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RELATING FLEXIBLE PAVEMENT ACCEPTANCE CRITERIA TO PERFORMANCE USING MEPDG SIMULATIONS AND PIECEWISE CUBIC SPLINE INTERPOLATION

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Abstract. The performance of the highway system is inevitably linked to its quality of design and construction. To control the quality of construction, elaborate Quality Assurance (QA) programs have been developed by highway agencies based on statistical sampling and acceptance procedures to ensure that the work is in accordance with the plans and specifications. The QA procedure is intended to ensure that the constructed pavement would perform well during its design life. However, numerous field investigations and research studies over the years have identified a gap in our understanding of the relationship between the QA test results and pavement performance (fatigue cracking, rutting, etc.). This paper is intended to present the framework for developing an understanding of the relationship between QA tests and flexible pavement performance, which is essential for developing Performance Related Specifications (PRS). In the first part of the paper, the Michigan Department of Transportation's (MDOT) QA program and Long-Term Pavement Performance (LTPP) databases were used to empirically investigate any relationship between key QA variables and various pavement performance measures. In the second part of the paper, the Mechanistic-Empirical Pavement Design Guide (MEPDG) software was used together with an accurate and efficient interpolation technique to develop many simulations for the purpose of showing the effect of variability in QA parameters including plant air voids, in-situ density and asphalt content on flexible pavement performance.

Keywords: quality assurance, rutting, cracking, mechanistic-empirical design guide, percent within limits (PWL), LTPP.

1. Introduction

The acceptance criteria for Hot-Mix Asphalt (HMA) pavements (generally in-place density, air voids, Voids in between Mineral Aggregates (VMA), and asphalt content) have not changed much since their inception (AASHTO 1996; Burati *et al.* 2003, 2004). Over the years, however, various investigations and research studies regarding distress initiation have identified other factors that contribute to both good and poor pavement performance (Chatti *et al.* 2005; Masad *et al.* 2006). These factors include adequate pavement support, varying material properties/characteristics, HMA permeability, and asphalt film thickness etc. The above suggests that current acceptance criteria for pavements need to be re-evaluated and possibly revised/updated to better conform to the deterioration process of the pavements during their service life.

There has been a growing interest in the development of Performance-Related Specifications (PRS) for highway pavement construction over the past 25 years. Although similar to quality assurance specifications, the measured acceptance quality characteristics in PRS should be directly related to pavement performance through mathematical relationships. Performance is defined by key distresses and smoothness, and is directly related to the future maintenance, rehabilitation, and user costs of the highway (Darter *et al.* 1993).

A Quality Assurance (QA) procedure is intended to ensure that the end product from the construction would perform well in the period that it was designed for; i.e. during its design life (Benson 1995). This requires that the tests which are conducted during or immediately after construction under a given QA procedure be directly related to expected performance. Even with the current state-of-the-art knowledge, relationships of these QA test results with performance are not very well understood in a quantifiable way (Manik, Buttlar 2005).

One approach towards understanding the relationships between the types of tests used in QA programs and pavement performance would be to determine them empirically. This would require that both the QA test data and performance data be gathered for various projects. These projects should be sufficiently old to be adequately judged for their actual in-service performance. Therefore, the initial approach for the research study described in this paper relied heavily on gathering and analyzing historical data from various in-service pavements in the state of Michigan. However, efforts to gather such data revealed that very little data from QA test results are available for MDOT projects from the time of construction. Therefore, it was decided that along with continued exploration of empirical data from MDOT projects, other alternative approaches should also be explored.

The main objective of this paper is to lay down the framework for exploring the relationships between QA test results and pavement performance by employing a novel simulation technique developed for use with the Mechanistic-Empirical Pavement Design Guide (MEPDG) software. Such relationships are very helpful in the development of a robust Performance Related Specifications (PRS) system as several scenarios can be evaluated in a short time by running multiple simulations. It is shown that it is very difficult to establish such relationships solely using the LTPP data or the Michigan DOT database.

2. Data extraction from MDOT and LTPP databases

The LTPP database contains material, design and construction data including physical inventory data, material properties from in-situ and laboratory tests (LTPP 2005). Performance data are reported in the form of rut depth, fatigue cracking, longitudinal cracking, transverse cracking, IRI etc. Flexible pavement data were collected from General Pavement Study (GPS) experiments. Table 1 lists the categories of data that were extracted from the LTPP database. Although there is appreciable amount of data for the categories listed in Table 1 in the LTPP database, they come from several different projects. Therefore, the factors affecting the relationship between these variables

Table 1. Categories of data extracted from LTPP database for flexible pavements

Flexible Pavements	
Construction number	
Traffic opening date	
Maximum specific gravity	
Bulk specific gravity	
	Mean
	Minimum
	Maximum
	Standard deviation
	Number of samples
Asphalt Content	
	Mean
	Minimum
	Maximum
	Standard deviation
	Number of samples
% Air voids (in-situ)	
	Mean
	Minimum
	Maximum
	Standard deviation
	Number of samples
Voids in mineral aggregate	
Effective asphalt content	

and performance would vary and are very difficult to decipher from such data. It was also observed that there are very few QA data available for the state of Michigan (at least for the older pavements).

3. Relationship between existing acceptance parameters and pavement performance

In a QA program similar to the one used by Michigan, the portion of payment to the contractor completely depends on the percent within limits (PWL) achieved for one quality characteristic (NCHRP 2005). For example, 40% of payment in Michigan flexible pavement construction depends on the in-situ density achieved immediately after final rolling. The PWL for density, therefore, is expected to be directly related to pavement performance. PWL is calculated from the achieved quality (in-situ density in this example) and it takes into account the mean as well as the standard deviation. Thus, PWL, irrespective of the state and the mix used, should be indicative of the expected pavement performance. Therefore, the relationship between PWL for various quality characteristics and performance is of interest in this research study.

A study of end-result specifications used by several states showed that the majority of states follow statistical specifications using PWL. It was also observed that the specification limits used by these states are very similar to the ones currently used in Michigan. For example, most of the states use 91.5% or 92% as their lower specification limits for in-situ density, target ±0.4% or ±0.5% as limits for asphalt content and 4±1% or 4±1.2% for air voids at N_{design} for plant HMA samples. Also, the procedure followed by different states for calculating PWL is almost always identical. Therefore, it is possible to apply a common procedure to calculate PWL from data originating from different states and then relate them to observed performance.

4. LTPP data analysis

As shown in Table 1, the inventory database in LTPP has mean bulk specific gravity for the as-placed mixture along with maximum specific gravity. Therefore, the mean in-situ density can be calculated for these projects. The same database also provides standard deviations of bulk specific gravity and the number of samples used for calculating the standard deviations. However, standard deviations have not been provided for all the projects. Calculation of percent within limits requires mean and standard deviation for the projects. Therefore, those projects which had both types of data were filtered and extracted from the database. This filtering reduced the available data points from 2027 to 306.

Cracking performance for the LTPP projects is reported in a different database termed "monitoring" in LTPP in the form of low, medium and high severity fatigue, longitudinal and transverse cracking. LTPP recommends that if distinction between severity levels does not have to be made in an analysis, they can be added together. This was done in this study for the three categories of cracking. In the next step, the projects which had enough details for calculation of PWL in the inventory database were matched against those projects which had cracking performance reported. Three-dimensional plots were generated with each data point having its own time in the third dimension using a new plotting system developed in-house using Matlab®.

4.1. Pavement performance vs PWL (in-situ density) and age

Fig. 1 shows three-dimensional plots of pavement performance (fatigue cracking, transverse cracking, longitudinal cracking, and rutting) at different times during the service life of projects versus PWL for in-situ density. Each of these plots has 306 data points. However, any one project can have more than one point which corresponds to the different times at which the distress was measured. Each of the pavement performance measures is separately considered below.

From Fig. 1, it appears that projects having PWL close to or equal to 100% show more distress than those with lower PWL values, which is counter-intuitive. However, this is not necessarily true. In QA programs, generally a window around the target for each of the quality characteristic is allowed. As long as the quality characteristics remain within that window, PWL values would be 100%. Therefore, a very large percentage of projects would have 100% PWL even if the mean and standard deviations of the quality characteristics vary. Also, many such points with 100% or near 100% PWL plot on top of each other and the points which have more fatigue cracking become more visible while hiding other points.

The presence of data points with lower PWL and good cracking performance does raise doubts about PWL being the criterion of choice for payment. Existing design methods have largely been empirical in nature. Pavements constructed with such a design, as described above, may have a longer or shorter performance life than the theoretical design life period. This issue has been further studied using simulation and is discussed in greater detail in the following sections of this paper.

Fig. 1 for fatigue cracking also displays several projects for which PWL values are much lower than 100%, in some cases as low as 50%, which is the trigger point for 'remove and replace' in QA programs, and yet they have no or almost no fatigue cracking. This is a very important observation from a QA point of view.

4.2. Pavement performance vs PWL (plant air voids) and age

The LTPP database has plant air voids documented for several projects for which standard deviations have also been reported. All such project data records, numbering 452, were filtered and extracted from the database. These projects were then matched with their cracking and rutting performance from the monitoring database and their ages were determined from the inventory database. Fig. 2 presents three-dimensional plots of pavement performance versus PWL (plant air voids) and age. The plot for

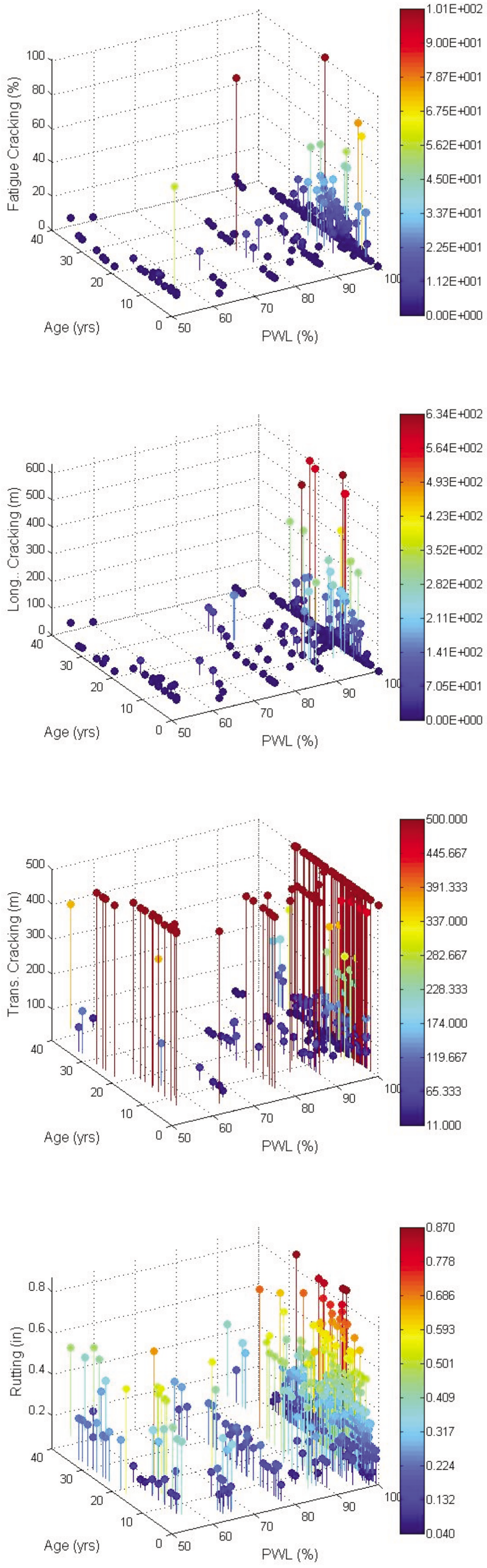

Fig. 1. Pavement performance versus PWL (in-situ density) and age from LTPP database

fatigue cracking, for instance, shows more projects which have poorer PWL (plant air voids) having greater fatigue cracking compared to those with PWL values closer to 100%. In most of the States, including Michigan, any project having PWL between 90% and 100% is not penalized and the contractor is paid in full. Therefore, in this case, most of the projects that were paid in full did not show much fatigue cracking. This seems to indicate that PWL (plant air voids) may be directly related to cracking performance. There are several projects, however, with lower PWL (which means they would have been penalized) that do not show any fatigue cracking. In summary, based on these few plots, it can be said that while lower PWL does not necessarily mean poor performance at a given time, the probability of better performance certainly goes up with higher PWL.

There is a substantial amount of data in the LTPP database for different categories of input variables as well as performance surveys on in-service pavements. However, any given construction project is unique because a variety of factors affect it in a combined manner. Although numerous factors affect pavement performance, not all of them can be controlled at the time of construction. This can be easily observed in those cases where quality control is very poor and the pavement starts developing premature distresses. However, in the majority of pavements being constructed, it is assumed that the quality control is good to excellent. Therefore, it is important to study how relatively minor changes in quality affect service life or the performance of the pavement. The MEPDG software (NCHRP 2004, 2006) lends itself well to such analysis even though it is known that the performance predicted by MEPDG may not be accurate all the time. Nonetheless, the software can show relative effects in a consistent and rational manner. The next section presents analysis performed using MEPDG to study the influence of QA variables such as plant air voids, insitu density and asphalt content on flexible pavement performance.

5. MEPDG simulations

The latest MEPDG software contains different nationally calibrated performance models for predicting pavement properties and performance together (NCHRP 2004, 2006). This makes it possible to study the effect of various quality characteristics on pavement performance. A significant advantage of using MEPDG is that the interactive effect of multiple input variables or quality characteristics on performance can be studied together rather than individually, thus lending itself to realistic sensitivity analyses. The models used in the MEPDG, like all mechanistic-empirical models, have limitations and inaccuracies associated with them. This is expected as we are trying to model natural materials which vary both by their location and with changing environment and complex failure mechanisms over extended periods of time. But it should also be accepted that these models are constantly evolving and are currently the best that the transportation industry can muster at this point of time.

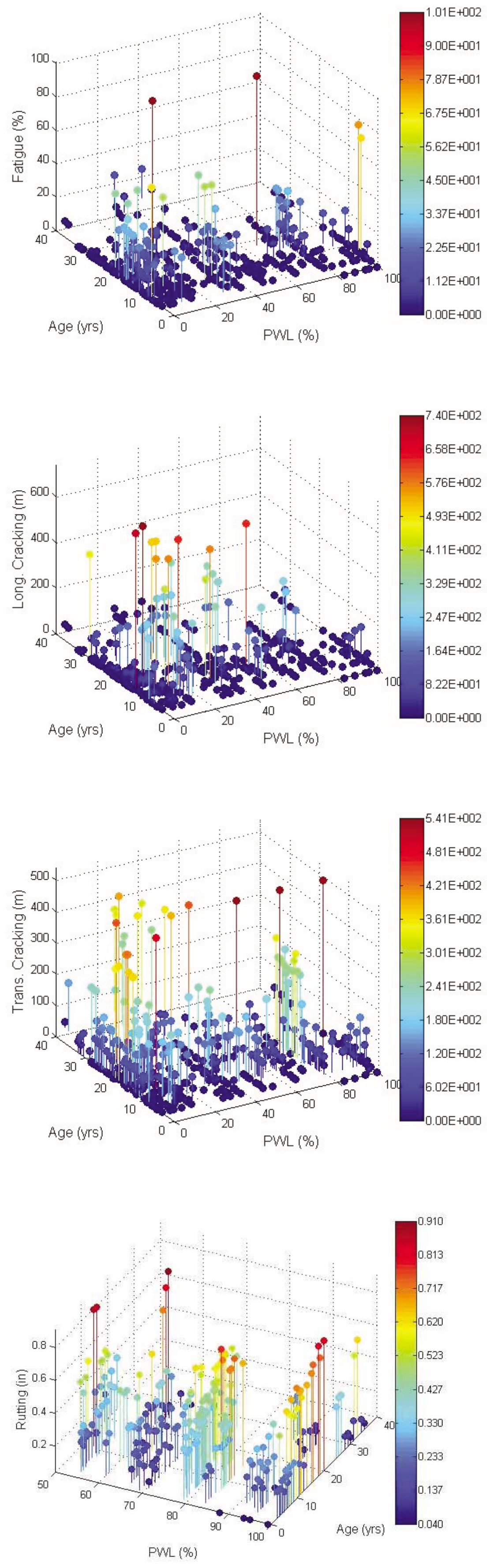

Fig. 2. Pavement performance versus PWL (plant air voids) and age from LTPP database

In this paper, case scenarios simulated using advanced statistical methods are presented and MEPDG was used to determine the results of these case scenarios. As stated earlier, the LTPP database has mean and standard deviation values for input variables like in-situ density and asphalt content along with the number of samples used for determining standard deviation, although individual data used for the calculation are not documented. Statistical methods were used to generate simulated values of in-situ air voids and asphalt content which would have the same means and standard deviations as those reported in the LTPP database. This was done by writing a computer program in Matlab®. These numbers would be very similar to those observed in real life projects under a QA program.

The next step would be to input each scenario in MEPDG and determine expected pavement performance in terms of fatigue cracking, longitudinal cracking, rutting etc. To better appreciate what this entails, the example of data plotted in Fig. 1 (for fatigue cracking) is considered. Each data point in the plot represents the mean of fatigue cracking for one project (LTPP section). Each project would have a number of samples tested for determining mean and standard deviation of in-situ density and asphalt content. Combining the number of samples from all the projects plotted in the figure and for density as well as asphalt content, the total number of MEPDG runs required would be 7,884. Each run using MEPDG to predict distresses for 30 years would take an average of 50 minutes. Therefore, the total time required for carrying out all the runs for a single plot would be 273 days, assuming that there are no errors or crashes while the runs are conducted. For all practical purposes, it is almost impossible to execute this task. An alternative is presented below which can make this task much more efficient.

The proposed alternative, in principle, is to run the MEPDG to develop a response surface and use it to determine the performance for all 7,884 case scenarios through advanced interpolation techniques in n+2 dimensions, n being the number of variables being considered. Response surface methodology (RSM) explores the relationships between several explanatory variables and one or more response variables (Box, Wilson 1951). For developing the response surface in this case, the entire range of in-situ density and asphalt content should be identified. Then some points in between the maximum and minimum values should be identified. In this analysis, three more values between the extremes were identified, making for a total of 5 values each for density and asphalt content. Then, a full factorial matrix is defined using all possible combinations of the values of asphalt content and density. This would make for 5 x 5 = 25 runs. Two different mixtures and the associated input characteristics in MEPDG were identified. Then all the 25 runs were executed for each of the mixtures.

The results from the 50 runs (25 runs for each mixture) were categorized in terms of fatigue, rutting, etc. All the 25 cases defined here were real combinations of input variables derived using MDOT designs. One can then imagine a response surface where the four dimensions represent density, asphalt content, age and fatigue (or rutting, etc.). Such response surfaces were created in Matlab®.

Each of the required 7,884 runs of MEPDG correspond to one combination of density and asphalt content and the response would be required for varying ages in each case. The response surface created in the analysis actually contains each of these points as long as density and asphalt content fall within the range identified for running the 25 cases with MEPDG. Therefore, using the *piecewise cubic spline interpolation technique* in four dimensions, fatigue and rutting responses for all of the 7,884 cases were generated. This was done by writing a computer program in Matlab®. In the final step, fatigue cracking corresponding to each project was calculated by averaging all the fatigue values corresponding to different samples.

Piecewise cubic spline interpolation technique was chosen in this case because it fits a n-dimensional cubic surface locally to each portion of the surface while maintaining continuity in the magnitude and slope of the surface with the neighbouring areas of the surface in all dimensions. This makes this technique extremely versatile to be used on diverse types of surfaces while maintaining excellent accuracy all across the surface. Regression or model fitting can lead to appreciable errors in certain ranges of input variables especially when it has to be fit in more than two dimensions. A brief discussion on the application of piecewise cubic spline interpolation technique is first presented before discussing the results from MEPDG simulations.

6. Piecewise cubic spline interpolation

A cubic-spline is a spline constructed of piecewise third-order polynomials which pass through a set of control points (Knott 2000). As an interpolation method, the cubic-spline interpolation method also tends to derive the unknown values with the help of the known ones and tries to interpolate the values as closer to the original ones as possible. Piecewise representation of cubic spline interpolants is useful for semi-analytical computations of derivatives and integrals of the interpolating polynomials. The piecewise representations can be used for piecewise polynomial interpolations of any order (Forsythe *et al.* 1977).

In cubic spline interpolation, the goal is to derive an interpolation formula that is smooth in the first derivative as well as continuous in the second derivative, and both within an interval and at its boundaries. Since a straight polynomial interpolation of evenly spaced data tends to build in distortions near the edges of the table or matrix, cubic splines are popular as they avoid this problem and produce a curve that appears to be seamless. In addition, they are also easily implemented.

The basic algorithm for cubic spline interpolation involves constructing a piecewise-cubic polynomial $g(x)$ that interpolates the real-valued function $f(x)$ at the $N + 1$ points $x_0 < x_1 < ... < x_N$ at which the values of $f(x)$ are known (Dyer, S. A., Dyer, J. A. 2001; Dyer, He 2001).

7. Discussion of results from MEPDG simulations

Fig. 3 shows mean fatigue cracking estimated using the response surface for different case scenarios. Some of the cases were added to get a better picture of what happens when PWL is lower than 90%. The plot shows the expected trend of more fatigue cracking with increasing pavement age. It is also clear that as PWL (in-situ air voids or density) increases, the projects have less fatigue cracking for the same age.

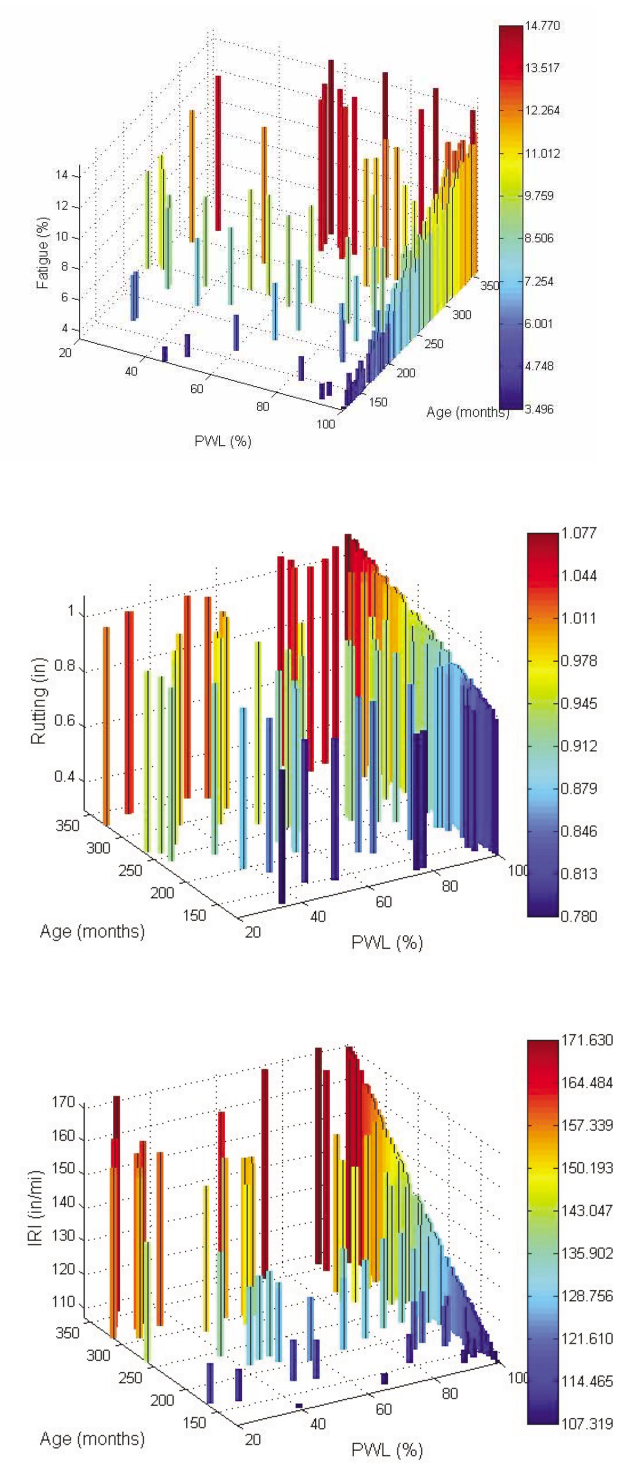

Fig. 3. Pavement performance versus PWL (in-situ air voids) for mix 1 using MEPDG results

It is also noticeable that for very similar PWL, different projects show different amount of fatigue cracking. This is because fatigue cracking in each project is estimated by sampling. As long as the range, mean and standard deviation of two samples are same, they would have the same PWL. But the average fatigue cracking can vary depending on where each of the sample falls within the specifications. For example, hypothetically, if a project has samples with all their densities equal to 93%, PWL would be 100%. If the density of all the samples were 98%, still PWL would be 100%. But the fatigue performance for the 98% density project would be much better than that for the project with mean density of 93%.

Rutting performance estimated using the MEPDG simulations for the same example projects is also shown in Fig. 3. This figure shows that rutting performance improves as PWL approaches 100%. In this example, the improvement is very small. In other words rutting performance is not so sensitive to PWL (in-situ air voids) according to MEPDG results. Fig. 3 also shows similar results in the case of IRI. The plot shows that IRI too is not much influenced by PWL (in-situ air voids).

It must be mentioned that all these results are for one type of mix. It is important to study different types of mixes to assess how PWL values affect performance for each one of them. It is quite possible that this effect may be much more pronounced in other types of mixes.

8. Summary and findings

To control the quality of construction, elaborate Quality Assurance (QA) programs have been developed by highway agencies based on statistical sampling and acceptance procedures to ensure that the work is in accordance with the plans and specifications. The QA procedure is intended to ensure that the constructed pavement would perform well during its design life. However, numerous field investigations and research studies over the years have identified a gap which exists in our understanding of the relationships between the QA test results and pavement performance in a quantifiable way.

The main objective of this paper was to explore the relationships between QA test results and pavement performance by employing a novel simulation technique developed for use with the Mechanistic-Empirical Pavement Design Guide (MEPDG) software. Such relationships are very helpful in the development of a robust Performance Related Specifications (PRS) system as several scenarios can be evaluated in a short time by running multiple simulations. Two HMA mixes from amongst several that MDOT uses on Michigan highways were analyzed using the simulation technique to demonstrate the proposed methodology. In-situ density (or in-situ air voids) and asphalt content were used as example variables for the demonstration purpose. The significant findings from the study are:

- It was shown that it is very difficult to establish relationship between QA test results and pavement performance solely using LTPP data or Michigan DOT database;

- Based on MEPDG simulation results, the pavement performance did not vary much for varying density and asphalt content values. Obviously, the outcome of such analysis would be different for different mixtures/projects simulated. However, this example clearly demonstrates that the method proposed in this paper can be used to relate pavement acceptance criteria to performance in an extremely efficient manner;
- It was also demonstrated that use of piece-wise cubic spline gives accurate results, which is not possible with traditional curve/model fitting techniques. The traditional methods become increasingly inaccurate as the number of dimensions (i.e. the number of QA variables being analyzed) increases. The piece-wise cubic spline method, however, can provide the same high level of accuracy even for higher number of dimensions;
- It must be mentioned that the results from MEPDG presented in this paper are for two specific mixes only. To assess specific quality assurance programs all the mixes being used by the highway agency should be analyzed for all the QA variables which are part of the program.

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LANKSČIŲJŲ DANGŲ ATRANKOS KRITERIJŲ SUSIEJIMAS NAUDOJANT MEPDG MODELIUS IR DALINĘ KUBINĘ SPLAININĘ INTERPOLIACIJĄ

A. Manik, K. Chatti, K. Gopalakrishnan

Santrauka

Greitkelių sistemos darbas (funkcionavimas) yra neišvengiamai susijęs su jo projektavimo ir statybų kokybe. Greitkelių agentūros, remdamosi statistinėmis atrankos ir ėmimo procedūromis, parengė kokybės užtikrinimo (KU arba QA) programas, kad būtų kontroliuojama statybų kokybė ir užtikrinamas darbas pagal planus ir specifikacijas. KU (QA) procedūra siekiama užtikrinti, kad pagaminta danga gerai funkcionuotų projekte nurodytą laiką. Tačiau metams einant, atlikus daugybę natūrinių ir mokslinių tyrimų, buvo nustatytas didelis santykio tarp KU (QA) bandymų rezultatų ir dangos darbo (funkcionavimo) (plyšių atsiradimo dėl nuovargio, provėžų ir kt.) vertinimo skirtumas. Šiame darbe skatinama plėtoti supratimą apie ryšius tarp KU (QA) bandymų ir lanksčiųjų dangų funkcionavimo, kuris yra nepaprastai svarbus kuriant su darbu (funkcionavimu) susijusias specifikacijas (PRS). Pirmoje darbo dalyje buvo naudojamos Mičigano transporto departamento (MDOT) KU (QA) programos ir ilgalaikės dangos darbo (funkcionavimo) (LTPP) duomenų bazės, siekiant empiriškai ištirti bet kuriuos santykius tarp pagrindinių KU (QA) kintamųjų ir įvairių dangų darbo matavimų. Antroje darbo dalyje buvo naudojama mechanistinio ir empirinio dangų projektavimo vadovo (MEPDG) programinė įranga kartu su tikslia ir efektyvia interpoliacijos technika, siekiant sukurti modelius, kuriuose perteiktas KU (QA) parametrų kintamumo poveikis lanksčiųjų dangų funkcionavimui, įskaitant augalų oro ertmes, vietinį tankį ir asfalto sandarą.

Reikšminiai žodžiai: kokybės užtikrinimas, provėžos, skilinėjimas, mechanistinis ir empirinis projektavimo vadovas, procentas, neviršijantis nustatytas ribas (PWL), LTPP.

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