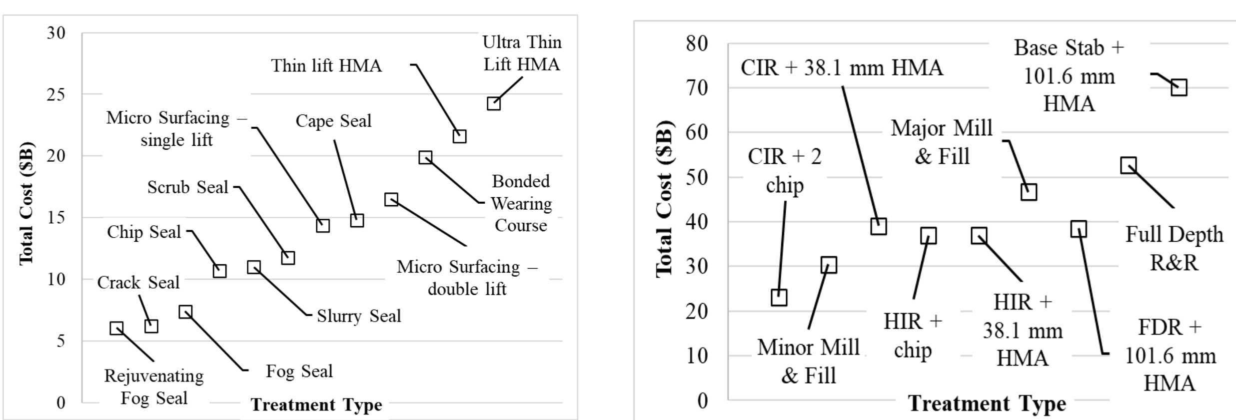

Figure 4.9 Life-cycle cost of maintenance treatments (left) and rehabilitation treatments (right) over entire Arkansas DOT network.

emphasizing the economic costs of each treatment over an extended time period). Along with the default costs for each treatment, the standard life extension values were also leveraged.

Two very interesting trends can be seen in Figure 4.9. First, as treatments become more intensive, the total price increases. Looking at the maintenance treatments, the treatments only using asphalt emulsion (e.g., fog seals) are less expensive than those using aggregate (e.g., chip seals or micro surfacing). However, all emulsion-based treatments are less expensive than the HMA-based treatments. The lower intensity treatments are generally placed on roads in better condition, so applying maintenance treatments on roads that are still in good condition can save agencies a significant amount of money. Second, while all maintenance treatments cost under $25 billion, all but one rehabilitation treatment costs over $30 billion. Therefore, it becomes clear that maintenance is cheaper than rehabilitation. While the references discussed earlier in this section have slightly different costs and life extensions, all of them follow this same trend. Placing maintenance treatments on roads in good condition reduces long-term costs, and maintenance is always cheaper than rehabilitation.

As mentioned earlier, the senior-level course activity assumed that one treatment was placed across the entire network. Realistically, as mentioned above, this is not good practice and is not recommended (as FHWA has said, “right treatment, right pavement, and right time”). Even so, the exercise did expose the students to the benefits of proper pavement maintenance, allowed them an introduction to each treatment, and the chance to see how their own treatments compared to their peers’ treatments. Realizing the inappropriateness of placing a single treatment on an entire network, Casillas and Braham (2021) developed a new class exercise in which students looked at groups of treatments. Using the same data from Arkansas DOT as the initial class project and RoadResource.org, the 2018 budget was allocated to each highway type based on vehicle miles traveled. This was an important assumption, as freeways are by far the lowest lane-miles in the state, but have the highest traffic, whereas the opposite is true with two-lane highways (i.e., high lane-miles and low traffic). Thus, the following treatments were placed on each highway type:

- Freeway: rejuvenating fog seal, micro surfacing, minor mill and fill, CIR with HMA, and full-depth remove and replace.
- Multilane highway: rejuvenating fog seal, scrub seal, CIR with two chip seals, CIR with HMA, and FDR with HMA.
- Two-lane highway: rejuvenating fog seal, chip seal, CIR with two chip seals, CIR with HMA, and FDR with HMA.

By applying a specific algorithm, which can be found in the paper (Casillas and Braham, 2021), the time to achieve “pure” pavement preservation was calculated. *Pure preservation* was defined as all roads being in good condition (PCI A or B) with a remaining service life of zero lane-mile-years. In short, this means all roads are in good condition, and the network is not getting better or worse. This algorithm involved first treating all PCI A roads, second, treating the same percentage of PCI D and F roads, and third, maximizing the remaining service life within the budget. It was assumed that over time, the number of PCI D and F roads would decrease, as once they were rehabilitated, the road would be in PCI A condition and would remain there. Although several assumptions were made within this exercise, it was discovered that by using this algorithm along with the treatments listed above, the Arkansas DOT network could reach pure preservation in just over 46 years. At which time, it is estimated that Arkansas DOT could save approximately $154 million per year on maintenance.

These classroom project-based papers are just two examples of how applying pavement maintenance treatments to roads in good condition (a key part of proper pavement preservation) can reduce costs to agencies. As mentioned above, there are many published articles available that explore the life-cycle cost of pavements, and all tell a similar story, albeit with slightly differing numbers. It has been proven that keeping a roadway network in good condition costs less than keeping a network in poor condition. Placing maintenance treatments costs less than rehabilitation treatments. There are many papers available on the economic perspective of pavement preservation, but there is a significantly smaller number of papers available on the environmental perspective—albeit a number that is growing.

Environmental Impacts of Treatments

While there are several ways to quantify the potential environmental impacts, there seems to be a growing consensus around using LCA, communicated via environmental product declarations (EPDs) by material/product manufacturers.

LCA is a methodology to quantify the potential environmental impacts of a product or a process defined by ISO 14040: Life-cycle assessment principles and framework and ISO 14044: Life-cycle assessment requirements and guidelines. LCA can be conducted for various scopes—cradle-to-gate looking at individual construction material emissions or cradle-to-grave looking at entire pavement life cycle. FHWA published a comprehensive report on the LCA framework for pavements (Harvey et al., 2016), but the broad concepts are as follows:

In short, a pavement LCA takes the inputs and outputs of the four life-cycle stages:

1. Production;
2. Construction;
3. Use; and
4. End of life.

Such inputs include the fuel, electricity, and materials used associated with the extraction, transportation, production of the pavement materials, the transportation to construction site and construction of the pavement, the use of the pavement, any preservation, maintenance, or rehabilitation, and the end-of-life. Outputs include wastes and emissions to air, soil, and water associated with each input. Wastes can include solids, liquids, or hazardous wastes. A key part of the LCA is to translate the flows from nature and to nature into potential indicators of environmental and human impacts, known as life-cycle impact assessment phase. Such impacts can include depletion of resources, human health, and the ecosystem, as well as others.

EPDs, defined by ISO 14025, are essentially a standardized LCA. As such they are a method for material/product manufacturers to communicate the environmental impacts of their given product, such as asphalt binder, aggregate, additives, or the asphalt mixture as a whole. As LCAs, even EPDs can be of various scopes. For construction materials, EPDs are typically cradle-to-gate LCAs, thus including the potential impacts from raw material extraction, transportation, and material manufacturing and can be product and facility specific. EPDs can be related to nutrition labels on the side of a cereal box, but instead of nutritional information, environmental information is provided.

The largest reason EPDs are gaining popularity is that many agencies are moving toward requiring them in procurement. As of early 2022, California is the only agency that requires EPDs, but there are multiple state and local agencies moving in a similar direction. Through the Buy Clean California Act, it's required that all structural steel, concrete reinforcing steel, flat glass, and mineral wool board insulation must have a global warming potential (GWP) below specified limits. These limits are summarized in Table 4.3.

Table 4.3 GWP Limits in California

Eligible Material	Maximum Acceptable GWP limit (Unfabricated)*
Hot-rolled structural steel sections	1.01 MT CO_2 eq./MT
Hollow structural sections	1.71 MT CO_2 eq./MT
Steel plate	1.49 MT CO_2 eq./MT
Concrete reinforcing steel	0.89 MT CO_2 eq./MT
Flat glass	1.43 MT CO_2 eq./MT
Light-density mineral wool board insulation	3.33 kg CO_2 eq./1 m^2
Heavy-density mineral wool board insulation	8.16 kg CO_2 eq./1 m^2

Note: MT = metric ton; CO_2 = carbon dioxide.

It is important to recognize that EPDs are the end product of a sequence, which begins with a LCA and then moves to a product category rule (PCR). After the LCA and PCR are developed, the EPD can be written. However, if existing PCRs exist then future LCAs must follow the published PCR.

The PCR sets the rules, requirements, and guidelines for conducting the LCA and developing the EPD which is published by an EPD Program Operator. This is what sets standardizes the LCA and sets EPDs apart from other LCAs. In efforts to harmonize EPDs for construction materials, ISO Standard 21930 published in 2017 serves as the "core PCR" for all construction products and services. As such, ISO 21930 states a broader set of rules that apply to all construction materials like asphalt, concrete, steel, as well as construction works such as pavements and buildings. Without a PCR, EPDs cannot be created, unless there was a strong case to use ISO 21930. The main components of a PCR include

- Product category definition and description;
- Goal and scope definition, stages;
- Inventory analysis, additional environmental information;
- Impact category, inventory data categories;
- Materials and substances to be declared; and
- Instructions for producing data, content, and format.

The program operator is the entity that oversees the development of the sub-category PCRs and verifies EPDs developed based on this PCR. A program operator works with various industry associations and interested stakeholders (e.g., public agencies) to form a "PCR Committee" that oversees the development of a "sub-category PCR" for an individual construction material. PCRs are typically only valid for 5 years and require both public review and a third-party panel review. Note that the LCA "informs" a PCR and that the PCR can be developed in tandem with an LCA. However, the LCA must be completed prior to the PCR being completed. This can be a lengthy process spanning at least a year.

After the LCA and PCR are developed, the EPD is written. The intent of an EPD is to provide LCA-based and other types of environmental information. Such EPDs are defined by ISO 14025. Like a PCR, an EPD requires a third-party review panel. A typical EPD has many sections, but also contains a key for a summary table of material quantities of various types. For example, the NAPA has developed a tool (i.e., Emerald Eco Label) that allows member companies to develop EPDs for one short ton of asphalt mixture (NAPA, 2022). There are many examples of EPDs available on NAPA's website, which can be downloaded for free. These EPDs provide information on multiple parameters such as GWP, ozone depletion, acidification, eutrophication, and smog air. Also found on the website are these emissions summarized in a table across the life-cycle stages (cradle-to-gate) of asphalt mixtures. Meanwhile for asphalt binders, the

Asphalt Institute (AI) completed a cradle-to-gate LCA for asphalt binder in 2019 and is currently in the process of developing an EPD program for the same scope. Rather than becoming the program operator, AI has contracted a program operator called “SmartEPD.” Currently, smartEPD has formed a PCR committee with 20 participants from asphalt binder industry to the external stakeholders from the FHWA, U.S. Environmental Protection Agency and others to develop a “sub-category PCR” for asphalt binder. The AI LCA is for four types of asphalt binder: asphalt binder without additives, asphalt binder with styrene butadiene styrene, asphalt binder with terminally blended ground rubber tire, and asphalt with polyphosphoric acid and is currently the dataset prescribed by the NAPA PCRs for asphalt mixtures and used in the NAPA tool to create asphalt mixture EPDs. The AI LCA can be found on AI’s website (2021).

At this point, almost all asphalt-based EPDs incorporate only the production stage. The EPDs defined by NAPA include raw material extraction and processing (A1), transporting of raw material to the plant (A2), and production (A3) of the asphalt for various asphalt mixtures (with and without RAP) and gradations, and both hot mix and warm mix. Like NAPA, the AI LCA only includes the production stage, or the cradle-to-gate stage.

Finally, the Pavement Preservation and Recycling Alliance is in the process of developing eight EPDs for asphalt emulsions:

1. Neat asphalt emulsion;
2. Neat asphalt emulsion with rejuvenating agents;
3. Neat asphalt emulsion with fuel oil;
4. Neat asphalt emulsion with rejuvenating agents and fuel oil;
5. Polymer-modified asphalt emulsion;
6. Polymer-modified asphalt emulsion with rejuvenating agents;
7. Polymer-modified asphalt emulsion with fuel oil; and
8. Polymer-modified asphalt emulsion with rejuvenating agents and fuel oil.

To date, all established EPDs in the pavement industry look only at the production stage, or cradle-to-gate. However, when considering pavement maintenance and rehabilitation, it would be of great importance to explore the construction, use, and end-of-life stages of pavements as well. Preliminary research has shown that treatments utilizing asphalt emulsion produce fewer emissions than treatments utilizing HMA (Casillas and Braham, 2020). Treatments within this study that used asphalt emulsion (e.g., CIR with two chip seals) have up to a 63% greenhouse gas reduction when compared to a minor mill and fill. There is significant work still to be done within this area, but based on LCCA trends, it is anticipated that proper pavement preservation and maintenance will reduce the environmental impact.

Context-specific standardization is necessary for appropriately utilizing both LCCA and LCA in the context of pavements. While the pavement domain stakeholders have experience working with the LCCA methodology, the concept of LCA through mechanisms such as EPDs are being currently explored and there is a room for further standardization in the future. Although the research is accelerating, it is widely acknowledged that a more standardized system of developing PCRs and EPDs is necessary for moving forward in order to better implement EPDs (Mukherjee et al., 2020).

Conclusions

The use stage, or life stage, of a pavement must consider many different perspectives, including evaluating roadways, relating observed distresses to either surface or structural issues within the pavement, tying distresses to specific treatments, quantifying the economic impacts, and capturing the environmental impacts of treatments. Each of these perspectives can be briefly summarized:

- Both visual and vehicle-based systems can evaluate the skid resistance, roughness, profile, deflection, and layer thickness of existing pavements.
- Based on the data from this evaluation, pavement distresses can be sorted into surface issues or structural issues. Surface issues can generally be addressed using pavement maintenance, while structural issues require either rehabilitation or complete reconstruction.
- Once the pavement's distress is properly identified, an appropriate treatment must be selected to address the distress. These treatments can be loosely sorted into five categories:
  1. Surface treatments, liquid-only,
  2. Surface treatments, liquid plus fine aggregate,
  3. Surface treatments, asphalt concrete-based,
  4. Structural treatments, asphalt concrete-based, and
  5. Structural treatments, in-place recycling.
- It is important to cite sources and assumptions while performing an economic analysis of pavement, especially a LCCA. However, it has been widely proven that keeping a roadway network in good condition costs less than keeping a network in poor condition, and that placing maintenance treatments costs less than rehabilitation treatments.
- While quantifying potential environmental impacts from pavement treatments or materials may be a new topic for pavement domain stakeholders, standardized mediums such as EPDs, based on the robust method of LCA, are paving the way towards implementation.

References

Arkansas DOT. 2021 Weighted Average Prices, 2014 Specification, Arkansas Department of Transportation, 2021. https://www.ardot.gov/divisions/program-management/construction-contract-development/construction-contractors/weighted-average-prices/. Accessed August 2022.

ASTM. Standard Test Method for Measuring Rut-Depth of Pavement Surfaces Using a Straightedge. ASTM E1703-10. ASTM International, West Conshohocken, Pa., 2016.

ASTM. Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique. ASTM E965-15. ASTM International, West Conshohocken, Pa., 2019.

ASTM. Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys. ASTM D6433-20. ASTM International, West Conshohocken, Pa., 2020.

ASTM. Standard Test Methods for In-Place Density and Water Content of Soil and Soil-Aggregate by Nuclear Methods (Shallow Depth). ASTM D6938-17. ASTM International, West Conshohocken, Pa., 2021a.

ASTM. Standard Test Method for In-Place Density (Unit Weight) and Water Content of Soil Using an Electromagnetic Soil Density Gauge. ASTM D7830-14. ASTM International, West Conshohocken, Pa., 2021b.

BEA. Current-Cost Net Stock of Government Fixed Assets, Table 7.1, Bureau of Economic Analysis. Last Revised on August 19, 2021.

Braham, A. Comparing Life Cycle Cost Analysis of Full Depth Reclamation versus Traditional Pavement Maintenance and Rehabilitation Strategies. *Transportation Research Record: Journal of the Transportation Research Board, No. 2573*, 2016, pp. 49–59.

Braham, A. Applications of Asphalt Emulsions (Certificate 2). Pavement Maintenance and Rehabilitation Professional Development Courses, University of Arkansas, Fayetteville, Ark., 2017.

BTS. Public Road and Street Mileage in the United States by Functional System, Table 1-5, Bureau of Transportation Statistics. Updated December 2021.

Casillas, S., and A. Braham. Exploring the cost benefit value and relative emissions of pavement preservation treatments using RoadResource.org. Pavement, Roadway, and Bridge Life Cycle Assessment 2020: Proceedings of the International Symposium on Pavement. Roadway, and Bridge Life Cycle Assessment 2020, LCA 2020, Sacramento, Calif., 2020.

Casillas, S., and A. Braham, A. Quantifying Pavement Preservation in Arkansas. *Journal of Transportation Engineering, Part B: Pavements*, Vol. 147, No. 4, 2021.

Gu, F., and N. Tran. Best Practices for Determining Life Cycle Costs of Asphalt Pavements. NCAT Report 19-03. National Center for Asphalt Technology, Auburn, Ala., 2019.

Hajj, E., L. Loria, and P. Sebaaly. Performance Evaluation of Asphalt Pavement Preservation Activities. *Transportation Research Record: Journal of the Transportation Research Board, No. 2150*, 2010, pp. 36–46.

Harvey, J., J. Meijer, H. Ozer, I. Al-Qadi, A. Saboori, and A. Kendall. Pavement Life-Cycle Assessment Framework. FHWA-HIF-16-014. Federal Highway Administration, U.S. Department of Transportation, 2016.

Kiihnl, L., and A. Braham. Exploring the influence of pavement preservation, maintenance, and rehabilitation on Arkansas' highway network: an education case study. *International Journal of Pavement Engineering*, Vol. 22, No. 5, 2021.

Miller, J., and W. Bellinger. Distress Identification Manual for the Long-Term Pavement Performance Program. FHWA-HRT-13-092. Federal Highway Administration, McLean, Va., 2014.

Mukherjee, A., C. Bhat, and J. Harvey. Challenges in Meeting Data Needs for Use of Environmental Product Declarations in Pavement Design and Construction: State of Practice and Future Scope. FHWA-HRT-20-022. Federal Highway Administration, U.S. Department of Transportation, 2020.

Musselman, J., and R. West. Life Cycle Cost Analysisz—End of Life Considerations. NCAT Report 20-05. National Center for Asphalt Technology, Auburn, Ala., 2020.

NAPA. Emerald Eco Label. National Asphalt Pavement Association. Developed by Trisight. https://asphaltepd.org/. Accessed August 2022.

Peshkin, D., T. Hoerner, and K. Zimmerman. *NCHRP Report 523: Optimal Timing of Pavement Preventive Maintenance Treatment Applications*. Transportation Research Board, Washington, D.C., 2004.

Peshkin, D., K. Smith, A. Wolters, J. Krstulovich, J. Moulthrop, and C. Alvarado. SHRP 2 Report S2-R26-RR-2: Guidelines for the Preservation of High-Traffic-Volume Roadways. Transportation Research Board, Washington, D.C., 2011.

PPRA. RoadResource.org. Pavement Preservation and Recycling Alliance. www.roadresource.org. Accessed August 2022.

Thinkstep. Life Cycle Assessment of Asphalt Binder. On behalf of the Asphalt Institute, v2.1, 2019.

CHAPTER 5

Current Activities and Readily Implementable Technologies and Processes

Background

The first third of the workshop consisted of foundational presentations on the life cycle of a pavement. The primary concepts of these three presentations can be found in Chapters 1 to 4, as seen in Figure 5.1. The middle third of the workshop consisted of breakout groups, where the content of the presentations was discussed through the lens of pavement materials, pavement design, and pavement use stage, using the following questions as seed questions:

- What are today's opportunities to break down the silos?
- What can we immediately implement?
- What are problems or issues that we face?
- What is the biggest gap, biggest need that we face to break down the silos?
- What are current activities and readily implementable technologies and processes?
- What are specific next steps, specific groups that could begin working together more to move forward?

The last third of the workshop consisted of a panel session, where five panel members discussed the presentations, the breakout group discussions, and some of their own perspectives on the seed questions. The five panel members, with their roles

Figure 5.1 Foundation presentations setting the stage for breakout group discussions.

at the time of the workshop, were

- Silvia Caro, Professor and Associate Dean for Academic Affairs, Universidad de los Andes.
- Amy Epps-Martin, Professor, Texas A&M University.
- Barry Paye, Chief Materials Engineer, Wisconsin DOT.
- David Peshkin, Vice President and Chief Engineer, Applied Pavement Technology.
- Dominique Pittenger, Research Assistant Professor, University of Oklahoma.

The rest of this chapter will be divided into two parts. First will be a summary of the breakout notes, and second a summary of the panel discussion. The attempt of this chapter was to capture the concepts covered during the breakout groups and panel session and to minimize any editorial comments by the workshop organizers. Chapter 6 will provide both a reflection on these topics moving forward and the content of the entire workshop by the workshop organizers.

Breakout Notes

There were five sets of breakout groups that discussed the seed questions: material selection, structural design, construction, maintenance, and a virtual group. The notes taken during the breakout groups are summarized below, including a recap of participants who remotely attended the session. Figure 5.2 shows the breakout groups in action.

Figure 5.2 Breakout groups discussing material selection, structural design, construction, and maintenance.

Material Selection

The first breakout group discussed material selection. One of the questions asked was: do current tests run on materials predict performance? This led to discussion on whether the community even has the necessary tests to tie mixture performance in the lab to the anticipated structural performance. It was noted that a lot of the existing tests are index tests performed on plant mixed lab-compacted samples. While there is nothing inherently wrong with this approach, it was acknowledged that acceptance thresholds for these tests were necessary. In addition, it was recognized that a “good enough” practical test (preferably an index test), was necessary that could be input into the M-E design software being used by the structural designers. Finally, there was discussion on the need to connect lab tests with QA in the field, which would also provide a link to asset management of materials.

In addition to a robust discussion on material testing, there was also a reflection on how much time and energy has been invested into our body of knowledge dealing with virgin material (mainly aggregate and asphalt binder). However, this robust set of work is often set to the side when we simply “throw in a random material.” Random materials have included ground tire rubber, RAP, recycled asphalt shingles, re-refined engine oil bottoms, and plastics. While strides have been made in incorporating these recycled materials, it was discussed that the community needs to pay more attention to these new materials and their properties, and how we manage the addition of these recycled materials. The groups felt that, over time, the quantity and number of recycled materials being placed in AC are only growing, so we need to establish models, measurements, incentives, pay items, and potential environmental benefits in order to quantify the addition of these recycled materials. Next, we need to take these findings and justify the use of the materials from a business decision perspective. With these newly developed tools, we will be more prepared for future generations of recycled materials being added into AC pavements.

Finally, there were three other topics that were briefly discussed in the materials group. First, there was some discussion on whether existing aging protocols are sufficient, and how the aging protocols can be applied to perpetual pavements. Second, it was acknowledged that we often do not know the genesis of the issues we currently have with AC pavements: is it just the asphalt binder, just the aggregate, or a combination? Finally, third, the concept of BMD was discussed, and the importance of performance testing to evaluate mixtures, especially in relation to cracking and rutting.

Structural Design

The structural design breakout group made geotechnical engineers proud by starting with a discussion on the materials below the bound layers of the pavement structure. They asked a series of questions related to this part of the structure design, including:

- Are stabilized bases appropriate for perpetual pavement? If so, how are compressive strains at the bottom of fully bound layers treated?
- Is nonlinear modeling of stabilized base materials important?
- If strain at the bottom is already low, why do we need a fatigue-resistant base course?

This led to further discussion on the importance of balancing pavement layer thickness with the possibility of modifying unbound materials.

In addition to the discussion on unbound materials, there were also conversations around design strategies. There were thoughts on balancing the thickness of bound layers and modifying the bound layers, and how these two concepts impact, and ideally improve, fatigue resistance. In addition, it was acknowledged that there is a disparity between mechanistic pavement design and managing cracking. There was also discussion on including more parameters into the pavement design process, including the desired life of the pavement (years) and constructability of the pavement structure. Finally, while there has been some movement toward incorporating variability and cost into the design, there needs to be a better understanding of these two concepts.

Finally, there were two additional items discussed. First, how does the community standardize performance measures, and then incorporate these performance measures into the design. Second, it was recognized that there is a need to calibrate transfer functions to predict performance better.

Construction

The construction breakout group began with discussion on field controls. They determined that a more robust strategy for identifying the field controls was necessary. Once the field controls were identified, an evaluation of the field controls should be executed to determine which field controls could be relaxed, or even removed. Two specific examples were provided for field controls. The first example was the importance of maintaining material properties during construction, and the second example was the need to put more work into percent within limits (PWL). For the PWL, the group talked about the importance of quantifying the return on investment of PWL. If the quality goes up, it will cost *x* more but will save *y*; however, exactly what *x* and y represent is not currently clear.

In addition to talking about field controls, the construction group also discussed the importance of emerging technologies. Minnesota DOT was cited as being a leader in this area, as they are a lead state in the National Road Research Alliance. Some projects that have been funded over the years include enhancements of material delivery management systems, asphalt real time smoothness, continuous moisture measurements of pavement foundations, intelligent compaction, and other such topics.

Maintenance

When talking about the maintenance of our roads, the topic of life span will almost always come up, and the maintenance breakout group was no exception. There was discussion on how we can design preservation over the life span of the road, ensuring that the proper treatment is placed on the proper road. The conversation continued on the importance of including reliability in the life-cycle design, and how both planning and budgeting of roads should be life-cycle-based. Along these lines, the group talked about the importance of data collection and data quality management, and the challenges associated with data, including the expense and high level of labor necessary.

There was also discussion on how to move agencies toward more preservation and maintenance of roads. For example, the group felt that there currently is no place holder for maintenance, most owners currently jump right to rehabilitation. Therefore, a space needs to be carved out that recognizes and acknowledges maintenance. This includes collecting and using data and aligning this data with the pavement system. Some tools that were identified to help along these lines included Artificial Intelligence and geographic information system-based data. Cost incentives were also discussed, including changing specifications for agencies and contractors to pursue the best solution, and making a financial case for preservation and maintenance. Finally, the group saw the need for maintenance manuals and decision trees to better anticipate distresses, and therefore better anticipate which treatment to apply.

The group wrapped up discussion with identifying some potential challenges facing agencies, including implementation, communication, feedback, and how to synthesize internal platforms. In addition, work needs to be done on identifying when and where to apply treatments, as treatments are too often applied inappropriately as a band-aid solution. It was recognized that a more holistic approach was necessary to pavement design.

Virtual Audience

The virtual breakout group consisted of participants from around the world and they had a robust discussion on all facets of the workshop. They framed part of the problem as the life cycle stages behaving like silos, specifically silos that do not do a good job of communicating with each other. However, they did believe that there were opportunities to break down these silos. For example, they felt that perpetual pavements are a tool at hand and available that can capture the whole life cycle, and perpetual pavements do an especially good job of tying materials to structural design. They reiterated the need for pavement preservation and applying the right treatment at the right time during the life span of the pavement. This includes thinking long term and accommodating the information we have on hand and realizing the information we have on our hands and what is feasible to implement. Finally, they discussed the importance of buy-in from the upper administration, and the importance of the upper administration to coordinate with all the people in charge of the various areas.

The virtual breakout group also discussed specific next steps. They started with charging upper administration to get buy-in from materials, structural design, and maintenance folks to clearly define specific steps to move in the proper direction. They continued with stating the need to recommend specific cracking and rutting tests to address distresses. This was enforced with discussion on how there are so many existing cracking tests out there, including bending beam fatigue, S-VCED, Illinois I-FIT, LTRC SC(B), disc-shaped compact tension, and IDEAL-CT. Which of these tests ties the mixture performance in the lab to the anticipated structural performance in the field? A similar discussion could be had with rutting tests. The final next step discussed was the importance of identifying when and where to apply treatments and including these discussions in a more holistic approach to pavement design.

Panel Session Notes

The panel session consisted of a question and answer (Q&A) with the five panel members and an invitation for people in the audience to ask questions and put forth thoughts and recommendations as well. At the end, each panel member provided some final thoughts. Like the breakout notes, the intent of this section is to capture the concepts covered during the panel session and to minimize any editorial comments by the workshop organizers. Figure 5.3 shows the panel members in action.

The panel began the discussion with an interesting perspective: should we frame the workshop discussion around tearing down silos or building bridges between islands. While there are many similarities between the metaphors, the latter starts the conversation on a more positive note.

Discussion of the panel then transitioned into the need for better data sharing and better data setup. However, there were many candid questions, including how do we share data? How do we track and retain? How do we then leverage the data? While pavements are not necessarily associated with big data, the panel felt that pavements are an excellent example of the potential power of big data, as there is a significantly large amount of data to analyze, and it is a dynamic data set that is literally changing daily with weather and traffic. One specific example discussed was from the Wisconsin

Figure 5.3 Amy Epps-Martin, Silvia Caro, Barry Paye, David Peshkin, and Domique Pittenger discussing the presentations and breakout sessions.

DOT, which has fully transitioned into numbering projects statically and discretely, so the project number won't change over time and is based solely on the location of the project. The conversation on data finished on two primary points: the need for data integration and the need for data education.

The panel also discussed some of the hot topics of the day. For example, they talked about how the community has built a solid case for the economic case for preservation, maintenance, and rehabilitation, especially through LCCA. However, with a shift toward climate change and resiliency, is the community ready for LCAs? Two specific examples were given. First, there are environmental pressures to use recycled materials, but we need to develop models, specific measurements, incentives, and pay items, to take the perceived environmental benefits and make a business case. During audience discussion, it was mentioned that Florida has been using RAP since 1976, which means the RAP has been through the cradle-to-cradle cycle two or three times. These experiences need to be captured, quantified, and shared so others can learn and move in that direction. Another line of discussion for recycled materials revolved around the "positive pressures" to include other waste materials, such as plastics and fibers. Our specifications are very strong on virgin materials, but with this continued push for more recycling materials, we need to build more robust specifications. The second LCA discussion revolved around in-place rehabilitation treatments. It is recognized that CIR has less trucking, uses less diesel, and has fewer emissions than standard AC. But since EPDs are being written from cradle-to-grave, how do we capture the benefits and make the business case for CIR, which has many of the listed benefits in the use stage and would require a cradle-to-grave analysis to capture those benefits. However, it was recognized that states are beginning to require LCAs (Minnesota) or EPDs (California), so these are conversations that will need to be held sooner rather than later.

The conversation transitioned into the importance of buy-in from all players. This starts with administration, where they need to take the lead in coordinating all the people in charge (i.e., materials, structures, and maintenance) with defined specific steps. One potential tool that can capture the whole life cycle is the concept of perpetual pavements, as this design strategy uses specific materials in specific locations of the pavement structure to maximize the benefits of the materials: thus, building a bridge between the materials and structural design islands. This could easily be extended into programming maintenance on this beautiful pavement structure to preserve the structure and restore the surface with preventive maintenance. They also discussed how a robust system needs to be developed so that when individuals change, whether hired or elected, the system will not change. Along these lines, there was much talk about the need to increase retention in the field and the importance of training younger generations. All the panel members were engineers, but they acknowledged that engineers need to do a better job of interacting with planners and extending out a little more. Finally, they did recognize that time and resources (primarily money) were necessary to get all the groups together to talk about the best way forward.

The conversation continued with discussion on how complex the issues we face are. One example discussed was laboratory versus field prediction. We spend a lot of time and resources developing tests and transfer functions that try to tie materials in the lab to field performance, but at the end of the day, the road will only work as well as constructed. We can design the perfect predictor, but with low quality construction, the end product will not succeed. This could be minimized by tightening our construction contracts. It could also be minimized by connecting lab tests with QA in the field. If there is a threshold in the lab, how will that impact the QA in the construction? The panel also talked about how regulations that were originally developed for the benefit of our roadways may end up getting in our way. For example, there were restrictions on the maximum asphalt binder content in roads in an attempt to reduce rutting. It was also discussed how many agencies will not add rut resistant polymer-modified binder because of the restriction, even though it doesn't behave as the material did when the specifications were written. Therefore, diligence is necessary when making regulations to minimize potential negative impacts. Finally, there was discussion on the need to review and adjust specifications over time.

One interesting discussion about a potential solution to building bridges between the islands was the development of a pavement owner's manual. During this, the pavement designers, both materials and structures, are not just designing a virgin pavement, but they are designing a pavement life cycle. A structural designer should think about the maintenance. If it is a high RAP mix, when will the maintenance be performed and which treatment is the best for a high RAP mix? This will change with different mix designs, different climates, and different traffic, but it is necessary to think beyond initial traffic and initial materials. It was pointed out that more data would certainly be necessary in order to achieve this, but the idea of a pavement owner's manual was well received.

The panel wrapped up by talking about the need for everyone to be more introspective. The panel asked: how do engineers, in organizations such as TRB, FHWA, state DOTs, etc., effectively address the challenge of being grouped in specific subdisciplines rather than be more broadly aligned with transportation engineering on the whole? In TRB, should we consider developing a joint subcommittee, perhaps a life-cycle design subcommittee, that would span the five TRB committees that sponsored the workshop (Design and Rehabilitation of Asphalt Pavements; Asphalt Materials, Selection, and Mix Design; Asphalt Mixture Evaluation and Performance; Pavement Preservation; and Pavement Maintenance). They also talked about pavement engineering crossover with other subdisciplines, such as energy harvesting, low carbon materials, and innovative design approaches. When interactions with other subdisciplines in engineering come about, all parties involved must be open to engaging in the opportunities. The panel acknowledged that something this big will require a lot of perseverance, leadership, and personnel. However, it also needs to be made a priority. Data were also identified as being key, especially for preservation and maintenance. There is currently a lack of data, or perhaps a lack of access to data, to make informed decisions. Finally, the panel ended on an optimistic note, talking about how they believe all the pieces are in place, we simply need to connect them. However, in order to do this, we need to change our culture.

CHAPTER 6

Moving Forward

Chapter 5 presented the perspectives of the breakout groups during the workshop and of the panel. As mentioned, the authors of this e-circular attempted to simply summarize the thoughts of the room and to avoid any sort of commentary. In this Chapter 6, each of the authors will give a short summary of what they ascertain to be the next steps for moving forward.

Leslie Ann Myers

The aim of the workshop was in part to identify which practices are currently in place to integrate the pavement life cycle, such as the application of the PEP approach or the use of the perpetual pavement design concept. These are two existing paths forward for tying the materials stage to the structural design stage, along with right-sizing pavement preservation (i.e., applying the right treatment at the right time during the life span of a flexible pavement). Examples of these practices exist at the agency level, whether via legislative means or by exploratory research and pilot projects. Additionally, applied research endeavors have been reported by universities, agencies, and consultants that highlight tools that can be used to bridge the gaps that exist in the pavement life cycle. Recognition of what information and data is at-hand, and how that data can be leveraged and accessed in the long term, is key to helping support implementation and garnering buy-in from upper administration at the agency level (federal, state, and local).

One clear impression from the workshop is that there was consensus on the need to move to a more holistic approach to flexible pavement design into practice. Doing so presents an endeavor that requires an abundance of perseverance, leadership, and trained personnel; in short, it would be helpful for FHWA to continue its focus on integrating the various phases of the pavement life cycle.

Some considerations for specific next steps that might help in moving the integration of the flexible pavement life cycle forward include the following.

- Upper administration support at agencies that encourages the materials, structural, construction, and maintenance units to clearly define specific steps for integration of their unit activities.
- Materials engineers that place focus on putting specific cracking, rutting, and durability tests into practice for mixture design and production, incorporated into design and preservation decisions, that capture distresses and result in increased life-cycle benefits and pavement sustainability.

- Engagement of the planning unit as part of the design and decision-making process can increase the potential success of life-cycle integration. Data from planning simulations represent the predicted land use changes which can improve the accuracy of expected traffic during the pavement's life cycle. In addition, there are additional potential silos expected that come along with new legislation at the federal or state level (e.g., energy harvesting, connected vehicles, innovative materials) and connecting and communicating often with the planning and operations units can help pavements to achieve intended life cycle in the face of change. As a result, pavement engineers must think broader in understanding why and how planners, traffic managers, and asset managers apply their data and define their goals, prior to initiation of materials and pavement design.
- There are emerging and underutilized technologies and tools available for providing data during the construction stage, that can start to inform materials and pavement design on the front end, while also be used on the back end for better selection of preservation and maintenance treatments. There are agencies such as Minnesota, North Dakota, Ohio, and Texas DOTs, to name a few, that have examples of how they are incorporating information from various construction technologies into the flexible pavement life cycle.
- As part of the PEP and Sustainable Pavements initiatives, the FHWA continues to apply and refine tools that support data collection and analyses that aid in the use of LCCA and LCA. FHWA is continuing to identify examples and share information from LCA demonstrations in various agencies. In addition, international efforts (such as those in Australia, Costa Rica, etc.) which are making progress in the area of LCA and quantifying the return on the investment by engagement of economic specialists, in pavement design decision-making can be shared. Another area to explore is the integration of life cycles for other transportation modal networks, specifically the freight railroads in North America and passenger railways internationally.

David Timm

There are many avenues for improving the life cycle of long-life performance-based pavement design and construction. A critical one is the rapid assessment and integration of new materials into perpetual pavement cross sections. Efficient use of recently developed or innovative materials requires successful material property characterization and quantifying performance characteristics. This can often take years, especially to properly measure the performance characteristics. Shortening this time frame and overall cost of evaluation is essential to more readily adopt and, in some cases reject, new or innovative materials for perpetual pavements.

Future maintenance and rehabilitation of long-life pavements are also of concern. To maximize efficiency, these pavements should only require periodic surface treatments and shallow rehabilitation. How and when these treatments, milling, inlays and overlays are done are critical to the long-term success of the perpetual pavement. Furthermore, consideration should be given to the pavement's existing materials and how they may be handled during rehabilitation. For example, some materials may be more readily milled and recycled than others. Careful study and planning should be employed to ensure success.

Rehabilitating existing pavements into perpetual pavement structures, otherwise known as "perpetual by conversion", is a third critical area since the United States and much of the developed world is working with existing roadway infrastructure. Many of these roads, if properly rehabilitated, could be turned into perpetual pavements. While simply adding thickness to existing, non-distressed, pavements to increase structural capacity is straightforward, it becomes much more complicated with distressed pavements. There are currently no perpetual pavement design criteria to prevent reflective bottom-up cracking. Therefore, this is an area for future research. Meanwhile, well established techniques to prevent cracks or joints from propagating through the newly place AC may be used.

Kevin Hall

The renewed emphasis on producing long-life pavements is exciting. Note that I used the term "renewed interest." Certainly, the quest to achieve long-life pavements is not new; I started my pavement-related career as a masters' degree student in 1988, and this was a topic of importance well before that. I am excited because we now have tools—material tests, mathematical modeling, field characterization and condition assessment (to name a few)—that allow us to do so much more than we ever have before. A key element, therefore, is the proper and appropriate use and application of those tools. One caveat, however: we absolutely have much more to learn, particularly in terms of new materials and sustainability.

I agree with my colleagues, that for the most part, *we know what to do* in order to construct and maintain a long-life pavement. There are ready examples of projects in which true perpetual pavement performance has been achieved. It is reasonable, then, to ask: *why can we not achieve this in every project?* Consider (*a*) many public agencies with responsibility for pavements are (relatively) risk-averse; that is, they need to ensure a particular design procedure, test, or model works before investing substantial sums of the public's money in a particular technology. It sets up quite a paradox, which is basically a cliché: we want experience, but may not be willing to provide it. And (*b*) we in the pavement community have not yet "cracked the code" in successfully convincing the taxpaying public that (potentially) increased investment *up front*, even if it means fixing less miles for a given budget, will result in a stronger, more durable pavement network *in the long term*. It is my opinion that no technical advance in materials, construction, treatments will impact our networks to their greatest extent unless and until we can successfully get this message into the public consciousness.

Finally, a plea for those working in academia (full disclosure: my career has been at a Carnegie R1 research university). Yes, we need to continue to push boundaries, or as I like to say: *don't think outside the box—redesign the dang box*! Yes, we need to continue to produce Ph.D.'s who will have to make "an original contribution" to the field. **However**, *we need to work much, much harder on implementing what we already know how to do*. Why do we avoid applied research? Given what we know today about perpetual pavements, one of my biggest fears is that we will re-do this workshop in 2030, and will have the same, exact conversations that we had in 2022. We have (some, if not many) answers right now; let's not let perfection be the enemy of good.

Andrew Braham

After reflecting on the four presentations, the breakout groups, and the panel discussion, the one item that stuck out to me most was that all the pieces are in place, it is simply a matter of mobilizing the pieces and moving them in the right direction. How can I argue with that? Leslie began with discussing the importance of the life cycle of a pavement. Dave continued with a deep dive into structural design and construction, while Kevin presented material selection and production. The amount of knowledge in these presentations was phenomenal, all three presenters had a deep understanding of the topic. However, taking a step back and thinking about how to build bridges between these islands is what I believe the biggest challenge is. I believe that if we can design and build perpetual pavements, and then simply take care of the surface of the pavement, we would all but eliminate any structural failures of roadways, thus reducing costs and environmental impacts. The million-dollar question is, how do we get there?

I have been fortunate enough to work with Kevin Hall at the University of Arkansas for the past 12 years. While his background is strong in materials and pavement design, my background is stronger in materials and pavement preservation, maintenance, and rehabilitation. However, something that we have purposely done is to design our curriculum around the life cycle of a pavement. Kevin, who now serves in the dean's office, teaches transportation materials. I teach three graduate courses: structural design, production and construction, and use phase of pavements. Thus, our curriculum has been built around the life cycle of a pavement. At the beginning of each of the graduate courses, I make it a point to go over the life cycle of a pavement and show how the semester's content fits into the larger picture. I believe that from an educational standpoint, this is a powerful message to the students. If, from step one, our young professionals think of our pavement infrastructure from the perspective of the pavement life cycle, I believe that we will move in that direction going forward.

However, I do think that there are things that can be done today. I believe that in our research and service (i.e., TRB standing technical committees), we should emphasize how the area we are examining fits into the larger picture. When talking about materials, discuss how your findings will impact the structural design, or the use phase of the pavement. When serving on a committee, for example, TRB's Standing Committee on Pavement Preservation, think about how the preservation phase fits into the materials and structural design phases. I also believe our professional organizations—NAPA, AI, FP^2, Asphalt Emulsion Manufacturers Association, International Slurry Surfacing Association, Asphalt Recycling and Reclaiming Association, and PPRA—need to come together and work as a team to showcase the promote the benefits of flexible pavement. If the entire community begins thinking of each of these islands with respect to the other islands, I believe that bridges will naturally start forming, and we will begin to integrate each of the phases.

Abbreviations and Symbols

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
AC	asphalt concrete
AI	Asphalt Institute
APA	Asphalt Pavement Alliance
BEA	Bureau of Economic Analysis
BTS	Bureau of Transportation Statistics
CO_2	carbon dioxide
CIR	cold in-place recycling (of asphalt concrete)
EPD	environmental product declaration
ESAL	equivalent single axle loads
FHWA	Federal Highway Administration
FDR	full-depth reclamation (of asphalt concrete)
GWP	global warming potential
HIR	hot in-place recycling (of asphalt concrete)
HMA	hot-mix asphalt
ISO	International Organization for Standardization
LCA	life-cycle assessment
LCCA	life-cycle cost analysis
MEPDG	*Mechanistic–Empirical Pavement Design Guide*
MT	Metric Ton
NAPA	National Asphalt Pavement Association
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
PEP	performance-engineered pavements
PCR	product category rule
PWL	percent within limits
RAP	reclaimed asphalt pavement
SHRP	Strategic Highway Research Program
TRB	Transportation Research Board
UTBWC	ultra-thin bonded wearing course