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MAP Brief Spring 2022

Best practices and promising technologies that can be used now to enhance concrete paving

Mechanistic-Empirical Design Methods for Concrete Pavement Solutions

Spring 2022

PROJECT TITLE
Mechanistic-Empirical Design Methods for Concrete Pavement Solutions

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Introduction

Significant advancements in the design of concrete pavements and concrete overlays have been made over the past two decades with the development, acceptance, and adoption of mechanistic-empirical (ME) approaches to pavement design over empirical methods.

An empirical pavement design approach bases new designs on past observations of pavement performance. The AASHTO 1993 design guide (AASHTO 1993) is an example of an empirical design method that has been applied successfully in the past but has significant limitations when extrapolating to higher traffic levels, alternative climatic zones, and modern pavement structures, such as concrete overlays and shorter slab systems.

An ME pavement design approach, however, uses calculated pavement responses (stresses and deflections) based on the road structure, materials, and climate inputs in order to predict the expected pavement performance in terms of cracking, faulting, and the international roughness index (IRI). An example of a state-of-the-art ME method is AASHTOWare Pavement ME Design (AASHTO 2008; AASHTO 2020).

The major benefit of ME over empirical methods is the consideration of climatic, material, and traffic factors, as well as of pavement design features that significantly influence concrete pavement performance. The design inputs for ME methods include the pavement type, layer and material properties, traffic characterization (e.g., axle type, load levels, and lateral distribution), local climate, and design features (e.g., joint spacing, slab width, shoulder type, and joint details).

With ME design, site-specific inputs can significantly increase the reliability and cost effectiveness of the final design. Currently, all rigid pavement design solutions, such as new jointed plain concrete pavement (JPCP), continuously reinforced concrete pavement (CRCP), overlays with JPCP or CRCP, and short-jointed concrete slabs (new or overlay) have ME procedures readily available for pavement engineers. The survey results in Figure 1 show that about half of state agencies now use AASHTOWare Pavement ME Design.

Objectives

The purpose of this MAP brief is to describe the main capabilities, inputs, outputs, and limitations of the primary ME design methods for various concrete pavement solutions. ME rigid pavement design and rehabilitation methods encompass new JPCP, short-jointed slab, CRCP, concrete over concrete (COC), and concrete over asphalt (COA)

Figure 1. Structural pavement design methods applied by states, with some using more than one design method (from FHWA AID-PT 2019/2020 Annual Report, FHWA Peer Exchange 2019)

pavement systems. ME concrete overlay designs include both bonded (-B) and unbonded (-U) design options as well as short and standard slab sizes.

Mechanistic-Empirical (ME) Design Methods

The most prominent ME concrete pavement procedures include AASHTOWare Pavement ME Design (AASHTO 2020), ACPA's PavementDesigner.org (Ferrebee et al. 2018), unbonded concrete overlay (UBOL) design (Khazanovich et al. 2020), BCOA-ME (Vandenbossche et al. 2016), and OptiPave 2 (Covarrubias and Binder 2013). Table 1 summarizes these distinct ME design procedures and their recommended applicability to specific rigid pavement structures. Figure 2 illustrates the various concrete overlay design options (COC and COA), which can be further explored and reviewed in the Guide to Concrete Overlays, 4th Ed., by Fick et al. (2021).

If designers are unsure which ME pavement design options and procedures to use, Figure 3 provides recommendations on the appropriate ME methods for specific concrete pavement structures. Thus, to select the correct ME design method, first the designer has to determine the feasible types of pavement structures, especially if it is a new or overlay concrete pavement. This decision will dictate which available ME procedure is best suited for the structural design. For example, when designing a new JPCP there are three recommended methods (AASHTOWare Pavement ME Design, OptiPave 2, or PavementDesigner.org).

The next question is how to select the most appropriate ME method. This is a function of the design method's reliability level, number of inputs, design types to consider, design features to evaluate, and final pavement type selection decision-making process. AASHTOWare Pavement ME is the most comprehensive procedure in that it analyzes almost all concrete pavement types and has the most site-specific inputs, such as local climate data, traffic data, and material properties. For example, if CRCP and JPCP short slab systems are viable pavement structures, then the ME design procedures to evaluate would be AASHTOWare Pavement ME and OptiPave 2.

The following sections provide an overview of the ME methods presented in Figure 3, including their main capabilities, applicability, performance prediction outputs, and design limitations.

AASHTOWare Pavement ME Design for JPCP, CRCP, and Overlays

The AASHTOWare Pavement ME procedure is the most advanced design method available for new concrete pavements and overlays. It incorporates state-of-the-art concrete pavement analysis, materials characterization, axle-load spectra, climatic data, design features, and performance predictions. This comprehensive method has a user-friendly interface that allows for complex project inputs but also provides default inputs for more standard pavement designs. The software is capable of single-design analysis, batch processing, design optimization, and sensitivity analysis (AASHTO 2020). Pavement engineers should consider attending or reviewing a training session to become more familiar with the software's various input modules and levels, outputs, and interface capabilities. Enhancements are continuously being incorporated

Table 1. Summary of ME rigid design procedures and recommended applicability

ME Design Procedure	Concrete Pavement Design Options
AASHTOWare Pavement ME Design	JPCP, CRCP, COC-B and COC-U, COA-U; COA-B with short slabs
PavementDesigner.org	JPCP
OptiPave 2	JPCP with short slabs
UBOL Design	COC-U with short and standard slab sizes
BCOA-ME	COA-B with short and standard slab sizes

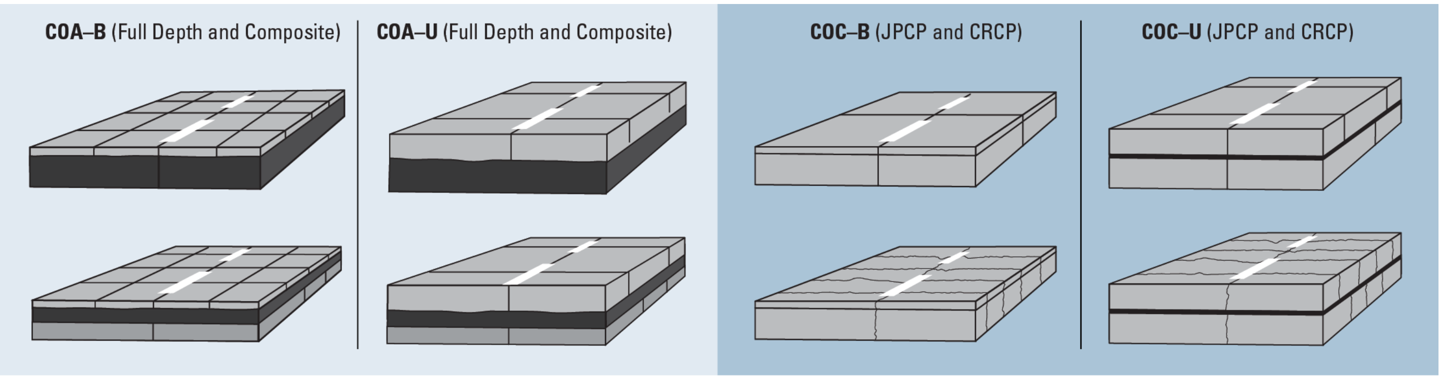

Figure 2. Concrete overlay types (Fick et al. 2021)

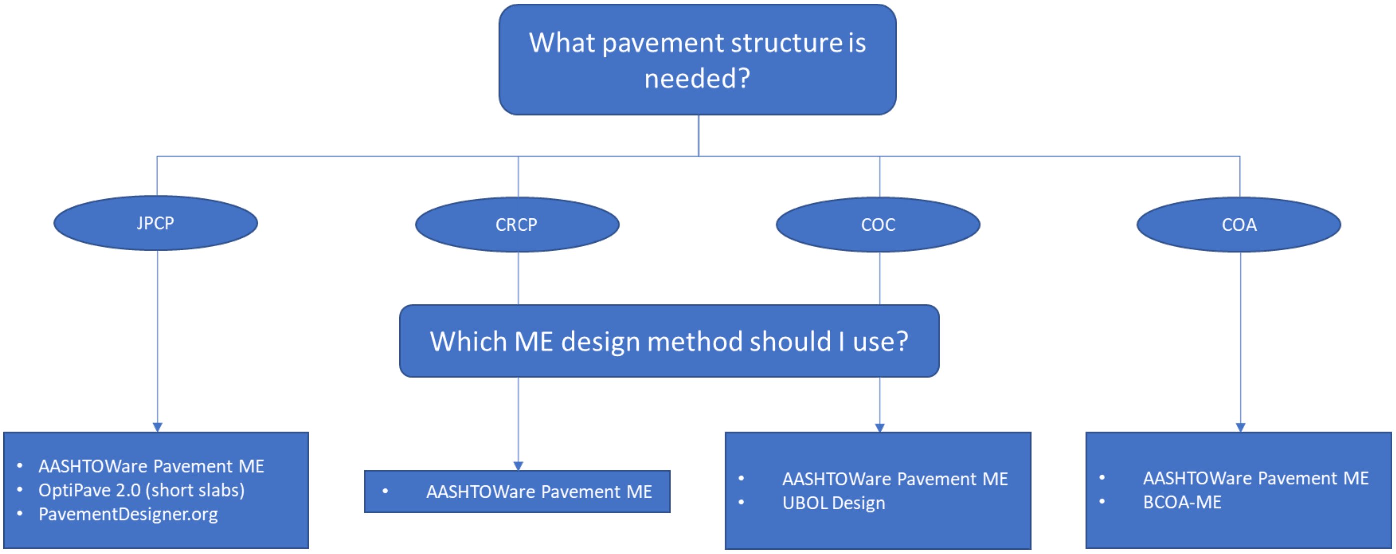

Figure 3. Selecting an appropriate ME design procedure based on the desired concrete pavement structure

to improve design, most recently documented in Geary (2021). AASHTOWare Pavement ME can be used to design new JPCP and CRCP systems.

For rehabilitation projects, bonded or unbonded concrete overlays are possible solutions for existing asphalt or concrete pavements, as presented in Fick et al. (2021). Only conventional joint spacings, i.e., 12 to 20 ft, are allowed for JPCP designs in AASHTOWare Pavement ME, except for the short-jointed COA-B module, where slab sizes can range from 5 ft to 8 ft. The primary inputs for the AASHTOWare Pavement ME Design procedure include the following:

Design features:
- JPCP or CRCP: new or overlay
- Design life
- Slab thickness
- Joint spacing and details
- Shoulder type
- Widened lane
- Slab–base interface condition
- Reliability

Traffic:
- Axle-load spectra

Concrete material properties:
- Strength
- Mixture design

Support layers:
- Number and type of layers
- Layer material properties
- Climate data (city, state)

AASHTOWare Pavement ME outputs the predicted transverse cracking percentage, faulting, and IRI versus pavement age. Detailed information about its design guide, software, licensing, training, and technical support can be found at AASHTOWare Pavement ME. Pavement engineers can review a more detailed explanation of the AASHTOWare Pavement ME inputs, outputs, and design sensitivities in other publications (Schwartz et al. 2011; Roesler and Hiller 2013; Saboori et al. 2021).

OptiPave 2 for JPCP with Short Slabs

OptiPave 2 is an ME design procedure optimizing the slab geometry for new JPCP such that no more than one set of wheels from a truck axle are on any given slab (Covarrubias and Covarrubias 2008; Covarrubias and Binder 2013). This method is also referred to as short slab design, where slab panel sizes are reduced to limit traffic load and curling stresses, thereby decreasing the required slab thickness relative to conventional JPCP slab sizes. The OptiPave 2 procedure is based on similar ME design and analysis principles, equations, and processes as AASHTOWare Pavement ME (Covarrubias et al. 2010). The key inputs for the OptiPave 2 procedure include the following:

Design features:
- Design life
- Slab thickness
- Joint spacing and details
- Shoulder type
- Widened lane
- Reliability

Traffic:
- Equivalent single-axle loads (ESALs) or axle-load spectra

Concrete material properties:
- Strength and macrofibers

- Mixture design

Support layers:
- Number and type of layers
- Layer material properties

Climate:
- Chile or generic regions
- Built-in curling

The OptiPave 2 design software outputs percentage of total slabs cracked (sum of transverse, longitudinal, and corner cracking), joint faulting, and IRI over the design life. Slab sizes must be between 4 ft to 8 ft and slab thicknesses between 2.5 and 10 in. Conventional joint spacings are not included in this ME design method. Also, the climate input module provides the distribution of temperature differentials for the country of Chile or for other generic climate regions. The OptiPave 2 design software is free but the short-jointed slab system called TCPavements® is patented and requires a royalty fee for constructing the slabs with optimized geometry, which may or may not make its final pavement selection cost-effective. A general overview of the software, licensing, design guide documentation, and technical support can be found at OptiPave 2.

TPF-5(269) – UBOL Design for COC-U

Unbonded concrete overlay (UBOL) design is an ME procedure for COC-U developed by Khazanovich et al. (2020) for a state pooled fund study (TPF-5[269]). This ME procedure can be used to design JPCP overlays of deteriorated concrete or composite pavement with an asphalt concrete (AC) or geotextile separator layer and either conventional joint spacing or short slabs. The key design inputs for this overlay procedure are as follows:

Design features:
- Design life
- Overlay slab thickness
- Joint spacing and details
- Shoulder type
- Reliability

Traffic:
- Average daily truck traffic (ADTT) and axle-load spectra

Concrete material properties:
- Overlay flexural strength
- Existing concrete modulus

Support layers:
- Interlayer type and properties
- Existing slab thickness

Climate location (city, state)

The UBOL design software outputs the minimum concrete overlay thickness, estimated traffic in ESALs, and the predicted cracking and faulting at the end of the design life. This procedure has a fixed number of climate locations and the load spectra only assume the truck traffic classification level 1 (TTC-1) distribution defined within AASHTOWare Pavement ME. The UBOL procedure allows for slab sizes to be either 6 ft by 6 ft or slab lengths between 12 and 16 ft by 12 ft slab widths. This cloud-based software can be accessed and run at https://ubold-esign3.azurewebsites.net/, with the details of the ME overlay models, procedure, and user guide published in Khazanovich et al. (2020).

BCOA-ME for COA-B

BCOA-ME is a cloud-based concrete overlay design procedure for COA-B (Vandenbossche et al. 2016). Its required slab thickness is determined by satisfying the following failure criteria for the design inputs: fatigue cracking (transverse, longitudinal, or corner), joint faulting, asphalt fatigue, and reflective cracking potential. The primary inputs for this COA-B design procedure are as follows:

Design features:
- Design life
- Overlay slab thickness
- Joint spacing and details
- Shoulder type
- Reliability

Traffic:
- ESALs

Concrete material properties:
- Strength
- Macrofibers
- Mixture design

Support layers:
- AC thickness
- AC mixture properties
- Foundation composite k value

Climate location (city, state)

The BCOA-ME design procedure outputs the required concrete overlay thickness to meet the fatigue cracking criteria and then checks to see if this thickness also meets the faulting model prediction over the design life. The procedure allows for slab sizes from 2 ft by 2 ft up to 15 ft by 12 ft. The design software, technical documentation, design examples and sensitivities, and training videos can be accessed through the BCOA-ME website.

ACPA's PavementDesigner.org for JPCP

ACPA's PavementDesigner is a cloud-based design procedure for concrete roads, streets, parking lots, and intermodal facilities (Ferrebee et al. 2018). This user-friendly ME design tool for JPCP is based on the original Portland Cement Association (PCA) method for fatigue and erosion analyses. The design tool, methodology, documentation, and tutorials can be accessed at https://www.pavementdesigner.org. The tool requires the following main design inputs:

Design features:
- Design life
- Slab thickness
- Shoulder type
- Dowel bars
- Reliability

Traffic:
- Axle-load spectra

Concrete material properties:
- Strength
- Macrofibers

Support layers:
- Composite k value

The software outputs the recommended design thickness to meet the fatigue cracking and erosion criteria, the maximum allowable joint spacing, and a sensitivity analysis on the required slab thickness as a function of k value, flexural strength, design life, reliability, and percentage of slabs cracked at the end of the design life. Although the software also has CRCP and overlay design modules, these are based on the empirical AASHTO (1993) method so are no longer preferred options for concrete pavement design.

Summary

With mechanistic-empirical (ME) pavement design procedures available for concrete pavements and concrete overlays, pavement engineers are able to confidently design any type of concrete pavement without employing empirical procedures that can potentially lead to erroneous results or produce uneconomical designs. Current ME procedures for concrete pavements calculate the theoretical pavement responses from the inputted pavement layers and materials, design features, expected traffic, and local climate in order to predict cracking, faulting, and ride performance over the life of the pavement. There are a number of validated ME design procedures available for new concrete pavements and concrete overlays. AASHTOWare Pavement ME has the most capabilities in terms of types of concrete pavement structures considered, design inputs, site-specific features, and predicted performance over time. Several other ME methods for concrete pavements, however, complement AASHTOWare Pavement ME, such as for short-jointed slab systems (OptiPave 2), unbonded concrete overlays with short slabs (TPF-5[269] UBOL), bonded concrete overlay of asphalt (BCOA-ME), and new JPCP (PavementDesigner.org).

References

AASHTO. 1993. *Guide for Design of Pavement Structures*. American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO. 2008. *Mechanistic-Empirical Pavement Design Guide—A Manual of Practice*. Interim Edition. American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO. 2020. *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice*. Third Edition. American Association of State Highway and Transportation Officials, Washington, DC.

Covarrubias, J. P. T., and J. P. Covarrubias. 2008. "'TC' Design for Thin Concrete Pavements." Proc., *9th International Conference on Concrete Pavements: The Golden Gate to Tomorrow's Concrete Pavements*, 905–917.

Covarrubias, J. P., J. Roesler, and J. P. Covarrubias. 2010. “Design of Concrete Slabs with Optimized Geometry,” *11th International Symposium on Concrete Roads*, October 20–22, Seville, Spain.

Covarrubias, J. P., and C. E. Binder. 2013. *OptiPave 2® Documentation & Design Guide* (Version 1.01), Santiago, Chile.

Ferrebee, E., A. Gierltowski, and G. Voigt. 2018. "Creation and Development of PavementDesigner.org—A Unified Industry-Wide Pavement Design Tool for Concrete and Cement-Based Solutions," *13th International Symposium on Concrete Roads*, June 2018, Berlin.

Fick, G., J. Gross, M. B. Snyder, D. Harrington, J. Roesler, and T. Cackler. 2021. *Guide to Concrete Overlays*. Fourth Edition. National Concrete Pavement Technology Center, Iowa State University, 152 pp.

Geary, G. M. 2021. *Updates to AASHTOWare Pavement ME Design Software Affecting Concrete Pavements: A Synthesis of the Changes to the Software Related to Concrete Pavements*. National Concrete Pavement Technology Center, Iowa State University. InTrans Project 15-532.

Khazanovich, L., J. M. Vandenbossche, J. W. DeSantis, and S. Sachs. 2020. *Development of an Improved Design Procedure for Unbonded Concrete Overlays*. FHWA TPF-5(269). Minnesota Department of Transportation. Report No. MN 2020-08, 328 pp.

Roesler, J., and J. Hiller. 2013. "Continuously Reinforced Concrete Pavement: Design Using the AASHTOWare Pavement ME Design Procedure." Technical Summary, Publ. No. FHWA-HIF-13-024.

Saboori, A., J. Harvey, J. Lea, R. Wu, and A. Mateos. 2021. *Pavement ME Sensitivity Analysis* (Version 2.5.3). UC Davis:

University of California Pavement Research Center.

Schwartz, C. W., R. Li, S. H. Kim, H. Ceylan, and K. Gopalakrishnan. 2011. *Sensitivity Evaluation of MEPDG Performance Prediction*. National Cooperative Highway Research Program, Transportation Research Board. NCHRP Project 1-47.

Vandenbossche, J. M., N. Duffala, and Z. Li. 2016. “Bonded Concrete Overlay of Asphalt Mechanistic-Empirical Design Procedure.” FHWA TPF-5(165). *International Journal of Pavement Engineering*, Vol. 18, No. 11, pp. 1004–1015.