Designing Pavements for Innovative Projects to Meet Structural and Functional Requirements

Sean Barnes, District Manager (Manitoba and Northwestern Ontario)
PCL Constructors Canada

Brian Clark, Vice-President
Plenary Group (Canada)

Khaled Galal, PhD, Pavement & Materials Research Team Leader
Stantec Consulting

Rick Haldane-Wilsone, P.Eng., Principal and Manager, Bridges and Structures
Wardrop Engineering

Robert Kuylko, P.Eng., Senior Transportation Engineer
Stantec Consulting

Leanne Whiteley-Lagace, M.A.Sc., P.Eng., Pavement Engineer (1)
Stantec Consulting
1400 Rymal Road East
Hamilton, ON L8W 3N9
Phone: (905) 381-3243
Fax (905) 385-3534
Email: leanne.whiteleylagace@stantec.com

(1) Corresponding author

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ABSTRACT

Transportation agencies traditionally design asphalt pavements for 20 or 25 years. However, innovative asphalt pavement projects such as those designed and constructed under warranty specifications or through public private partnership (P3) programs tend to demand a longer design period such as 30 or 35 years and beyond.

This paper provides a case study of a P3 project. This project required a 30-year design life. In addition, this project required to be maintained at an acceptable serviceability level throughout the design life of the pavement (i.e. 30-year).

Initially, the pavement structure was designed in accordance with the AASHTO 1993 Pavement Design Guide based on geotechnical and traffic information included in the preliminary pavement design report. The geotechnical information and material properties will be verified, and amended if necessary during the final design phase of this project. Based on the AASHTO 1993 pavement design method, two pavement structural design options were developed:

- traditional asphalt surface constructed over granular base/subbase courses; and
- full depth asphalt pavement

Each design options was evaluated to assess the number of load repetitions (Equivalent Single Axle Loads - ESALs) to failure. A multi-layer elastic analysis routine was used to evaluate the stresses, strains and deflections at critical pavement locations. The pavement responses were evaluated using existing calibrated pavement performance models (transfer functions) to determine the number of load repetitions to both fatigue and rutting failures. Based on this information, the proposed pavement designs were adjusted to meet the number of load repetitions to failure; thereby resulting in a proposed pavement design that met both the structural and functional requirements over a 30-year design and analysis period.

This methodology can be expanded to suit other project functional or serviceable requirements and is recommended to be utilized by other transportation agencies for their innovative pavement projects.

INTRODUCTION

Transportation agencies traditionally design asphalt pavements for 20 or 25 years. However, innovative asphalt pavement projects such as those designed and constructed under warranty specification or through public private partnership (PPP or P3) programs tend to demand a longer design period such as 30 or 35 years and beyond. In addition, these project types may require certain performance requirements during a warranty period that may vary between three to 20 years or more.

A public private partnership is "a cooperative venture between the public and private sectors, built on the expertise of each partner, that best meets clearly defined public needs through the appropriate allocation of resources, risks and rewards." *(1)*

Traditionally, transportation agencies develop pavement designs by specifying layer thicknesses and materials to be used for the construction of the pavement. Contractors are only rewarded or penalized on meeting the agency materials and/or construction specifications.

On the contrary, for special projects such as warranty or P3 projects, contractors are allowed to use their own design methodology and select the appropriate materials for road construction. Contractors are however required to meet transportation agency "per-specified functional (e.g. international roughness index (IRI), distress severity level and extent) and/or structural (e.g. effective structural number, load carrying capacity) conditions throughout the contract or design period." *(2)*

These new approaches for design and construction of pavements allow innovation in design, materials selection, and construction practices; in addition to scheduling for preventative maintenance, routine maintenance or reactive maintenance and future rehabilitation alternatives throughout the design/analysis period. In other words, the new process allows both the agency and the contractor to forecast the pavement needs to maintain it at the pre-specified serviceability level.

Objectives

As part of this P3 contract case study, the design requirements included performance requirements in the areas of:

- Safety
- Functionality/Serviceability
- Durability/Maintainability
- Aesthetics

Of particular importance for the pavement structure, was the rutting performance requirement. Rutting, or permanent deformation, can be defined as the permanent depression in the wheel path and has two main causes:

- Structural rutting - rutting that occurs in the subgrade and/or in the unbound material (including subgrade layer) due to one or more of the following factors:
    - poor structural design

  - elevated truck loading/heavy traffic
  - poor subgrade soil
  - poor construction
- Hot Mix Asphalt (HMA) rutting - asphalt rutting that occurs only in the top HMA layers as a result of poor mix design. Poor HMA can result from one or more of the following factors:
  - low fine aggregate and coarse aggregate angularities
  - use of natural or round aggregate materials (fine or coarse)
  - increased asphalt content
  - poor field compaction
  - low asphalt stiffness
  - low mix stiffness

In this particular case, the roadway was expected to be maintained with rut depths of less than 14 mm (0.55 in) based on 500-metre (1640 ft) average values through the analysis design period.

In addition to the rutting criteria, the project team evaluated fatigue cracking, which is another undesirable pavement surface distress. Fatigue cracking is a load-associated distress that can result from under designed pavement structures, poor subgrade conditions, excessive loads that exceed those predicted during the design period, poorly constructed pavement, excessive moisture in the unbound materials (including subgrade layers), or a combination of these factors.

METHODOLOGY

The scope of work included:

1. Determine design Equivalent Single Axle Loads (ESALs)
   - Number of load repetitions during design and analysis period
2. Determine pavement Structural Number (SN)
   - Thickness design to determine the load carrying capacity of the pavement structure
3. Determine pavement structural requirements
   - Thickness of each pavement layer as a function of its layer coefficient to optimize layer stiffness and thickness
4. Determine pavement functional requirements
   - Limit rutting distress and eliminate structural rutting potential during design and analysis period and meeting a serviceability level of 4.2 during the analysis period
5. Determine pavement functional/structural requirements
   - Limit fatigue cracking and eliminate fatigue cracking potential during design and analysis period

Pavement Design – ESALs

The ESALs concept was developed and incorporated in the AASHTO 1993 pavement design process to ensure that a pavement structural design is capable of meeting the traffic demands during the design period. The ESALs are calculated as a function of a standard 18,000-lbs axle load of different vehicle classes and axles types for a design period. Transportation agencies have developed simplified equations as function of the Average Daily Traffic (ADT), Truck Percent (%T), and Truck(s) factor (TF), and traffic growth to express the accumulated truck traffic in terms of ESALs during the design period. The AASHTO 1993 ESALs design calculation can be calculated using simple or compound growth factors based on regional predicted traffic patterns.

Based on information provided in the preliminary pavement design report, the following traffic factors were used in the AASHTO 1993 ESALs calculation:

- Performance period: 30 years
- Two-way daily traffic: 45,000
- Percent of heavy trucks: 2.0%
- Number of lanes in design direction: 2
- Percent of all truck in design lane: 80%
- Percent of trucks in design direction: 50%
- Average initial truck factor: 1.9
- Annual truck volume growth rate: 0.5%
- Total ESALs (30-year design life): 8.06×10^6

These factors were obtained from the agency and/or by consensus in coordination with both the agency and the contractor based on traffic data. It should be noted that many Transportation Agencies in North America use 90% of all truck in the design lane, which will result in higher estimates for design ESALs.

Pavement Design – SN

In the AASHTO pavement design process, the ESALs are used along with a reliability level, initial serviceability index (ISI), and a terminal serviceability index (TSI), which are related to the road classification; as well as a standard deviation of the design and the subgrade resilient modulus to develop the asphalt pavement Structural Number (SN) and subsequently the pavement layer thicknesses.

The recommended AASHTO 1993 standard deviation for pavement design ranges between 0.45 and 0.49 to account for variability of the materials and construction, and potential errors associated with the traffic data when calculating the pavement SN. The resilient modulus of the subgrade soil or the ability of the subgrade soil to recover permanent deformation resulting from the traffic loading is one of the most important inputs used in the AASHTO 1993 pavement design method and can significantly influence the overall design. One of the objectives of any structural design methodology is to protect subgrade soils from excessive loading during design period or during the analysis period.

Based on the information provided in the preliminary pavement design report, the following design factors were used in the AASHTO 1993 SN calculation:

- 18-kip ESALs over initial pavement period: 8.06×10^6
- Initial serviceability: 4.2
- Terminal serviceability: 3.0
- Reliability (%): 85
- Overall standard deviation: 0.49
- Roadbed soil resilient modulus: 28,400 kPa (4,000 psi)
- Stage construction: 1
- Design structural number: 165 (6.41)

The recommended AASHTO reliability level for the roadway functional class ranges between 85 and 95.

Pavement Design - Options

Two different designs were initially developed that satisfy the calculated SN:

Design Option 1

Design Option 1 is a conventional asphalt pavement with two asphalt layers:

- 50 mm (2 in) asphalt layer
- 115 mm (4.5 in) asphalt layer
- 300 mm (12 in) granular base layer
- 600 mm (24 in) granular subbase layer
- Subgrade with 28 MPa (4,000 psi)

Design Option 2

Design Option 2 is a full-depth asphalt pavement with asphalt layers that are constructed directly on top of the compacted subgrade soils:

- 355 mm (14 in) full depth asphalt layer
- Subgrade with 28 MPa (4,000 psi)

All design options were developed and evaluated using the same ESALs and same design inputs. In addition, using the layer coefficients (a representation of the layer strength as described in the AASHTO 1993 design), the design options resulted in different SNs that satisfy the criteria to carry the calculated traffic ESALs during the design period:

- Design Option 1 SN: 168 (6.63)
- Design Option 2 SN: 164 (6.44)

Pavement Design – Meeting In-Situ Performance

The design of pavement structure alone cannot ensure proper in-service pavement performance. A pavement structural design (i.e., design layeres/thicknesses) and the associated material properties (i.e., in-place/as constructed materials and their in-situ properties) should be validated by means of transfer functions (pavement performance models). Fatigue or rutting performance models can calculate or predict the total number of load repetitions (ESALs) to a structural rutting or fatigue cracking failure. To check the AASHTO 1993 design calculation using published/calibrated transfer functions/pavement performance models, the computed total number of load repetitions to failure must meet or exceed the design ESALs used in the calculation of the AASHTO 1993 structural thickness design. It has been well established by published literature that asphalt pavements, under loading, fail in two common modes:

- Fatigue cracking (alligator cracking) failure
- Structural Rutting (Permanent deformation) failure

A pavement design recommendation can be evaluated and validated using existing fatigue and rutting calibrated pavement performance models.

The recommended pavement design options provided above were evaluated in terms of both fatigue cracking (traditional bottom-up alligator cracking in wheel path) and subgrade permanent deformation (subgrade “structural” rutting) using the Asphalt Institute and the Shell design fatigue and rutting transfer functions (also known as rutting and fatigue pavement performance models) (Table 1). These calibrated models, using actual performance field data, calculate total number of repetitions to failure using expected in-situ material properties. In-situ (as constructed) materials properties are typically determined by laboratory tests using field extracted materials (cores/bores) or using field testing such as the use of Falling Weight Deflectometer data and subsequent back calculation results and analysis.

However, these results are not available until the pavement is constructed. Thus, a transportation agency’s typical field or laboratory data should be used to validate a pavement structural design using these pavement performance models to validate a particular design by ensuring that the design will meet or exceed calculated traffic predictions in terms of ESALs.

These transfer functions are used for the current study. The Asphalt Institute fatigue function was incorporated in the newly developed AASHTO interim design guide known as MEPDG – Mechanistic-Empirical Pavement Design Guide; while, the Shell Pavement design equations were developed by the Shell company and went through rigorous calibration procedure that are also recommended for MEPDG model calibration. These pavement performance equations were adopted and utilized by several transportation agencies (with local calibration) across the world. *(3,4)*

These pavement performance models can provide a high degree of reliability to a particular pavement design by ensuring that it not only meets the design expectations, but that it also meets the performance expectations by avoiding structural-associated failure related to fatigue cracking and structural rutting.

Generally, pavement designers and practitioners agree that these two failure modes if avoided or eliminated can ensure longer in-situ performing pavement, especially when superior materials (e.g. multiple crushed faces and performance grade asphalt binders) and proper construction practices and specifications are selected and closely adopted for the construction of HMA pavements.

The rutting in the top layers of asphalt can be completely eliminated by selecting or designing the proper asphalt mixes that are produced using performance graded asphalt binders (i.e., PG grades) and are constructed using the appropriate construction techniques to ensure stone-in-stone contact especially for the upper pavement layers.

These HMA mixes (e.g. Stone Matrix Asphalt - SMA mixes) provide an excellent rutting and fatigue performance. In addition, they provide a higher HMA mix stiffness that better distribute pavement loads to lower layers, including subgrade soils.

To use pavement prediction/performance models, two major inputs are required:

- Resilient modulus or dynamic modulus of the asphalt layers to determine tensile strain at the bottom of the asphalt layers for fatigue predictions/calculations; and
- Resilient modulus of the subgrade soil to determine the vertical compressive strains at the top of the subgrade layer for structural rutting predictions/calculations.

The pavement responses also known as mechanistic pavement responses (stresses, strains and deflections) can be produced through a multilayer elastic analysis using typical layer(s) properties i.e., resilient layers moduli and its corresponding Poisson’s ratio (which are agency/materials specifics/dependent) and the recommended design thicknesses.

The following loading conditions and material property assumptions were made for the multilayer elastic analysis:

- Steering Axle Load = 6,800 kg (15,000 lbs) (Loading A)
- Single Axle Dual Load = 9,100 kg (20,000 lbs) (Loading B)
- Tire Pressure = 827 kPa (120 psi)
- Asphalt: Poisson's Ratio (ν)=0.35, Resilient Modulus (Mr)= 5,171 MPa (750,000 psi)
- Crushed stone subbase: ν=0.30, Mr=345 MPa (50,000 psi)
- Subbase: ν=0.35, Mr=138 MPa (20,000 psi)
- Subgrade: Mr=27.6 MPa (4,000 psi)

Based on the results of the multilayer elastic analysis, Design Options 1 and 2 failed under the rutting criteria. As such, the additional design options presented below were evaluated. Due to the cost associated with full-depth asphalt, subsequently on two conventional asphalt pavement structures were evaluated:

Design Option 3

Design Option 3 consists of a conventional asphalt pavement with asphalt layers on top of an aggregate base/subbase on top of the compacted subgrade soils:

- 50 mm (2 in) asphalt layer
- 100 mm (4 in) asphalt layer
- 100 mm (4 in) asphalt layer
- 150 mm (6 in) granular base layer
- 600 mm (24 in) granular subbase layer
- Subgrade with 28 MPa (4,000 psi)

Design Option 4

Design Option 4 consists of a conventional asphalt pavement with three asphalt layers:

- 50 mm (2 in) asphalt layer
- 75 mm (3 in) asphalt layer
- 75 mm (3 in) asphalt layer
- 300 mm (12 in) granular base layer
- 600 mm (24 in) granular subbase layer
- Subgrade with 28 MPa (4,000 psi)

The design options noted above resulting in the following SN values:

- Design Option 3 SN: 188 (7.41)
- Design Option 4 SN: 186 (7.32)

Table 2 summarizes the total predicted/calculated number of repetitions to failure for each pavement performance model and each combination of design and loading condition noted above.

CONCLUSIONS AND RECOMMENDATIONS

The results and analysis of this case study allow the following conclusions and recommendations to be made:

- While the first two design options satisfied the traditional AASHTO 1993 structural number requirement, they failed to meet the performance-related requirements over the 30-year analysis period; thereby indicating the potential for excessive rutting
- The Shell pavement performance models/equations resulted in higher total predicted number of load repetition to rutting or fatigue failures as compared to the Asphalt Institute performance model (i.e., Asphalt Institute design equations resulted in more conservative calculations compared to Shell design equations).

- The Asphalt Institute pavement performance models/equations resulted in a more conservative total predicted number of load repetition to rutting or fatigue failures. It is important to note that a modified Asphalt Institute equation is incorporated for use in the new mechanistic empirical pavement design guide.
- Steer axle loading resulted in lower total predicted number of load repetition to rutting or fatigue failures when compared to single axle - dual tire loading. Ideally the percentage of steer axle to single axle dual tire loading should be used to predict the total number of repetitions to failure.

REFERENCES

(1) The Canadian Council for Public-Private Partnerships, http://www.pppcouncil.ca/aboutPPP_definition.asp

(2) NCHRP Report 451, Guidelines for Warranty, Multi-Parameter, and Best Value Contracting, Washington, D.C, 2001

(3) NCHRP Report 1-37A, Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures, Final Report, March 2004

(4) NCHRP Report 1-40B, User Manual and Local Calibration Guide for the Mechanistic-Empirical Pavement Design Guide and Software (to be published)

TABLES

Table 1: Asphalt Institute and Shell Transfer Functions

Design Method	Fatigue Transfer Function	Rutting Transfer Function
Asphalt Institute Design Method	$N_f = 0.0796(\varepsilon_t)^{-3.291}(E)^{-0.854}$	$N_f = 1.365x10^{-9}(\varepsilon_v)^{-4.477}$
Shell Pavement Design Manual	$N_f = 0.0685(\varepsilon_t)^{-5.671}(E)^{-2.363}$	$N_f = 1.05x10^{-7}(\varepsilon_v)^{-4.0}$ (95% Reliability)

Table 2: Repetitions to Failure

Design Option – Loading Condition	Fatigue		Rutting	
	AI	Shell	AI	Shell
Option 3 – Loading A	40.1 x 10^6	392 x 10^6	148 x 10^6	1,020 x 10^6
Option 3 – Loading B	32.1 x 10^6	267 x 10^6	89.0 x 10^6	648 x 10^6
Option 4 – Loading A	17.9 x 10^6	97.6 x 10^6	201 x 10^6	1,342 x 10^6
Option 4 – Loading B	18.9 x 10^6	108 x 10^6	106 x 10^6	759 x 10^6