QUALITY ASSURANCE IN ROADWAY PAVEMENT CONSTRUCTION

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ABSTRACT: In the current pavement construction practice, the state agencies traditionally determine the quality of the as-constructed pavement mix based on individual mixture material parameters (e.g., air voids, cement or asphalt content, aggregate gradation, etc.) and consider these parameters as key variables to influence payment schedule to the contractors and the present and future quality of the as-constructed mixture. A set of empirically pre-determined pay adjustment schedule for each parameter that was differently developed and being used by the individual agencies is then applied to a given project, in order to judge whether each parameter conforms to the designated specifications and consequently the contractor may either be rewarded or penalized in accordance with the payment schedule. With an improved quality assurance system, the Performance Related Specification, the individual parameters are not utilized as a direct judgment factor; rather, they become independent variables within a performance prediction function which is directly used to predict the performance. The quantified performance based on the prediction model is then applied to evaluate the pavement quality. This paper presents the brief history of the quality assurance in asphalt pavement construction including the Performance Related Specifications, statistical performance models in terms of fatigue and rutting distresses, as an example of the performance prediction models, and envisions the possibilities as to how this Performance Related Specification could be utilized in other infrastructures construction quality assurance.

Keywords: Quality Assurance, Pavement Construction, Construction Specification, Performance Related Specification

1. INTRODUCTION

It is a traditionally common practice in many state transportation agencies that they evaluate the quality of the as-constructed asphalt mixture based on individual mixture parameters such as in-place air voids, asphalt content, aggregate gradation, and other volumetric-related properties. The individual parameters that are collected multiple times on site are transformed into a quality related index which is essentially an indicative of the in-place mix quality statistically determined by the normal distribution assumption. The quality index is then applied to a set of empirically pre-determined payment schedule where a decision is made whether the contractor will be penalized or awarded on the basis of the payment schedule and the quality index.

The underlying assumption on this penalty-bonus system in the pavement quality assurance is that the individual mix properties are strongly related to the pavement performance during its service life. While it is believed to be true in the view of historical observation and experience, it is thought to be unrealistic to utilize the empirical based payment schedule. This is because there currently is no such a clear methodology in the incentive-disincentive system that connects the individual properties to the eventual pavement performance, and quantifies the degree of influence to the performance by each of the individual properties.

The shortcoming of the current quality assurance in paving construction could be addressed by using a Performance Related Specification (PRS). According to Transportation Research Board Circular, *Glossary of Highway Quality Assurance Terms*, the term of PRS is defined as “QA specifications that describe the desired levels of key materials and construction quality characteristics that have been found to correlate with fundamental engineering properties that predict performance. These characteristics (for example, air voids in AC and compressive strength of PCC) are amenable to acceptance testing at the time of construction” [1]. The definition clearly indicates that quality assurance specifications can use performance instead of the individual properties, so long as a strong correlation is found between predicted performance and individual properties; and thus the performance can be predicted.

Therefore, if the PRS is successfully implemented under the mutual consensus between industry and agencies, it could be a more realistic and reasonable to the paving quality assurance system. In fact, the concept of the PRS can be extended to other infrastructures which currently employ individual properties as a quality characteristic rather than their performance. Examples would include residential and commercial buildings, bridges, slope stabilization, earth work, etc.

To implement the PRS in industry and make it available as a part of the routine quality assurance practice, however, there is one major challenge, among others, that should be overcome. That is development of the performance prediction model. The performance model should clearly elucidate the relationship between critical individual variables (i.e., the individual properties) and the performance; and subsequently the performance model must be able to predict the future performance of a structure of interest as accurately as possible.

This paper presents an example of performance models developed with respect to an asphalt pavement; two statistical models predicting the asphalt pavement distresses (rutting and fatigue cracking). The predicted performance is analyzed both deterministically and stochastically where the analysis takes into account the variability of the independent variables (e.g., mean and standard deviation); and thus the variability of the predicted performance. The models envision how the current quality assurance system in roadway pavement construction could be improved through the performance prediction and its relationship of pay adjustment to the contractors. Understanding the most appropriate key variables, performance prediction, and pay adjustment system in roadway pavement will contribute better quality assurance programs that achieve further progress on the construction industry, from resources through to final production. This paper also envisions the possibility of using the PRS quality assurance system for other infrastructures.

2. QUALITY ASSURANCE SPECIFICATION IN ASPHALT PAVEMENT

2.1 History of Quality Assurance in Asphalt Pavement

The evolution of a QA program in pavement construction has been ongoing since the American Association of State Highway Officials (AASHO) Road Test [2] in the 1950's revealed the importance of recognizing variability of pavement material and the importance of implementing a statistically-based QA program [3]. One of the major achievements in the test was the realization of the existence of variability among pavement quality characteristics such as air voids, thickness, asphalt content, etc. This realization led to the birth of the QA program in the pavement area by experiencing the variability in the sampling and testing results. As a consequence, it became the major motivation of implementing statistically-based specification in the QA program in the 1960s.

In the early 1980s, the payment system (also known as the pay factor system) began to be incorporated in the QA program by most of state highway agencies. The early form of the pay factor system focused more on the penalization to the contractor rather than incentives, for the pavement mix not meeting the specified quality in accordance with the material quality characteristics. Presently, the payment system contains both incentives and disincentives; that is, if a pavement mix constructed by the contractor is expected to have superior quality to what it is supposed to be, the contractor would be awarded a type of bonus. This system seems to be more rational because when considering the post-construction cost for maintenance and rehabilitation to the poor pavement that has to be required to be repaired, a better quality pavement would reduce the cost in the long run in terms of pavement management systems and life cycle cost methodologies.

The payment system in the QA program at the time of 1980s, however, was not systematic but rather primarily dependent upon the end-result specification which penalized the contractor based on deviations from specified target level or percent within limit (PWL) of several material characteristics. The problem on this type of specification was that the penalization was neither directly related to the designed service life of pavement nor the degree of pavement performance. This shortcoming then led to a need of development of a new type of a specification that is required to be more related to pavement performance.

2.2 Performance Related Specification

A conceptual framework for PRS was firstly developed and introduced under the NCHRP sponsorship in the early 1990s [4]. The major advantage of this specification was on the consideration of expected quality performance in terms of degree of pavement distress. This rationality could be emphasized in the consideration of the payment system because the relationship between pavement performance and payment schedule would be more clearly established than the sole use of assumed key material characteristics. Since the advent of PRS in the 1990s, the PRS QA program has been moving toward implementation and development of an innovative PRS model.

It should be emphasized that the major feature of a PRS system, differing from other specification types, is that the payment system applied to the contractor is directly related to the performance of pavement that the contractor constructs. The pavement performance can be predicted by using the key variables such as asphalt content, air voids, etc, depending on types of distress of interest.

In addition, the PRS possesses more advanced features with regard to the assurance of the constructed pavement quality. Kopec summarizes the main features of PRS compared with conventional specifications as follows [5]:

- PRS minimizes the as-constructed life-cycle costs.
- PRS performance prediction model relates key quality characteristics to pavement performance
- PRS directly considers the lot variability of the quality characteristic and accounts for it in the development of pay adjustments
- PRS presents a procedure for computing pay adjustments
- The payment system provides both incentive and disincentive depending upon the relationship between pay adjustment and performance quality
- PRS SPT procedure requires actual testing of the in-situ pavement in order to provide a true assessment of its as-constructed properties

In order to implement the PRS in a pavement QA system, it is critical to develop a methodology to accurately quantify the quality of the as-built mix throughout the design life. There are two types of PRS models associated with this quantification: performance prediction models and the life-cycle cost (or maintenance cost) model [5].

The performance prediction model predicts major pavement distresses such as rutting, fatigue cracking, etc by using the construction material characteristics, which can be commonly measured in the as-constructed job site, such as thickness, air voids, etc. Maintenance cost model projects life cycle cost considering maintenance and rehabilitation costs during the designed service life. This model is developed based upon the degree of future pavement performance condition predicted.

A major advantage of using either of these models, regardless of the selection of the specific model, is that the as-constructed mix quality of concern is eventually quantified in terms of future service life or life-cycle cost. As a consequence, the quantified mix quality for both as-design and as-built mixes can be compared and utilized for the payment schedule system.

3. PERFORMACE MODEL DEVELOPMENT

3.1 Permanent Deformation Prediction Model

Sotil originally developed the comprehensive asphalt concrete permanent deformation (i.e., AC rutting) prediction methodology for his dissertation work [6]. Throughout the comprehensive statistical (design of experiments analysis) study, the original number of 63 variables that were thought to be correlated with the rutting distress was able to be reduced to be five statistically significant variables. The variables include climate, AC thickness, vehicle speed, asphalt binder type, and volumetrics. The developed methodology was based on a total number of 768 data predicted from an AC distress performance prediction tool, the Mechanistic-Empirical Pavement Design Guide (MEPDG) simulations.

The form of the model is a simple power equation as shown below:

$$\Delta RD = a(E^*_{eff})^b \tag{1}$$

Equation 1 is simply a function of effective dynamic modulus (E^*_{eff}) and two regression variables, a and b, which are not constant values but vary dependent on the asphalt mix characteristics. The rut depth change (ΔRD) is predicted based on the coefficients and the dynamic modulus. There are also two additional power models similar to Equation 1 which shows a relationship between the rut depth and the environmental locations; and vehicle speed in a given pavement structure. Therefore, hundreds of the family power curves exist for determination of rut depth prediction. Equation 1 is later revised by Jeong [7] by directly combining the three major variables: asphalt dynamic modulus, vehicle speed, and environmental location. The revised model form is as follows:

$$\Delta RD = p_0\left(T_{eff}\right)^{p_1}\left(E^*_{eff}\right)^{p_2}\left(v\right)^{p_3} \tag{2}$$

The new equation is a closed-form solution and thus it simplifies the prediction methodology previously used where an interpolation scheme was required to take into account three separate variables. In addition to the simplicity advantage, the prediction accuracy of Equation 2 has been improved. The comparison plot between rut contribution of each sublayer by the model and the MEPDG simulation results is illustrated in Figure 1. It can be seen that the closed form solution is an excellent predictor of AC sublayer rutting within the MEPDG.

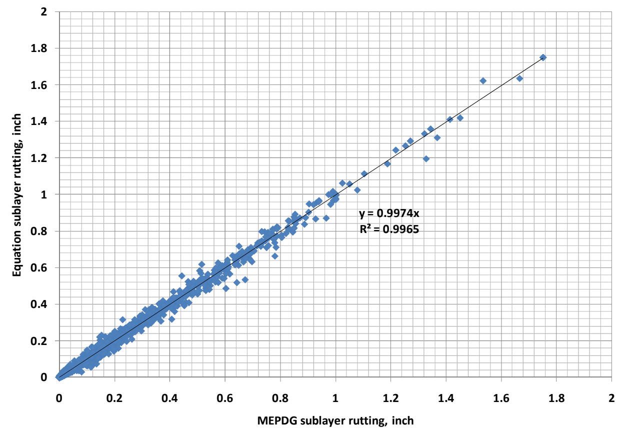

Figure 1 Comparison Plot of Rut Depth between the Developed Performance Model and the MEPDG [7]

3.2 Fatigue Cracking Prediction Model

The development of a performance prediction model for the fatigue cracking was based upon a similar process to the rutting model development. The following procedure was originally developed by El-Badawy and Jeong [8] and later slightly revised by Jeong in his dissertation [7]. Several design parameters that were felt to significantly affect fatigue cracking were initially selected in the modeling work. Three climatic locations were selected for the simulations. They were chosen to cover a broad range of temperature conditions as follows:

- Cold Region (Grand Forks, ND)
- Moderate Region (Oklahoma City, OK)
- Warm Region (Key West, FL)

Twenty years of design life was selected for the simulation; and all the simulation runs were performed using the classical 18-kip Equivalent Single Axle Load (ESAL) approach. The number of traffic repetitions used in the analysis was set at 2×10^6 ESALs in 20 years. Four traffic speeds ranging from creep speed to highway speed, were used in the study. These speeds are as follows:

- 0.5 mph: intersections, parking lots, traffic jams
- 15 mph: school zones
- 45 mph: local roads and collector
- 60 mph: city freeways and interstate highways

Seven AC layer thicknesses were used to cover a wide range of AC thicknesses used in practice. They were selected to ensure that the extreme fatigue conditions would be assessed in the study. Three levels of asphalt binder Performance Grades (PG) were selected according to the Superpave system: PG 82-10, PG 64-22, and PG 52-40. These grades cover a very soft binder (PG 52-40) typically used in cold climatic regions through a very stiff binder (PG 82-10) used in hot regions. Additionally, three levels of Voids Filled with Bitumen (VFB) and one set of appropriate gradation were used. The combination of these mix characteristic levels contributed to changing effective dynamic modulus (E^*_{eff}), which ranged from approximately 30 ksi to 3,000 ksi for the different AC layer thickness and vehicle speeds used for the simulations.

Fatigue cracking is greatly affected by the foundation stiffness. Thus, the individual thicknesses and moduli of all layers beneath the Hot Mix Asphalt (HMA) layers influence the fatigue behavior of the AC mixture; and an imaginary foundation stiffness combining all the underneath layers moduli was developed and termed the Composite Foundation Modulus (E_{cf}). This fact necessitated running a matrix of different E_{cf} to cover a broad range of unbound/bound base/subbase and subgrade materials that may represent the foundation for the pavement structure in the field. Six E_{cf} values covering low to high composite foundation moduli values were used for the study.

Based on the simulated 4536 MEPDG runs; a general comprehensive model to predict fatigue damage as a function of the effective AC modulus, AC thickness, VFB, and E_{cf} was developed. The E^*_{eff} for fatigue was found to depend upon the aggregate gradation of the AC mixture, VFB, traffic speed (effective loading frequency), and the binder viscosity stiffness at the effective temperature. The fatigue damage prediction model is a closed-form solution which as the aforementioned variables:

$$\log N_f = a_1 - \{[(a_2\log(h_{ac})^2 - a_3\log(h_{ac}) + a_4)\log(E^*_{eff}) + a_5\log(h_{ac})^2 + a_6\log(h_{ac}) + a_7]\log(E_{cf})^2 + [a_8\log(E^*_{eff})^2 + a_9\log(E^*_{eff}) + a_{10}]\log(E_{cf}) + [a_{11}\log(h_{ac})^2 + a_{12}\log(h_{ac}) + a_{13}]\log(VFB)^2 + [a_{14}\log(h_{ac})^2 + a_{15}\log(h_{ac}) + a_{16}]\log(VFB) + a_{17}\log(E^*_{eff})^2 + [a_{18}(h_{ac})^2 + a_{19}(h_{ac}) + a_{20}]\log(E^*_{eff}) + a_{21}\} \quad (3)$$

Equation 3 contains a total of 21 coefficients. Non-linear optimization was performed to determine two sets of the coefficients: one for pavement structure less than 3 inches and another for more than 3 in. structure. Figure 2 shows a comparison between damage predicted using the developed general model and damage predicted using the MEPDG for the 4536 computer simulation runs. The model shows excellent prediction accuracy with a Se/Sy = 0.045 and adjusted R2 of 0.998 in the logarithmic scale.

4. LIFE EXPECTANCY

The predicted performance of both the as-designed and as-built mixtures, from the developed prediction methods, is then converted into predicted service life. It is quite important to know that the final pay factor is estimated based on the predicted life difference between the two mixes.

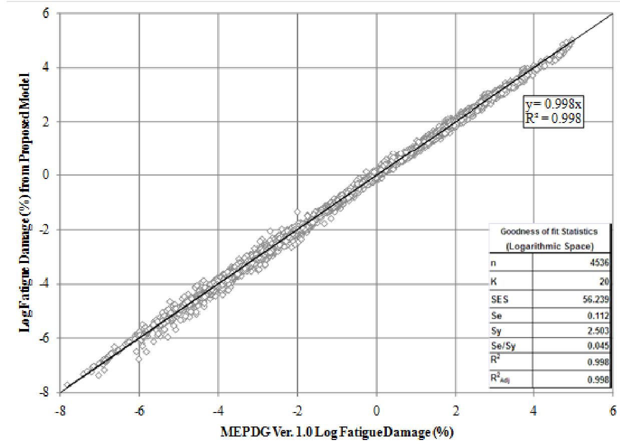

Figure 2 Fatigue Damage Predicted using MEPDG Vs Damage Predicted using the Proposed Fatigue Model [7]

The conversion methods for the rutting and fatigue cracking distress are theoretically similar. They utilize the relationship between traffic (i.e. ESAL) and the distress. The concept of predicting a service life for a certain mix is quite straightforward. Figure 3 depicts the concept of service life prediction as an example using fatigue distress. A design or standard or target mix projects 30% fatigue damage at the end of the design life, 20 years. If the quality of a simulated mix is worse than the design mix (MCS_1 in the figure), then the mix would cause the same damage as that of the design mix prior to the design life. This will result in the predicted life less than 20 years (SL_1 in the figure). On the other hand, a simulated mix quality is better than the design mix, it will take more time to reach the damage that the design mix will cause, i.e., the predicted service life for this mix will be more than the design life of 20 years (MCS_2 and SL_2 in the figure).

It must be, therefore, recognized that the predicted service life is a relative value to a standard service life which is deterministically calculated from a design mix. The standard service life becomes a criterion. This criterion will be used as a target or standard value to compare.

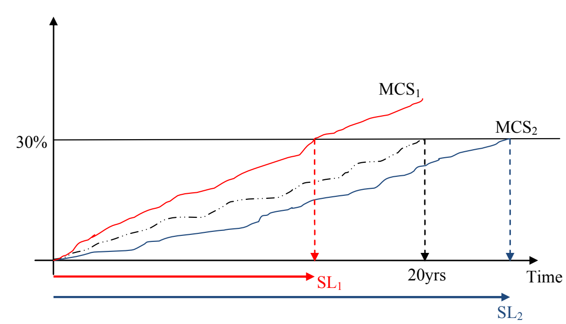

Figure 3 Conceptual Example of Service Life Prediction

5. IMPROVED PAYMENT SCHEDULE

The concept of the pay factor system is that the contractor is penalized or awarded incentives depending upon the expected performance of the end product or specified material specification. The quality of the as-built mix evaluated by the performance prediction models is converted into its predicted service life or life cycle cost. It is then compared with the as-designed mix. The difference in life quantified between the two mixes (design versus as-built) becomes a basis of the payment system.

One of the objectives for the use of a pay adjustment factor system is to motivate the contractor to conform to the given specification by way of compensation for a better quality of the pavement than required. In view of the long-term life-cycle cost analysis, the system becomes more reasonable because a poor quality pavement would cause unexpected maintenance and rehabilitation costs in order to sustain the intended serviceability and provide it with the public [9].

Another important objective of the payment system is to make up the expected loss of maintenance cost due to the poor quality pavement from the contractor's portion of the construction fund. This system is better than for the agency to have merely two options of acceptance and rejection to determine the as-built mix quality [9]. In any event, both objectives of implementing the payment system are interrelated and the primary objective is to provide the public with a good serviceability in using the roadway system during the intended service duration.

Figure 4 shows two traditionally used pay adjustment systems. The earliest form of payment system was a stepped style in which a pay factor was assigned based upon the Percent Within Limits (PWL). The PWL is one of the measures to represent the quality of the as-built mix and can be defined as "The percentage of the lot falling above the LSL (Lower Specification Limit), beneath the USL (Upper Specification Limit), or between the LSL and the USL." [1]. Alternative way to apply the measured quality to the pay factor system is to use a continuous line (i.e. an equation) as shown in Figure 3.

A new payment system has been developed in the NCHRP 9-22 project [10], which is a combination of the two traditional systems (i.e., combined continuous and stepped system) as shown in Figure 5. A major change in the new payment system is that the system uses a new type of a quality measure: predicted service life difference. The new measure is represented in a more practical and rational way, such that both agency and the contractor can easily understand the approach and decision.

The quality of the as-built mix, represented by the amount of predicted distress of concern is converted into its predicted service life. The same process is also completed for the as-designed mix. These mixtures are then compared with each other (i.e. comparison between as-designed and as-built mixes in terms of predicted service life). The Predicted Life Difference (PLD) between the two mixes becomes an independent variable to determine the pay factor. The use of the gain or loss in the service life to determine the pay factor has a major advantage in that it is much more understandable and rational to practicing engineers.

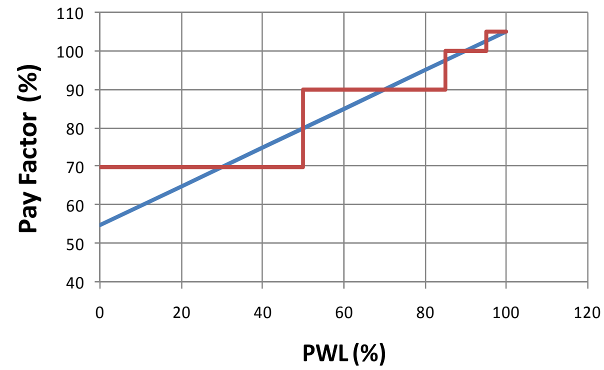

Figure 4 Example of Stepped and Continuous Pay Factor System [9]

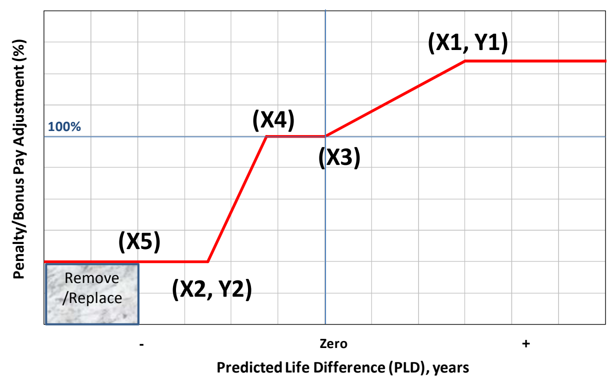

Figure 5 Example of Pay Adjustment Schedule for T ypical Distress [10]

Figure 5 conceptually shows an example of the pay factor plot for one of the typical distresses interested. Percent of the pay incentive / disincentive adjustment is determined based upon the PLD. As the PLD increases (e.g., the anticipated as-designed mix life is greater than the anticipated as-constructed mix life), the percent pay adjustment increases to a certain point, i.e., the contractor is given an incentive. To prevent an excessive amount of incentive, a maximum bonus line is set as (X_1, Y_1) in the figure, i.e., beyond the point the incentive goes constant. Similarly, the percent pay adjustment reduces as the PLD goes to smaller values. Minimum penalty or disincentive line is set as (X_2, Y_2) and the PLD goes beyond a certain point (X_5), it is required to take a replace / removal action.

It is important to understand that the determination of the pay factor schedule is dependent on several linear functions of PLD. Each linear function is subjectively decided by the agency (or agency / contractor) prior to the construction. At the end of the pavement construction, the PLD is determined and simultaneously the pay adjustment is readily determined based upon the payment schedule. Note that each distress type can (and probably should) use a different pay adjustment schedule.

7. CONCLUSIONS

The PRS system can improve the current quality assurance system that most state agencies typically use in quality assurance practice where the constructed roadway pavement mix quality is evaluated based on individual mix properties. Although it is historically and empirically known that the individual properties of the asphalt mixture play an important role in performance, there may be no rational explanation in terms of having the contractors to get penalized or awarded when the individual properties are used as direct indicator to determine the future quality of the pavement.

The PRS system may overcome this shortcoming and provide a more scientific and rational methodology for the agencies and contractors. The PRS utilizes performance models to predict the future performance of infrastructures of interest as a surrogate of the mix properties. The performance quantified with life expectancy is employed in the PRS system in evaluating the pavement quality and accordingly the contractors receive the incentive – disincentive decision by the agencies based on the life computed in the PRS system.

The performance prediction models introduced in this paper are worthy examples that could be incorporated into the PRS system for the pavement quality assurance practice. The PRS system could be extended to other infrastructures with regard to their construction quality related evaluation over understanding the most appropriate key variables from common construction processes. In general, the construction work that is produced by interrelated trades with many players is inspected and the results relayed back to the constructor, who may be required to correct any defects. Therefore, there is an urgent need for a set of standardized and repeatable structured procedures that learn from the application of the PRS system, kept predicted and updated in order to perform and evaluate a constructors' work successfully. Examples may include dam, bridge, building, soil stabilization, slope stability, etc.

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