Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 7(6):425-433

Stochastic Analysis of Thermal Cracking Distress of Asphalt Pavements Using the MEPDG Thermal Cracking Model

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Abstract: The objective of the National Cooperative Highway Research Program (NCHRP) 9-22 project was to develop a Quality Assurance (QA) system for asphalt pavements in conjunction with Performance Related Specifications (PRS). The project was originally intended to use the Mechanistic-Empirical Pavement Design Guide (MEPDG) as the performance prediction simulator. However, since the probabilistic assessment of the MEPDG required hundreds, if not thousands, of solution simulations; the computational time was found to be excessive as a quicker solution was critically necessary. The study presented in this paper has been conducted as part of the effort associated with the development of a rapid thermal cracking (TC) prediction methodology and the estimation of the variance of TC. The Rosenblueth method and the Beta frequency distribution were used to estimate the first and second moments (average and standard deviation) of TC and its service life. The proposed TC stochastic framework showed a successful performance and was accordingly incorporated into the PRS QA system developed under NCHRP 9-22. The ultimate purpose of the developed QA system is to stochastically evaluate the incentive / disincentive for the contractors.

DOI: 10.6135/ijprt.org.tw/2014.7(6).425
Key words*: Asphalt pavements, MEPDG, Thermal cracking, Quality assurance.*

Introduction

In pavement construction, it is traditionally typical Quality Assurance (QA) practice to evaluate the as-constructed asphalt mix quality based upon individual asphalt mixture material parameters (e.g., gradation, asphalt content, density, etc.). These parameters are used to empirically determine the incentive/disincentive to contractors in many State agencies around the country, considering the key variables to play a significant role to have the intended quality in the mixture [1]. Recognizing the limit of this empirical-based QA practice, effort to implement performance based QA methodology has been exerted. At present, however, establishment of a precise relationship between the actual pavement performance and the magnitude of pay adjustments is known to be one of the major obstacles in implementing a reliable QA program [2].

The objective of the National Cooperative Highway Research Program (NCHRP) 9-22 project was to develop a computerized “next-generation” QA program implementing Performance Related Specifications (PRS) for Hot Mixed Asphalt (HMA) mixture [2]. This QA computer program was intended to be used as a QA tool for a relative evaluation of the as-constructed (or as-built) asphalt mix quality to the as-design Job Mix Formula (JMF) mix by stochastically predicting three major distresses on asphalt pavements (asphalt layer rutting, bottom-up fatigue cracking, and thermal cracking) with the Mechanistic-Empirical Pavement Design Guide (MEPDG) also known as Pavement ME Design. The stochastic solution (i.e., mean and standard deviation of pavement performance) is then applied to quantify the quality difference between the as-designed mix and as-built mix. The quality difference is in turn used to determine the pay factors to contractors and eventually whether the contractor is awarded or penalized.

One of the primary tasks in NCHRP 9-22 was to incorporate the stochastic analysis into the proposed PRS system by finding the average and variance of the pavement performance associated with the three distress types. A series of papers developed under NCHRP 9-22 describes the development of performance prediction models of asphalt layer rutting and bottom-up fatigue cracking and their statistical approach to find the average and variance of the distresses [3-5]. In this paper, the study of the thermal cracking, among the other distresses, is primarily focused for the development of the stochastic solution and its implementation in the QA program. The first major section of the paper briefly discusses the effort for the development of the alternative method that is capable of reproducing the MEPDG TC results as accurate and fast as possible. This effort was exerted due to the fact that the MEPDG software required a significant amount of computational time to predict one deterministic solution, while the stochastic solution typically needed multiple solutions to obtain an average and a variance. The second major section discusses the establishment of a stochastic framework for TC where the framework takes into account uncertainties that exist in HMA. The Rosenblueth’s point estimate method along with Beta frequency distribution was used to estimate the central tendency and dispersion of the TC and corresponding service life of a given asphalt mix. The last section provides an example to illustrate the usage of the developed methodology associated with the TC framework.

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Note: Submitted April 15, 2014; Revised July 7, 2014; Accepted September 27, 2014.

Development of Thermal Cracking Predictive Model

Nature of Thermal Fracture in Asphalt Pavements

TC distress is deemed to be one of the major distresses on asphalt pavement that is frequently observed in the northern part of the United State and in vast areas of Canada [6, 9]. TC is known as a non-load related distress [6-8]. Rather, environmental climatic condition, associated with a specific geographic location of pavement sections, is the most important factor influencing TC on asphalt pavements. The TC development mechanism is conceptually simple; a rapid decrease of temperature results in shrinkage of the material and development of the tensile stress, in turn, causes the crack propagation to occur [9-11].

A great deal of effort to define the mechanism inducing the TC has been developed by many researchers. In the Strategic Highway Research Program (SHRP), Hiltunen and Roque developed the TC mechanism for asphalt pavements by applying fracture theory. The mechanism was then adopted and implemented in the MEPDG as the TC analysis module for asphalt pavements [11].

The TC module currently implemented in the MEPDG consists of several analysis steps that are based upon a complicated mechanism. To identify the sensitivity of the variables in the TC module, a sensitivity analysis was conducted between the TC amount obtained by the MEPDG and several variables that were believed to be critical. Fig. 1 illustrates one distinct feature of the TC development over time based on the MEPDG TC sensitivity analysis. As an asphalt pavement experiences a sudden drop of temperature which induces a considerable stress on the pavement and exceeds the strength of the pavement, a tremendous amount of TC is developed at the moment. The vertical lines in Fig. 1 indicate a sudden "jumping" of TC within a relatively short period of time due to an abrupt temperature drop. It was also observed that asphalt pavements with a combination of softer binder (e.g. PG 52-40) and higher effective binder content endured long enough without experiencing any significant TC fractures, even in an extremely cold climatic region. In the figure, it is noted that the MEPDG TC model assumes that the maximum amount TC would be 800 meter per kilometer (4224 ft/mile) and the TC model stops the TC prediction when it reaches 50% of the maximum (i.e., 400 m/km or 2112 ft/mile) [12].

From this analysis, the following findings were drawn; 1) as the lower the temperature is and the more rapidly the drop of temperature goes, the more severe TC would be developed; 2) in hot climatic regions along with warm and mild winters, TC will never occur in the AC layer, irrespective of the other conditions; and 3) other factors that influence the development of TC are binder type and volumetric characteristics (asphalt content and air voids) existing in AC layer.

Statistics-based Modeling Approach

Development of a TC predictive model for asphalt pavements, which would make the time-consuming statistical analysis more prompt than the MEPDG TC model, was conducted based upon the statistical-regressive approach. The approach was simply to pre-run the MEPDG (version 1.0) for a wide range of climatic and volumetric conditions; and to develop reasonably accurate regression relationships between variables that characterize the conditions and the TC amount. Several parameters were used as variables that were considered significant to impact the TC development: AC Thickness of AC layer; Superpave binder performance grade (PG); volumetric characteristics of the mixture: effective binder content (V_{beff}) and air voids (V_a); and environmental location. A variable matrix was made to run the MEPDG shown in Table 1. A total number of 2000 simulations was run by the MEPDG with the level-3 option. While a significant statistical effort was undertaken to fit the MEPDG predicting with these variables, developing an accurate regression model turned out to be unsuccessful.

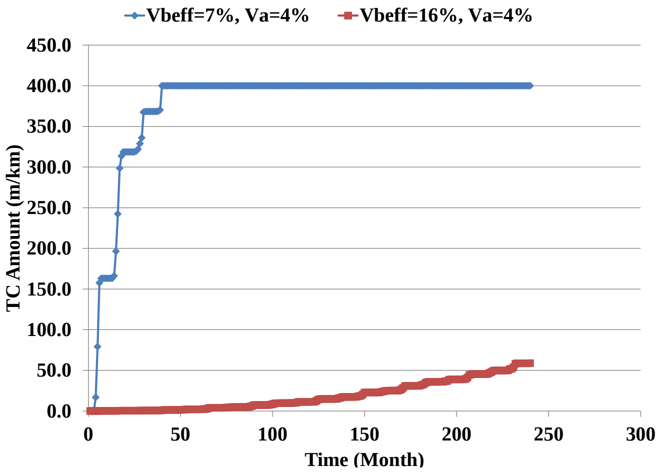

Fig. 1. Cumulative Thermal Cracking Development Pattern Over 20 Years from MEPDG (AC Thickness = 101.5mm, PG58-34, Barrow, AK).

Table 1 Matrix of the Variables for the MEPDG Simulation for the Development of Statistical-based Model.

Variable	Level	
Climatic Locations	Extremely Cold Region to Hot Region	10
AC Thickness (mm)	25.4, 50.8, 101.6, 203.2, and 508	5
Binder Type (PG)	Soft (PG52-40) to Stiff (PG 76-16)	5
Volumetric Properties (Combination of V_{beff} and V_a)	V_{beff}: 7% ~ 12 %, V_a : 3% ~ 12%	8
Total Number of Simulations: 10 × 5 × 5 × 8 = 2000		

Simple mechanistic models were then introduced and combined to improve the unsuccessful regression models. This approach was based on:

1. Finding the daily minimum air temperature, rather than estimating it, directly from the climatic data in the MEPDG: Hourly Climatic Database – also known as "hcd" files [13].
2. Computing estimates of the minimum surface pavement temperature and the maximum pavement temperature gradient at the pavement surface, using some regression equations.
3. Developing a creep compliance master curve of the following form:

$$D(t_r) = D_0 + D_1 t_r^m$$

where D = creep compliance, t_r = reduced time (t/a_T), t = time, a_T = temperature shift factor, and D_0, D_1, m = coefficients to fitting the power model.
4. Computing a representative stress within pavement using the

following approximation:

$\sigma = \alpha \cdot \Delta T / D$

where D = creep compliance at the minimum surface pavement temperature for one hour, α = thermal contraction coefficient, and ΔT = temperature gradient.

5. The ratio of stress to tensile strength was fitted to the MEPDG predicted TC.

This effort was again judged to be inadequate due to the unacceptably low goodness-of-fit of the model. Accordingly, it was concluded that a closed form solution for thermal cracking including linear and non-linear regression methods were found to be very difficult to develop accurate TC solutions. Thus, an alternative solution for the TC distress was obviously necessary.

Mechanistic-based Modeling Approach

The conclusions drawn from the sensitivity analysis and statistical modeling efforts implied that obtaining an accurate TC model should be to track the same fundamental theory that is currently used as a subroutine in the MEPDG thermal fracture module. As the source codes were not available at the time of developing the QA program, the original report to address the TC mechanism [11] was studied and a nearly identical solution was coded in a computer language of FORTRAN for the NCHRP 9-22 project.

It is of quite importance to note that the discussion about the theoretical background of the TC program development is not presented in the paper, as it is identical to the MEPDG level-3 TC modeling approach and already available in the literature as well as the MEPDG documentation [12]. Instead, the following discussion will focus upon addressing the main frame of the developed program along with comparisons of results between MEPDG and developed TC program. Explanation of the input, analysis, and output in the program followed by comparisons of the results are presented in the following sections.

Input

The user's input for the execution of the program is divided into five parts: AC thickness; Design period; Climate; AC mix properties; and Analysis Starting Date; explained as follows:

- AC thickness: The effect of the sub-surface layers such as base, subbase, and subgrade are generally negligible to the TC development. Thus, the only input value regarding pavement structure is the thickness of AC layer in inches. Even if the AC layers have different layer mix types, the total AC thickness is still considered as the input AC thickness.
- Design period: The program will produce estimates of TC amount on a monthly basis until the end of a given design life (maximum: 50 years).
- Climate: Since the AC pavement is extremely sensitive to temperature, climatic information for a certain geographical location is the most critical factor for the analysis of TC. The developed program requires a specific pavement temperature data file as a critical input. The temperature file can be created either by running the Enhanced Integrated Climatic Model (EICM) which, after installing the MEPDG, exists as a form of "im.exe" in the sub folder of the MEPDG (specifically C:\DG2002\bin); or by running the MEPDG itself. As described in the Rosenblueth method presented in the later part of the paper, three pavement temperature files are required to be created: 1) a temperature file for a given AC thickness, 2) one for the thickness plus standard deviation, and 3) one for the thickness less standard deviation.
- AC mix properties: The user's inputs for the AC mix property are the asphalt binder and its temperature susceptibility relationship parameters (commonly known as the intercept, A, and the slope of the relationship, VTS, values) in the RTFO condition, target in-situ air void (%), and the effective binder content (%). If multiple AC layer are used, it is important to recognize that the properties of the top AC layer are only used for the TC analysis, because the top layer prevails the TC initiation.
- Date of analysis: Since the TC development initiates immediately after the conclusion of the AC pavement construction, the developed TC program refers to this date as the analysis starting time.

Analysis

Upon acquiring the user's input, the program begins to analyze and produces estimates of TC predictions for a desired period. As previously mentioned, all these analytical processes are based upon precisely what is used in the MEPDG. Thus, detailed analysis steps can be referred to the relevant MEPDG documentation [12].

Results

The developed program was validated by comparing the TC output from the program with that from the MEPDG. As noted previously, the study initially selected a wide range of environmental and physical conditions of flexible pavement for the MEPDG simulation, as presented in Table 1. Ten environmental locations were originally selected to characterize climate. To have more reliable validation, it was decided to expand the database associated with environmental sites by adding 12 more locations and excluding five warm to hot locations, where no TC occurs, from the original ten locations, which resulted in 17 sites for validation across the nation. The other variable conditions (e.g. mix properties) remained identical as before.

Therefore, the final matrix employed in the analysis includes 17 geographically nationwide locations (cold to warm); five AC thicknesses (thin to thick); five binder type (soft to hard); and eight combinations of mix volumetric. The design life used in this verification study was set to 20 years although the program has an ability to predict TC up to 50 years. All these variables yielded a total number of 3400 MEPDG simulation runs (17 × 5 × 5 × 8 = 3400 runs). Fig. 2 shows the comparison of the TC amount predicted from the MEPDG and the proposed TC program that has been placed in the NCHRP 9-22 program code. Each data point presented in the plot is the TC amount after 20 years for given conditions (note that the TC amount is cumulatively computed from hourly-based pavement temperature for a given design year). The

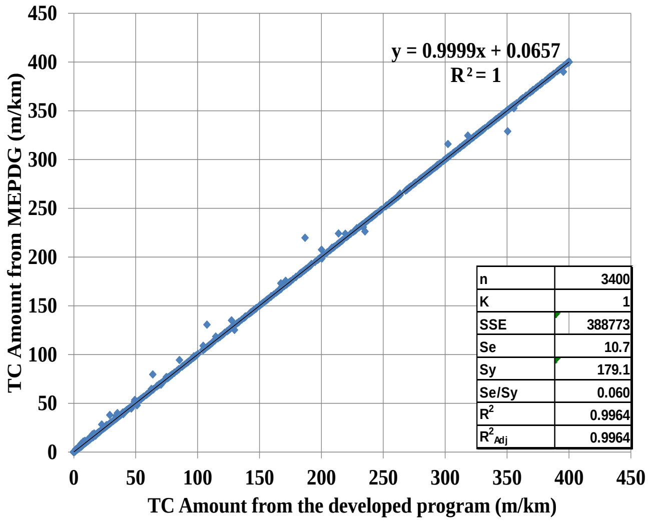

Fig. 2. Comparison of TC Amount between MEPDG and Developed Program (17 Sites, 5 AC Thicknesses, 5 PGs, and 8 V_{beff} -Va Combinations).

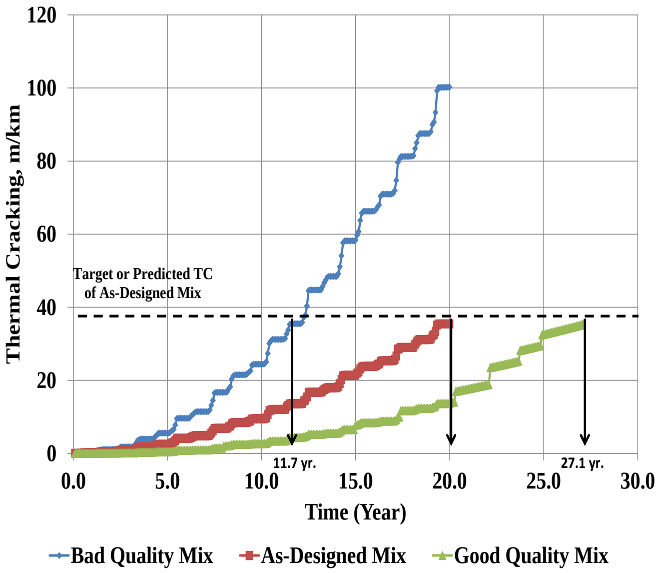

Fig. 3. Example: Determination of Service Life.

plot obviously indicates the predicted TC obtained from both methods is nearly identical for both solution techniques. The R-squared value is more than 0.9999 and the Se/Sy is 0.006.

It is hypothesized that a few pavement sections in Fig. 2 have small, but noticeable differences. Each analysis step between the MEPDG TC module and the computer system developed for the NCHRP 9-22 study was carefully compared. It was found out that several significant discrepancies occurred in the Power model parameters: D_1, D_0, and m-value. Since 40 different types of mixes (5 binder × 8 combinations of volumetric) were investigated in the analysis, the same number of Power models were produced. A careful check of the parameters by a manual calculation using Excel spreadsheet was conducted and it was concluded that the MEPDG version 1.0 code (specifically the "tcmodel.exe" code) occasionally produce incorrect parameters.

It was also found that the "tcmodel.exe" code uses the number of days in a month with an average value of 30.4 days. The code proposed for use in NCHRP 9-22 uses the actual calendar days. For example, 30 and 29 days were used in the developed program for January and February in 2008, respectively, while the 'tcmodel.exe' uses 30.4 days for a month regardless of its actuality.

Conversion of Thermal Cracking into Service Life

The idea on the conversion of TC to service life in the developed TC program is simple. To describe the conversion concept more effectively, an example is presented and explained.

Fig. 3 shows the TC development of several mixes as an example. The TC, over the design life, for a given as-design JMF mix is shown. After the design life of 20 years, the eventual amount of TC is approximately 35.4 m/km (187 ft/mile). This amount of TC becomes the criterion because the mix is the job mix design. The TC development obtained for an as-constructed "bad" mix reaches 35.4 m/km (187 ft/mile) of TC amount even before reaching the design life. This simply implies that the mix would not be satisfying the criterion, and the TC of the mix reaches almost 100.2 m/km (529 ft/mile) at the end of the design life. Therefore, it can be concluded that the mix has a relatively poor quality compared to the JMF mix. The service life of this mix is the moment when the mix TC reaches the target TC (criterion). In this example, the mix reaches the target TC (35.4 m/km) at 11.7 years after the pavement construction.

On the other hand, if an as-built mix is "good", compared to the design JMF mix; the TC development of the mix would increase slower over time than the JMF mix. Even after the design life, the TC amount would be less than that of the JMF mix. Again, this fact implies that the mix would have more service life. The TC program will compute this time when the given mix will reach the criterion TC on a monthly basis and the moment will be the probable service life. In Fig. 3, the good mix reaches the target TC (35.4 m/km) in 27.1 years which is assumed to be the service life of the mix. In cases where an exceptional mix is encountered and the TC of the mix may never reach the target TC; the maximum probable service life is assumed to be 50 years for the probabilistic distribution computations.

STOCHASTIC Analysis

The idea of the probabilistic analysis of TC deals with uncertainties that exist in the pavement system. For instance, if several cored samples are obtained after paving work in a job site, the mix properties such as air voids, binder content, etc may have a different value than the designed value. Average of the collected data from the cores should be theoretically close to the designed value. In the probabilistic analysis, this sort of uncertainties is accommodated by considering the second moment of the distribution: dispersion (or variance).

Determining the variability of TC would be easier if the developed TC prediction program was a closed-form regression model. For a non-closed form solution like the developed program for NCHRP 9-22, there are numerous complexities involved in determining the variability of TC. To deal with the determination of the variability in this type of problem, the Rosenblueth method [14] was incorporated in the program. The following section discusses the application of the method for the TC variability.

Rosenblueth Method

The Rosenbleuth method involves the determination of the probability distribution of a complex function f(x) using linear combinations of powers of adequately selected point estimates around any desired value x. For the first three moments of f(x), approximations using two points are appropriate for well-behaved functions [14]. The 2-point Rosenblueth equations are presented as follows:

$$V[y] = E[(y - E[y])^2] \tag{1}$$

If E[y] is assumed to be constant, the equation can be rewritten as:

$$V[y] = E[y^2 + (E[y])^2 - 2yE[y]] = E[y^2] + (E[y])^2 - 2(E[y])^2 \tag{2a}$$

$$V[y] = E[y^2] - (E[y])^2 \tag{2b}$$

The expectations of y and y^2 can be computed as:

$$E[y^m] = 0.5(y^m{}_{+} + y^m{}_{-}) \quad \text{for one variable } (y = f(x_1)) \tag{3a}$$

$$E[y^m] = (0.5)^2(y^m{}_{++} + y^m{}_{-+} + y^m{}_{+-} + y^m{}_{--}) \tag{3b}$$

for two variables ($y = f(x_1, x_2)$)

$$E[y^m] = (0.5)^3(y^m{}_{+++} + y^m{}_{++-} + y^m{}_{+-+} + y^m{}_{+--} + y^m{}_{-++} + y^m{}_{-+-} + y^m{}_{--+} + y^m{}_{---}) \tag{3c}$$

for three variables ($y = f(x_1, x_2, x_3)$)
where
m = index (superscript) for y and y^2
$y^m{}_+$ = y evaluated for x_1 plus one standard deviation of x_1
$y^m{}_-$ = y evaluated for x_1 minus one standard deviation of x_1
$y^m{}_{+-}$ = y evaluated for x_1 plus one standard deviation of x_1 and x_2 minus one standard deviation of x_2

One of the main advantages of the Rosenblueth method is that it may provide significant computational savings due to the limited number of f(x) estimates. Therefore, the Rosenblueth method makes it possible, even if the function is not a closed-form solution, to determine the variability of TC if standard deviation of each variable of interest is known. As a result, the next issue in using the Rosenblueth method is to determine the standard deviation of each variable.

Determination of Standard Deviation of the Variables

As indicated, the developed TC prediction methodology utilizes five variables as major inputs: AC thickness, air voids, effective binder contents, and binder characteristic parameters (A and VTS) under short term aged (RTFO) condition. For the as-designed JMF mix, the variances may be set by observing agency specification or historical data or reasonably assumed value. For the as-constructed mix, the variances are calculated from actual QA field data by lots. For example, the variance of AC thickness can be measured by cored samples in the project site if the number of samples is large. Among the variables used in the TC prediction, it was found that the most challenging is the determination of the variance of binder properties, A and VTS. Thus, the concept of how to assume the standard deviation of those binder parameters, A and VTS, is studied.

Standard Deviation of Binder Properties

The MEPDG-recommended default RTFO condition A and VTS values are based on one of the known binder grades: Performance Grade (PG) or asphalt penetration grade or asphalt viscosity grade [15]. Once the binder is selected for a given mix, the default RTFO A and VTS values are retrieved from the database. These default A and VTS values are then used as averages for the probabilistic analysis. To determine the standard deviation of the A and VTS values, it was necessary to utilize the following assumptions:

- The variability of the A and VTS values follows a normal distribution.
- The standard deviation of a given binder grade is obtained from its distance to the close neighbors (e.g. the standard deviation of A for PG 52-16 is computed from the A's of PG 52-22, and PG 52-10)
- If no overlap between the distributions of two binders is assumed, the distance between As or VTSs equals two times of 3σ (Fig. 4).

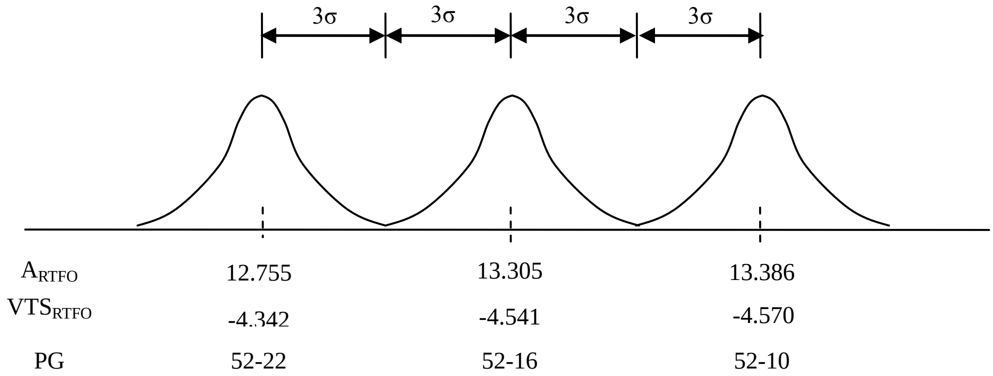

Fig. 4. Example**:** Concept of Standard Deviation of the A and VTS Values.

Based on these assumptions, the standard deviation of any asphalt binder parameter (A and VTS) can be calculated by dividing the absolute difference of the neighbors A and VTS values by 12. For example, Fig. 4 depicts the concept of how to compute the standard deviation of PG 52-16 binder. The neighbor PGs for PG 52-16 are PG 52-22 and PG 52-10 in terms of low temperature grade. Their A and VTS values at RTFO condition are obtained from the MEPDG default values. The standard deviations can be readily calculated as follows:

Standard deviation of A for PG 52-16:

|(13.386 – 12.755)| / 12 = 0.05258

Standard deviation of VTS for PG 52-16:

|(-4.570 + 4.342)| / 12 = 0.0190

If only one neighbor binder exists such as PG xx-10 and PG xx-46, the computation will consider two distributions (i.e. the PG of interest and its one neighbor). Therefore, the A and VTS values should be divided by 6, not 12.

Correlations among the five variables used in the model (air voids, effective binder contents, AC thickness, and asphalt binder parameters (A and VTS)) have been studied and it was revealed that a full correlation existed in the RTFO condition between A and VTS. For the developed TC prediction, it was therefore assumed that only A and VTS have the full correlation ($\rho_{A,VTS}$ = -1) and the other variables are completely independent of each other. Consequently, the number of variable that can be in reality used in the developed TC model is reduced to four and the total number of the Rosenblueth simulation will be $2^4 = 16$.

Beta Distribution

One of the main objectives of the probabilistic procedure is to see the distribution of the predicted distress data along with its statistics such as mean and variance. Many phenomena that occur in nature as well as industry are known to follow the normal distribution.

However, a major drawback of the symmetrical normal distribution is that it sometimes yields totally unreasonable number where data may fall on negative regions or go beyond a specified maximum value. For the TC, the irrational normal curve is most likely to occur when the mean value of TC is close to either minimum (i.e. 0 m/km) or maximum (i.e. 400 m/km) with a relatively large variance. As a more specific example, if the average of predicted thermal cracks is 378.8 m/km (2000 ft/mile) and the standard deviation is 56.8 m/km (300 ft/mile), then approximately 35% of the predicted TC will fall beyond the maximum TC, which is absolutely unacceptable. A conceptual plot for the TC normal distribution is presented in Fig. 5 (upper plot). In another case, the predicted TC using the normal distribution falls in a negative region, which is also irrational.

For this reason and to satisfy the condition in which the minimum and maximum TC values predicted is within pre-determined realm (i.e. range from 0 to 400 m/km), a Beta distribution was selected to fit the predicted distribution of thermal cracks. Beta distribution is very useful especially for a data set which has minimum and maximum values because the distribution limits them. Thus, the example described above will be replaced by the Beta distribution illustrated in Fig. 5, where all predicted TC are distributed within both sides of the restricted values. For the practical purpose of implementing Beta distribution, the maximum and minimum values are set as follows: TC, 0 ~ 400 m/km; and service life, 0 ~ 50 years. Beta distribution density function is presented in Eq. (4):

$$f(x) = \frac{(x-a)^{\alpha-1}(b-x)^{\beta-1}}{B(\alpha,\beta)(b-a)^{\alpha+\beta-1}} \quad \text{for } a < x < b,\ \alpha > 0 \text{ and } \beta > 0 \tag{4}$$

where a and b = minimum and maximum values of a given dataset, respectively,

$$\alpha = \rho_0\left(\frac{\rho_0(1-\rho_0)}{\rho_1}\right) - 1, \tag{5a}$$

$$\beta = (1-\rho_0)\left(\frac{\rho_0(1-\rho_0)}{\rho_1} - 1\right), \tag{5b}$$

$$\rho_0 = \frac{\mu - a}{b-a}, \tag{5c}$$

$$\rho_1 = \frac{\sigma^2}{(b-a)^2}, \text{ and} \tag{5d}$$

$$B(\alpha,\beta) = \int_0^1 t^{\alpha-1}(1-t)^{\beta-1}\,dt. \tag{5e}$$

Illustrative Example

An example illustrating the stochastic analysis presented in this paper is provided. A 101.6 mm (4 inches) thick asphalt pavement

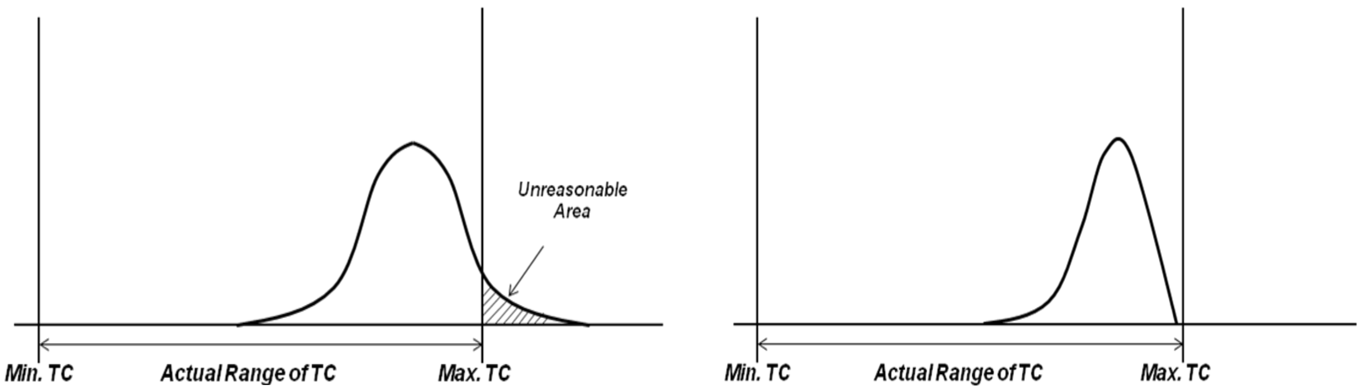

Fig. 5. Conceptual Illustration of Normal and Beta Distribution for Thermal Cracking.

Table 2. Input Conditions and Rosenblueth Result Table for the As-Design JMF Mix.

Variable		Average	Standard Deviation	C.V. (%)
AC Thickness (mm)		101.6	20.345	20.0
Target Air Voids (%)		7.50	0.685	9.1
Effective Binder Content (%)		8.99	0.198	2.2
PG76-16	A_{RTFO}	10.015	0.033	0.33
	VTS_{RTFO}	-3.315	0.012	0.35

Location: Chicago, IL

Design Life: 20 years

Rosenblueth Table							Output from the Program			
Run#	Term	h_{ac}(mm)	Va(%)	V_{beff}(%)	A	VTS	TC	$(TC)^2$	SL	$(SL)^2$
1	++++-	121.945	8.185	9.183	10.048	-3.327	90.7	8226	20	400
2	+++-+	121.945	8.185	9.183	9.982	-3.303	57.2	3272	20	400
3	++-+-	121.945	8.185	8.788	10.048	-3.327	128.2	16435	19	346
4	++--+	121.945	8.185	8.788	9.982	-3.303	90.7	8226	20	400
5	+-++-	121.945	6.815	9.183	10.048	-3.327	40.9	1673	21	441
6	+-+-+	121.945	6.815	9.183	9.982	-3.303	29.7	882	25	605
7	+--+-	121.945	6.815	8.788	10.048	-3.327	79.0	6241	20	400
8	+---+	121.945	6.815	8.788	9.982	-3.303	43.4	1884	21	441
9	-+++-	81.255	8.185	9.183	10.048	-3.327	149.1	22231	19	361
10	-++-+	81.255	8.185	9.183	9.982	-3.303	91.3	8336	20	400
11	-+-+-	81.255	8.185	8.788	10.048	-3.327	189.2	35797	16	240
12	-+--+	81.255	8.185	8.788	9.982	-3.303	150.9	22771	18	310
13	--++-	81.255	6.815	9.183	10.048	-3.327	67.8	4597	20	400
14	--+-+	81.255	6.815	9.183	9.982	-3.303	50.9	2591	21	458
15	---+-	81.255	6.815	8.788	10.048	-3.327	119.3	14232	19	346
16	----+	81.255	6.815	8.788	9.982	-3.303	71.4	5098	20	400
Sum							1449.8	162492	317.3	6348
Mean Thermal Cracking and Service Life							90.6		19.8	
Standard Deviation of Thermal Cracking and Service Life							44.1		1.9	

where

Mean of TC = $E[y] = \frac{1}{2^n}\sum_{i=1}^{2^n} y_i = \left(\frac{1}{2^4}\right)\sum_{i=1}^{2^4} TC_i = 1449.7/16 = 90.6 m/km$

Variance of TC = $E[y^2]-(E[y])^2 = \left(\frac{1}{2^4}\right)\sum_{i=1}^{2^4} TC_i^2 - (90.6)^2 = 1946.2$

Standard deviation of TC = $(1996.6)^{0.5}$ = 44.1 m/km

Mean of SL = $E[y] = \left(\frac{1}{2^n}\right)\sum_{i=1}^{2^n} y_i = \left(\frac{1}{2^4}\right)\sum_{i=1}^{2^4} SL_i$ = 317.3 / 16 = 19.83 years

Variance of SL = $E[y^2]-(E[y])^2 = \left(\frac{1}{2^4}\right)\sum_{i=1}^{2^4} SL_i^2 - (19.83)^2 = 3.47$

Standard deviation of SL = $(3.47)^{0.5}$ = 1.9 years

with 7.5% target in-place air voids, 9% effective binder content, and PG 76-16 binder in Chicago, Illinois is designed and the predicted TC of the pavement is stochastically analyzed. The average and standard deviation of the given variables are presented in the upper portion of Table 2. With the information given, the developed TC prediction program was run 16 times (24) according to the combination runs of the Rosenblueth table. The averages and standard deviations of the TC as well as the service life were computed and the results are presented in Table 2.

It is noted that these results from the as-designed mix are used as a reference to relatively evaluate the quality of the as-constructed mix in terms of the pavement performance related to TC and the projected service life of the pavement. The graphical presentation for the comparison between the two mixes is completed using Beta distributions. Fig. 6 shows a group of Beta distributions plotted by the Beta density and cumulative functions.

In the PRS system, the cumulative service life of the as-design JMF mix shown in the lower right corner of the figure is compared with that of as-constructed mix in order to estimate the predicted service life difference. This predicted life difference is eventually used to apply to the pay factor system and quantitatively determine the contractor's incentive or disincentive.

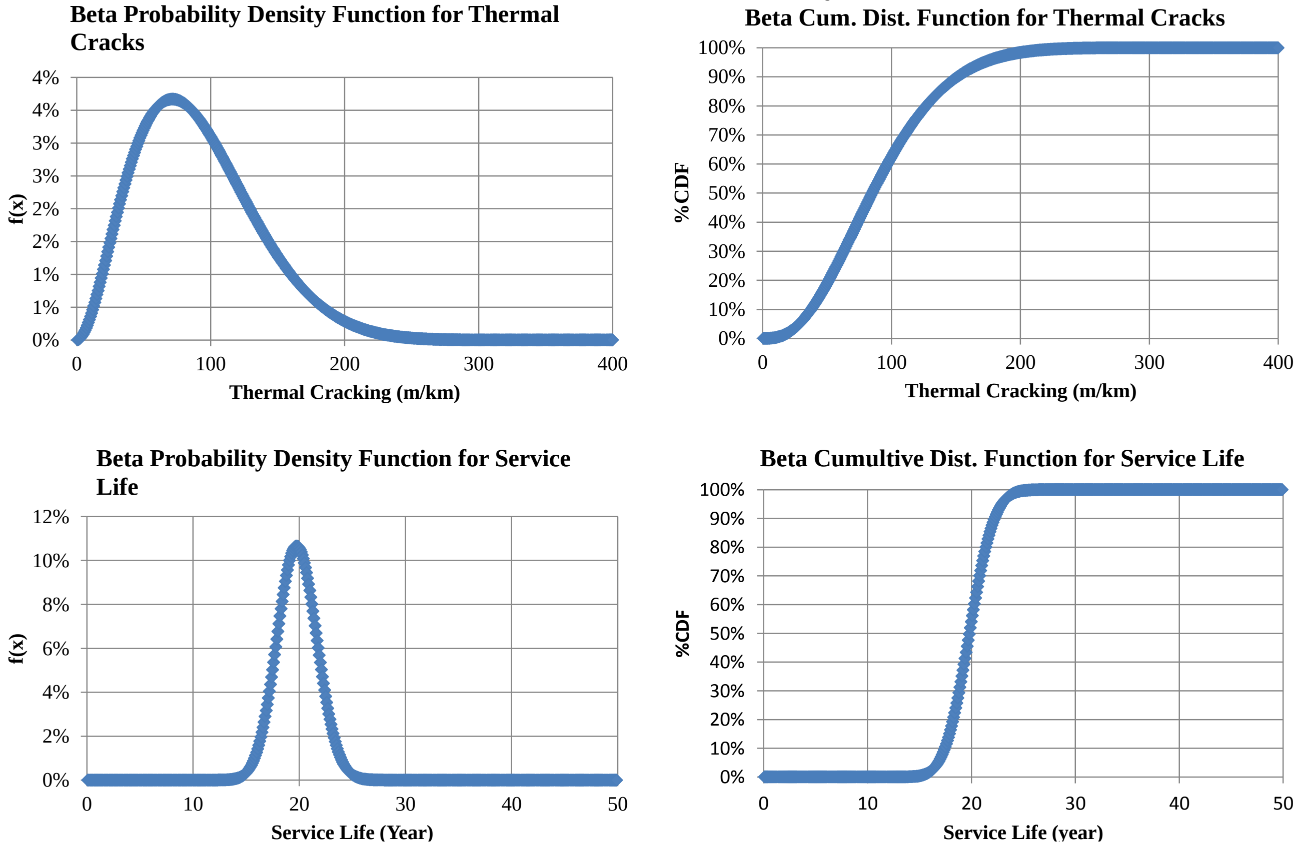

Fig. 6. Beta Distribution of Predicted Thermal Cracking and Service Life.

Summary and Conclusion

The methodology involved in the thermal cracking performance prediction and its relevant stochastic analysis is proposed. This methodology is the system that has been coded in the stochastic QA system for asphalt mixture in the NCHRP 9-22 project. The developed stochastic framework deals with the performance of both as-design JMF and as-constructed mixes associated with TC. The performances are represented by a cumulative Beta distribution of predicted service life. The average difference between the two distributions is eventually utilized to implement a pay factor system where the contractor is determined to be awarded or penalized based upon the prediction of the major MEPDG distresses.

This research draws two important conclusions; 1) the development of an accurate closed-form type TC prediction model based on the MEPDG is not feasible mainly because the complexities of the nature of TC and the MEPDG TC module; and 2) the TC analysis framework presented in this paper suggests a practical application in stochastically evaluating the TC performance of the as-constructed asphalt mix. It is also concluded that the Rosenblueth method was a reliable approach in estimating the mean and variance of the performance model, especially when the model is not a closed form solution. The Beta frequency distribution showed a more realistic fit to represent the TC dispersion.

Acknowledgements

The author of this paper acknowledges that the study presented was conducted as a part of NCHRP 9-22 (Beta Testing and Validation of HMA PRS). The authors would like to acknowledge the general overview guidance, valuable input and recommendations to enhance the manuscript from Drs. Matthew Witczak and Jacob Uzan.

References

1. Hughes, S.C. (2005). State Construction Quality Assurance Program. *NCHRP Synthesis 346*, Transportation Research Board, Washington, DC, USA.
2. Moulthrop, J. and Witczak, M.W. (2011). A Performance-Related Specification for Hot Mixed Asphalt. *NCHRP Report 704*, Transportation Research Board, Washington, DC, USA.
3. El-Badawy, S.M., Jeong, M.G., and El-Basyouny, M. (2009). Methodology to Predict Alligator Fatigue Cracking Distress Based on Asphalt Concrete Dynamic Modulus. *Transportation Research Record*, No. 2095, pp. 115-124.
4. El-Basyouny, M. and Jeong, M.G. (2009). Development of Database Solution for Prediction of the MEPDG Permanent Deformation. Paper presented at the 89th Annual Meeting of Transportation Research Board, Washington, DC, USA.
5. Jeong, M.G. and El-Basyouny, M. (2010). Statistical Applications and Stochastic Analysis for Performance-Related Specification of Asphalt Quality Assurance. *Transportation Research Record*, No. 2151, pp. 84-92.
6. Anderson, K.O., Shields, B.P., and Dacyszyn, J.M. (1996).

Cracking of Asphalt Pavements Due to Thermal Effects. *Proceedings of the Association of Asphalt Paving Technologists*, 35, pp. 247-262.

7. Marker, V. (1996). Introduction to Non-Traffic Load Associated Cracking of Asphalt Pavements. *Proceedings of the Association of Asphalt Paving Technologists*, 35, pp. 239-247.
8. Fromm, H.J. and Phang, W.A. (1996). A Study of Transverse Cracking of Bituminous Pavements. *Proceedings of the Association of Asphalt Paving Technologists*, 41, pp. 383-423.
9. Hass, R.C.G. and Topper, T.H. (1969). Thermal Fracture Phenomena in Bituminous Surfaces. *Highway Research Board Special Report 101*. Highway Research Board, Washington, DC, USA.
10. Hass, R.C.G. and Anderson, K.O. (1969). A Design Subsystem for the Response of Flexible Pavements at Low Temperatures. *Proceedings of the Association of Asphalt Paving Technologists*, 38, pp. 179-223.
11. Hiltunen, D.R. and Roque, R. (1994). A Mechanics-Based Prediction Model for Thermal Cracking of Asphaltic Concrete Pavements. *Proceedings of the Association of Asphalt Paving Technologists*, 63, pp. 81-117.
12. ARA Inc. (2004). Part 3. Design Analysis. Chapter 3. Design of New and Reconstructed Flexible Pavements. Final Report: Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, DC, USA.
13. Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. Guide ICM File Formats. http://www.trb.org/mepdg/ICM_Formats.htm. Accessed June 21, 2009.
14. Rosenblueth, E. Point Estimates for Probability Moments. (1975). *Proceeding of National Academy of Sciences of the United States of America*, 72(10), pp. 3812-3814.
15. ARA Inc. (2004). Part 2. Design Inputs. Chapter 2. Material Characterization. Final Report: Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, DC, USA.