Reliability-based Specification (RBS) for Low-Volume Traffic Asphalt Pavements

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ABSTRACT

The use of volumetric-based specifications that utilize air void and asphalt content for the quality control of asphalt pavements is a big concern as there is no direct correlation between these mixture properties and long-term pavement performance. Moreover, these specifications do not address inputs variabilities influence on the design target reliability and overall performance. The aim of this paper is to introduce a reliability-based specification (RBS) for the quality control of longitudinal cracking in low volume traffic asphalt pavements. The RBS criteria are developed using design inputs such as hourly traffic volume, asphalt layer thickness, base modulus and dissipated creep strain energy limit ($DCSE_{lim}$), which are observed to have significant influence on longitudinal cracking performance. For the development of the RBS, a number of field pavement sections with well documented performance history and high quality laboratory and field data were analysed using the mechanics-based design framework for variability conditions that are representative of low-volume traffic roads. Maximum deviations of 18% and 6% from design values is proposed as quality control criteria for the hourly traffic volume and $DCSE_{lim}$ inputs respectively. The proposed RBS can complement existing specifications for the quality control of longitudinal cracking in low volume asphalt roads.

Keywords: reliability-based, low-volume, longitudinal, mechanics-based, variability

1. INTRODUCTION

An effective construction specification with clearly stated quality goals is necessary in order to guarantee the quality construction of asphalt pavements, and to make sure the as-built pavement meets the as-designed conditions. The pavement specifications currently implemented by the various states in the United States use different criteria for the quality construction of asphalt pavements. Most States have implemented either quality assurance specifications (QAS) or performance-oriented specifications such as performance-related specifications (PRS) and performance-based specifications (PBS) [1, 2]. These specifications are distinct from one another as they use different performance measuring parameters, material models, performance prediction models and acceptance quality characteristics (AQCs) criteria [3]. The performance oriented specifications use either volumetric properties such as air void, asphalt cement content or void in mineral aggregates, or mechanical properties such as dynamic modulus or creep compliance to compute material properties and pavement response. For the long term performance prediction of pavements, these specifications rely on the Pavement-ME, which requires an extensive amount of information on traffic, climate, structural input and material properties [4, 5]. Moreover, these specifications put much emphasis on the quality of the asphalt mixture while not addressing properly the quality of other significant inputs such as traffic volume and layer’s thickness and modulus inputs. These specifications also do not properly quantify design inputs variabilities influence on the design target reliability and long-term pavement performance

To overcome this problem, a reliability-based specification (RBS), which considers the desired quality of design inputs in addition to their variability influence on the target reliability, can be developed and implemented for pavements quality control. The use of RBS for pavements application is at its early stage and there are limited studies regarding its development and application [6]. RBS can be developed using the load and resistance factor design (LRFD) procedure, which is a probabilistic-based design approach. The LRFD uses a set of partial safety factors which are developed using reliability analysis and considering inputs degree of influence and associated variability to represent design risk or safety level [7-10]. The use of probabilistic-based design and RBS for pavements application ensures reasonable performance while providing a rational mechanism for penalizing or awarding contractors and operators.

In this paper, a reliability-based specification is proposed for the quality control of longitudinal cracking in low-volume traffic asphalt pavements. The required quality control criteria are established using design inputs such as asphalt thickness (H_{AC}), base modulus (E_B), hourly traffic volume ($ESALs_{hr}$) and dissipated creep strain energy limit ($DCSE_{lim}$). The deviation between the design and actual reliabilities and the associated variation that arise between the as-designed and as-built structures is used to establish the specification criteria. For this purpose, a number of field pavement sections are evaluated using the reliability-based mechanics-based design framework.

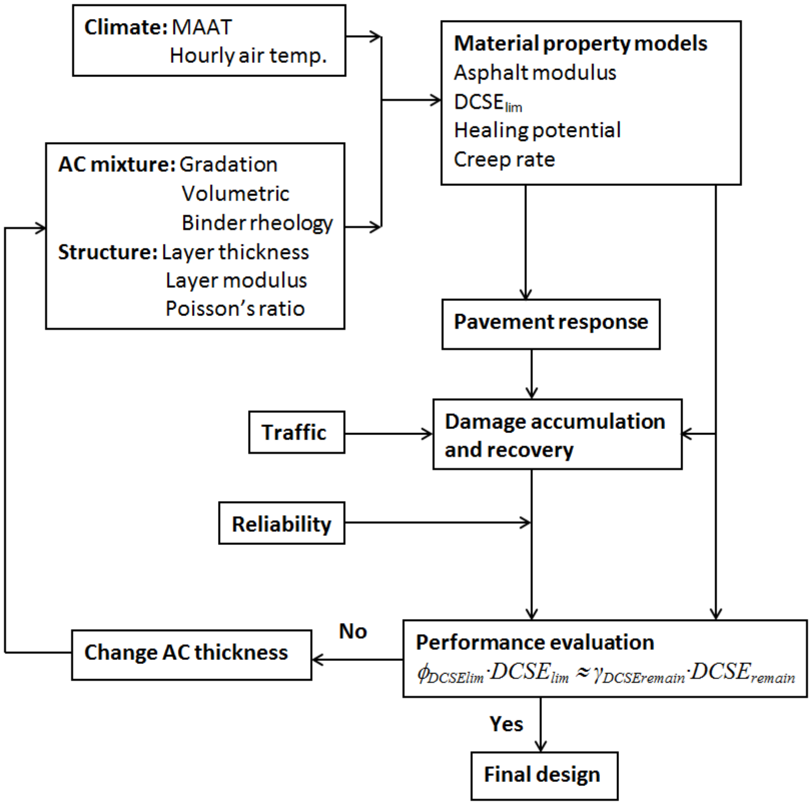

FIGURE 1 Flowchart for Mechanics-based Design Framework

2. METHODOLOGY

The RBS for the quality control of longitudinal cracking in low volume asphalt pavements is established by carefully analysing the deviation that arise in the design target reliability in the case when there is a variation in the significant design inputs (H_{AC}, E_B, $ESALs_{hr}$ and $DCSE_{lim}$). The mechanics-based design framework, which is a load and resistance factor design procedure, is used to optimize pavement sections for a given target reliability, and to estimate subsequently the variation that arise in the design inputs in the case when there is a deviation from original condition. The mechanics-based design framework is developed using a two-component reliability analysis methodology and variability conditions that are representative of low-volume traffic asphalt roads. A number of field pavement sections from the state of Florida, USA are used for the development of the mechanics-based design framework and for the establishment of the RBS.

2.1 Mechanics-based Design Framework

The mechanics-based design framework optimizes pavement sections in terms of their resistance to longitudinal cracking. It was developed on the basis of hot mix asphalt fracture mechanics (HMA-FM) and considering mixture morphology influence on key damage and fracture properties [11, 12]. The framework computes pavement response and damage accumulation due to traffic loading and environmental inputs considering factors such as healing and aging. The framework was calibrated and validated using a number of field pavement sections that encompass a wide range in design inputs and functional requirements. As a LRFD procedure, reliability is accounted in the design framework using a set of partial safety factors [7, 11]. Figure 1 presents the flowchart for the mechanics-based design framework.

Pavement design is performed in the mechanics-based design framework by comparing the factored $DCSE_{lim}$, which governs crack resistance, with the corresponding factored $DCSE_{accum}$, which represents accumulated damage after healing recovery [7]. Equation 1 is used to optimize pavement sections for a given design condition, which requires the factored values of the two parameters at the end of the design period to be equal.

$$\phi_{DCSE_{\lim}} DCSE_{\lim} \geq \gamma_{DCSE_{accum}} DCSE_{accum} \tag{1}$$

The evolution of the $DCSE_{lim}$ is predicted using an asphalt mixture morphology-based material model. The model accounts mixture morphology influence on the $DCSE_{lim}$ using a parameter called primary structure coating thickness (t_{ps}), which is the mastic thickness that coats the load bearing aggregate structure. Equation 2 presents the mathematical expression for the $DCSE_{lim}$ prediction model.

$$DCSE_{\lim} = k_1 (t_{ps})^{k_2} (t)^{(k_3 + k_4 \cdot \log(t_{ps}))} \tag{2}$$

where $k_1 = 2.38$, $k_2 = -0.79$, $k_3 = -0.33$ and $k_4 = -0.12$

The computation of $DCSE_{accum}$ requires complicated analysis and a number of inputs as it is a function of mixture properties, structural inputs, environmental conditions and traffic. The framework uses Equation 3 to compute $DCSE_{accum}$, which requires tensile stress (σ_{av}), creep compliance rate ($\dot{\varepsilon}_{p,\max}$), hourly traffic volume (ESAL) and healing potential (h_{ym}) as inputs. An asphalt mixture morphology-based material model (h_{ym}), which depends on initial $DCSE_{lim}$ and t_{ps}, is used to predict the healing potential characteristic and to calibrate the design framework. Equation 4 presents the healing potential equation. The calibrated framework has been observed to deliver accurate predictions which are in consistent with observed field performances.

$$DCSE_{accum}(t) = 0.05 \cdot \sum_{i=1}^{nhrs} ESAL_i \cdot \sigma_{av,i}^2 \cdot \dot{\varepsilon}_{p,\max,i} (1 - h_{ym,i}) \tag{3}$$

$$h_{ym}(t) = 1 - \left(\left[\exp\left(\frac{t_{ps}}{t}\right)^{-DCSE_{\lim,i}} \right]_{norm} \right)^{(14.09 t_{ps} - 4.4)} \tag{4}$$

2.2 Design Inputs Variabilities

Design inputs variabilities statistical characterization is a prerequisite for any reliability analysis. A literature review has been performed to establish the variability of inputs such as H_{AC}, E_B, $ESAL_{hr}$ and $DCSE_{lim}$, which are identified as significant inputs in a parametric study [7]. The full probability approach, which uses both the probability density function (pdf) and the coefficient of variation (COV), is used to model inputs variabilities. Table 1 presents the literature survey findings and the level of variabilities expected in low-volume traffic roads.

TABLE 1 Design Inputs Variabilities for Low Volume Roads

Inputs	Variability Survey	Low volume roads variability
H_{AC}	Normal, COV (3% - 12%)[13] Normal, COV (3% - 25%)[14]	Normal, COV (15%)
E_B	Lognormal, COV (15% -50%)[13] Lognormal, COV (5% -60%)[14]	Lognormal, COV (35%)
$ESAL_{hr}$	Lognormal, COV (30% -42%)[14] Lognormal, COV (42%)[15]	Lognormal, COV (50%)
$DCSE_{lim}$	Lognormal, COV (35%)[11]	Lognormal, COV (45%)

2.3 Reliability Analysis

A two-component reliability analysis methodology is used to compute pavements reliability and subsequently to formulate partial safety factors[7]. The first component using a response surface methodology (RSM) generates a surrogate model that effectively replace the performance equation with a mathematical expression. The second component computes reliability using the provided variability conditions and the Rackwitz-Fiessler (R-F) algorithm, which is one variety of the First order reliability method (FORM).

TABLE 2 Evaluated Pavement Sections

Section	County	Traffic /year (ESALs·10^3)	Target Reliability (%)
SR18	Bradford	6	75
SR16-6	Bradford	21	80
SR563	Polk	126	85
TPK-2	St. Lucie	166	90
SR80-1	Lee	221	90
I75-1A	Charlotte	573	95
I75-1B	Charlotte	558	95
I75-2	Lee	576	95

2.4 Pavement Sections

A number of pavement sections with high quality field and laboratory inputs and well-documented field performance history were used for the reliability analysis and for establishing the criteria for the RBS. These pavements sections encompass the wide range expected in design inputs and functional requirements[11]. The target reliability of these sections was established by following the stipulated guidelines in the Florida flexible pavement design guide[16]. Table 2 presents the studied pavement sections with their corresponding yearly traffic volume and target reliability.

2.5 Development of RBS

The Florida flexible pavement design guide is used to establish the target reliability of low-volume traffic roads and the required criteria for the RBS. A maximum reduction of 5% in the design target reliability is proposed as a quality control limit, which is used to compute the corresponding variation that arise in the design inputs. The mechanics-based design framework is used to obtain the optimum values of the design inputs for the respective target and actual reliability conditions. Equation 5 presents the mathematical expression used to establish the criteria for the RBS.

$$R_{tgt,d}(H_{AC,d}, E_{B,d}, ESAL_{hr,d}, DCSE_{\lim,d}) - R_{tgt,a}(H_{AC,a}, E_{B,a}, ESAL_{hr,a}, DCSE_{\lim,a}) \le 5\% \qquad (5)$$

where $R_{tgt,d}$ and $R_{tgt,a}$ are design and actual target reliabilities.

The variation in the design inputs that arise due to deviation in the design target reliability is computed by varying one input at a time while keeping the rest constant. Equation 6 is used to compute the percentage change in the design inputs.

$$\Delta\mu_i = \left(\frac{\mu_{i,d} - \mu_{i,a}}{\mu_{i,d}}\right)\cdot 100 \qquad (6)$$

where $\Delta\mu_i$, $\mu_{i,d}$ and $\mu_{i,a}$ are the change in percentage and mean values of a given input for the target and actual variability conditions respectively.

3. RESULTS AND DISCUSSION

The development of the RBS for the longitudinal cracking performance quality control of low volume traffic roads is achieved in two stages. The first stage using the reliability analysis methodology and the field pavement sections generates partial safety factors for the development of a LRFD procedure for the mechanics-based design framework. The second stage using these partial safety factors estimates the RBS criteria for the various design inputs on the basis of the allowable deviation between the target and actual reliabilities.

TABLE 3 Representative Partial Safety Factors

Functional class	Target reliability [%]	ϕ_{HAC}	ϕ_{EB}	$\gamma_{Traffic}$	$\phi_{DCSElim}$	$\gamma_{DCSEaccum}$
Low volume	70	0.956	0.921	1.151	0.915	1.706
	75	0.945	0.892	1.187	0.892	1.937
	80	0.931	0.865	1.233	0.865	2.229

3.1 Partial safety factors

The partial safety factors for the target reliabilities of 70%, 75%, and 80%, which represent safety levels for low volume traffic roads, and for design inputs such as H_{AC}, E_B, $ESALs_{hr}$ and $DCSE_{lim}$ were formulated by evaluating the pavement sections provided in Table 2 with the two-component reliability analysis methodology. The direction cosine, which provides information on each input contribution to the overall variance is used for the reliability calibration. The representative partial safety factors presented in Table 3 are generated by accounting the contribution of each pavement section, which allows the incorporation of various design features into the design framework.

3.2 Criteria for the reliability-based specification (RBS)

The criteria for the RBS were established using pavement sections Bradford-SR18 and Bradford-SR16-6, which are low volume traffic roads, and using Equations 5 and 6. The variation observed in the performance measuring inputs of the two pavement sections due to the deviation in the target reliability was averaged so as to obtain representative values. Table 4 presents the quality control criteria for the performance measuring parameters, which must be fulfilled in order to guarantee acceptable performance. As can be seen in Table 4, the traffic volume can be varied by almost 20% without affecting the target reliability significantly while for the $DCSE_{lim}$ and H_{AC}, the same variation will significantly affect the target reliability. The base modulus is observed to be moderately sensitive to the deviation in the target reliability. The reported values in Table 4 provide vital information on the sensitivity of longitudinal cracking towards each performance measuring parameter, which can be used to allocate funds and to prioritize quality control strategies that are effective. Moreover, the implementation of RBS for the quality control of asphalt pavements will encourage the use of non-destructive testing procedures for the measuring and monitoring of mixture properties and layer thickness and moduli inputs.

TABLE 4 RBS criteria for low volume roads

Functional classification	RBS criteria			
	H_{AC}	E_B	$ESALs_{hr}$	$DCSE_{lim}$
Low volume	$H_{AC} – 6\%·H_{AC}$	$E_B – 10\%·E_B$	ESALs + 18%·ESALs	$DCSE_{lim} – 5\%·DCSE_{lim}$

4. CONCLUSIONS

The specifications currently implemented for the quality control of pavements are mainly based on the volumetric properties of asphalt mixtures, which might not delivered the intended benefits as other significant inputs and their associated variability is not properly accounted for. A reliability-based specification (RBS), which accounts inputs variability influence on the target reliability and the deviation which arise in the target reliability due to variation in the performance measuring parameters, can be developed and implemented for the quality control of longitudinal cracking in low volume asphalt roads. The RBS provides the proper platform for controlling the variability of design inputs and monitoring their influence on the target reliability, which can be used as a pay factor for penalizing or rewarding contractors. The use of RBS requires the collection and processing of large data set thus encouraging the implementation of non-destructive testing procedures for routine pavement condition assessment.

The proposed approach for the development of the RBS has successfully captured design inputs variabilities influence on the predicted longitudinal cracking performance and target reliability. The target reliability is observed to be less sensitive towards $ESALs_{hr}$ while the variation in the $DCSE_{lim}$ and H_{AC} influences the target reliability significantly. The proposed RBS can complement currently implemented performance-based specifications for the quality control of longitudinal cracking in low volume roads. It can also be used for the allocation of scarce resources and the prioritization of various quality control strategies.

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