Composite Pay Index for Superpave Pavements in Kansas

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ABSTRACT: Statistical specifications for highway construction are usually part of a statistical quality control process. The specifications provide the means to measure the important quality control attributes and ensure their compliance. The pay adjustments in these specifications reflect the amount of reduction and the optimized risk distributed between owner and contractor. The Kansas Department of Transportation (KDOT) has built a comprehensive database of as-constructed properties of materials for Superpave pavements from the tests required as part of the Quality Control/Quality Assurance (QC/QA) program. Currently, KDOT pays incentives/disincentives for air voids and in-place density for Superpave pavements. A composite index which may include air voids, in-place density, asphalt content, and voids in mineral aggregate is needed to reflect the factors that affect the performance of Superpave pavements. The objectives of this study were to investigate the effect of levels of significance and lot size on contractor and KDOT, and to develop composite index and practical performance models in Kansas. Thirty five projects from six administrative districts of KDOT were selected for this study. Statistical Analysis Software (SAS) and Excel were used for statistical and control chart analyses, respectively. Lot-wise comparison showed that QC/QA means are significantly different in most of the cases. The number of cases with a significant difference in means increases with an increase in significance level. A composite pay index from multiple quality characteristics has been proposed as an integral part of performance-related specifications (PRS).

KEY WORDS: Composite index, QC/QA, lot size, control chart, composite index, PRS.

1 INTRODUCTION

The history of highway quality assurance has progressed from the early materials and methods specifications through statistical end-result specifications to the current trend toward performance-related specifications (PRS) based on mathematical models and statistical concepts (Weed 2000a).

Many states have adopted statistical quality control/quality assurance (QC/QA) programs. The properties controlled under statistical QC/QA programs should be either related to performance or desirable end-results. These end-result specifications are usually based on statistics from historical construction data (Schmitt et al. 1998, Parker and Hossain 2002). Many agencies now also include bonus provisions that award payment somewhat in excess of the contract price when the quality level substantially exceeds the level that has been specified (NCHRP 1995, Weed 2002, Weed and Tabrizi 2005). One of the advantages of statistical specifications is the production of accurate data from valid random sampling procedures. This data may be analyzed later to improve the specifications further (Afferton et al. 1992).

Some agencies are moving in the direction of PRS that specifies the desired levels of key construction quality characteristics that have been found to correlate with fundamental engineering properties which predict performance. When there are different types of tests to be performed on a particular construction item, it can become a complex matter to design an acceptance procedure that is fair, effective, and free from inconsistencies. Composite index avoids certain inconsistencies in practice that may occur with other methods for dealing with multiple quality characteristics. It leads to rational pay schedules in that it assures that all combinations of individual quality measures that predict the same level of expected life will receive the same amount of pay adjustment (Weed 2006).

2 PROBLEM STATEMENT

The Kansas Department of Transportation (KDOT) has built an impressive database of as-constructed materials properties for Superpave pavements from the tests required as part of the Quality Control/Quality Assurance (QC/QA) program. KDOT also has a Construction Management System (CMS) that captures data on selected attributes related to highway construction in Kansas. Burati et al. (2004) have argued that any specification must also be an evolutionary process. Since new information is constantly becoming available in the form of additional test results, and as new construction or testing processes are employed, the specification must be continually monitored to see if improvements are needed. Thus a review of the current QC/QA specifications of KDOT is needed to find the opportunities for improvement. This need has also been echoed by the recent FHWA QA Stewardship Review of KDOT with respect to the use of a different payment lot size, changing level of significance for statistical testing, developing composite index and practical performance model.

3 OBJECTIVES OF THE STUDY

The main objectives of this study were to:

- Investigate any systematic bias in KDOT QC/QA data;
- Compare lot-and sublot-wise means and investigate the possibility of changing lot size;
- Analyze the consequences of changing the level of significance from 1% to 2.5%; and
- Develop composite index and practical performance model.

4 PROJECT SELECTION

Thirty five Superpave pavements, built between 2004 and 2007, were selected based on total tonnage. The selected projects are such that multiple lots of 3 million kilograms were produced and placed on these projects. These projects are from all six administrative districts of KDOT. The length of the projects varies from 3.10 km to 49.6 km.

5 DATA COLLECTION

Random sampling procedures were used to collect QC/QA data. It is well established that random sampling procedures avoid biases and lead to a more reliable estimate of the as-built construction quality (Weed 1989). Air voids, in-place density, asphalt content, and voids in mineral aggregates (VMA) data have been used in this study.

5.1 Air Voids

The normal lot-size for air voids is 3 million kilograms. The lot is divided into four subolts of uniform size. KDOT specifies roadway sampling. Roadway samples are obtained for each sublot from behind the paver before compaction. A three-sided template is pushed into the mat prior to compaction. A square shovel is then used to extract all asphalt mixtures from the selected locations. The sample is obtained from a minimum of three locations randomly selected by KDOT personnel throughout one truck load of placed material. The selection process involves one random number for the sampled tonnage (truck load) and two random numbers for transverse and longitudinal locations (Elseifi et al. 2009).

The samples are transported to the test facility using a method to retain heat to facilitate sample quartering procedures. Air voids tests are performed on Superpave gyratory-compacted samples of a given mix design. A lot normally consists of results of four contiguous results of individual QC tests and one QA test.

5.2 In-place Density

KDOT considers the day's placement as a lot for density measurements. This lot is subdivided into five uniform sublots. Random test locations are selected by the Contractor or the Engineer. Mat density is typically measured with nuclear density gages but may also be obtained from cores. Contractor makes two and KDOT makes one independent mat density measurement for each sublot (2 to 1 sampling ratio) (Turochy and Parker 2007).

5.3 Data for Composite Index and Practical Performance Model

Burati et al. (2003) concluded that percent defective (PD) is well suited as a statistical measure of quality since it has been well studied, statistically unbiased, suitable for both normal and distribution-free (attributes) applications, and works equally well for single-sided or double-sided specifications. To develop composite index and practical performance models, data in Table 1 has been used. Acceptable quality level (AQL) has been taken as 10 percent defective for all variables whereas different rejectable quality levels (RQL) have been used partly to investigate the effect of different RQL on the models and partly based on the effect of each variable on the performance of the pavement. The expected life (EL) was taken as 10 years when PD=10 for all the variables whereas EL was taken as 5 years when one of the variables is at RQL level. These values can be updated based on actual performance data and experience of the agency.

Table 1: Data for composite index and PRS models

Percent Defective (PD) for Various Quality Measures				Expected Life (years)
Air Voids (VA)	**Density (DEN)**	**Asphalt Content (AC)**	**VMA**	
10	10	10	10	10
50	10	10	10	5
10	60	10	10	5
10	10	70	10	5
10	10	10	80	5

6 RESEARCH METHODOLODY

6.1 Comparison of Means

The F-test in analysis of variance (ANOVA) can signify that not all the means of the levels of the classification variable are the same, but it cannot indicate which means differ from what other means. Comparison methods for means provide more detailed information about the differences among the means. Four comparison methods for means have been used in this study. The methods are Fisher's Least Significant Difference (LSD) Test, Tukey's Honestly Significant Difference (HSD) Test, Student-Newman-Keuls (SNK) Test, and Scheffe's Test.

6.2 Development of Practical Performance Model

One of the first steps in developing a mathematical model is the choice of model form. Since most quality characteristics have points of diminishing returns, a model with an "S" shape may be appropriate (Weed 2006). Practical performance model of the form shown by Equation (1) has been developed using data in Table 1. Expected life (EL) was used as a measure of performance (dependent variable) whereas air voids (VA), in-place density (DEN), asphalt content (AC), and voids in mineral aggregate (VMA) were used as independent variables. Recent FHWA QA Stewardship Review of KDOT suggested developing composite index including air voids, in-place density, asphalt content, voids in mineral aggregate, and pavement roughness, but an analysis of the responses to a nationwide survey reported by Weed (2000b) showed the effect of quality levels of smoothness on service life of asphalt concrete pavement is essentially independent of the quality levels of air voids asphalt content, etc. As a result, roughness was not included in the composite index.

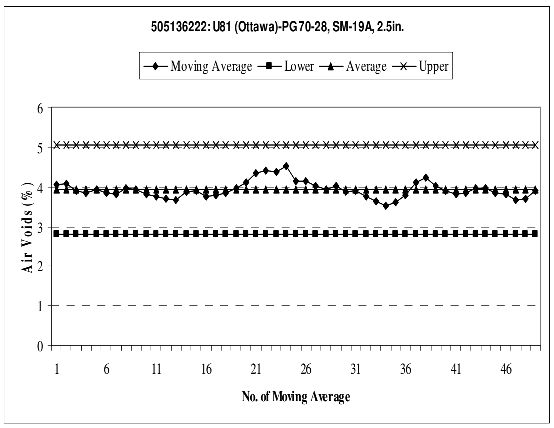
Different shape factors (C) were assumed and simultaneous equations were solved using Excel for the model coefficients. Similar procedure was followed to develop composite index using the same independent variables for expected life.

$$EL = e^{B_0 + B_1 PD_{VA}^C + B_2 PD_{DEN}^C + B_3 PD_{AC}^C + B_4 PD_{VMA}^C} \tag{1}$$

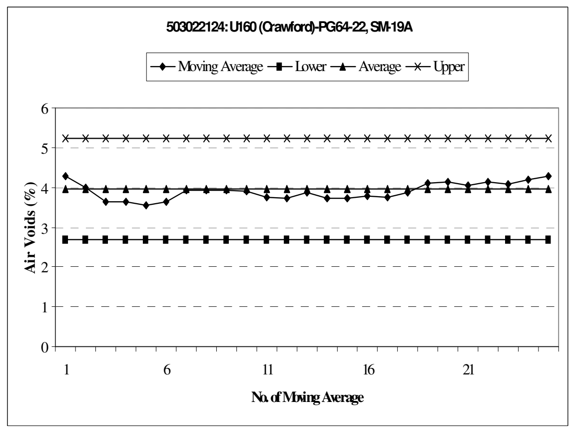
7 RESULTS AND DISCUSSIONS

7.1 Control Charts

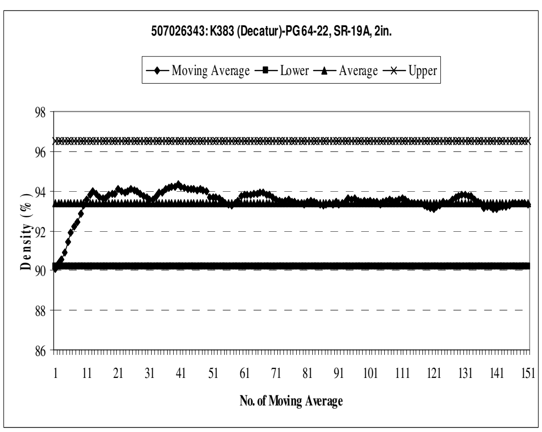
Microsoft Excel was used to calculate moving averages, average, lower, and upper limits (minus/plus three times standard deviation) for different variables. Figures 1(a) and 1(b) show typical QC air voids (VA) control charts for KDOT Districts 2 and 4, respectively. The moving average values are sometimes lower and higher than average values though the difference is not significant. All moving average values are within $\pm 3\sigma$, where σ is the standard deviation. Figures 1(c) and 1(d) show control charts for QC and QA densities. These are the only cases in which the moving averages are outside $\pm 3\sigma$. This shows density at the beginning of the project was very low compared to the rest. Except for the first few readings, the rest show the same trend as that of air voids control chart.



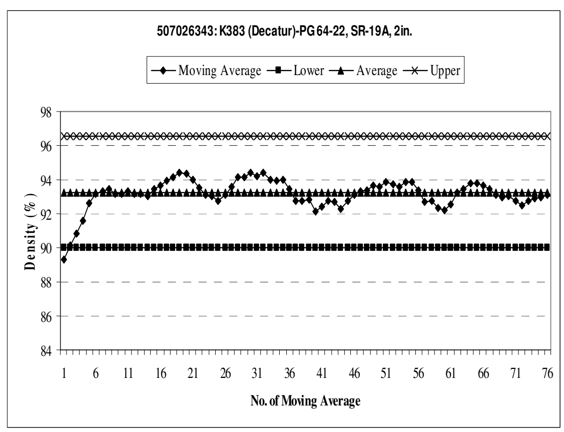
(a) Typical VA control chart for District 2



(b) Typical VA control chart for District 4



(c) QC density

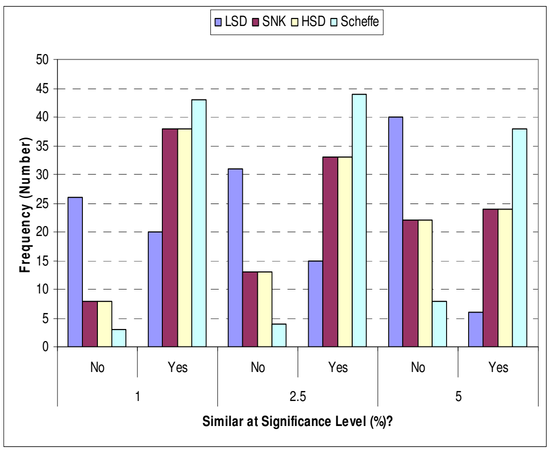


(d) QA density

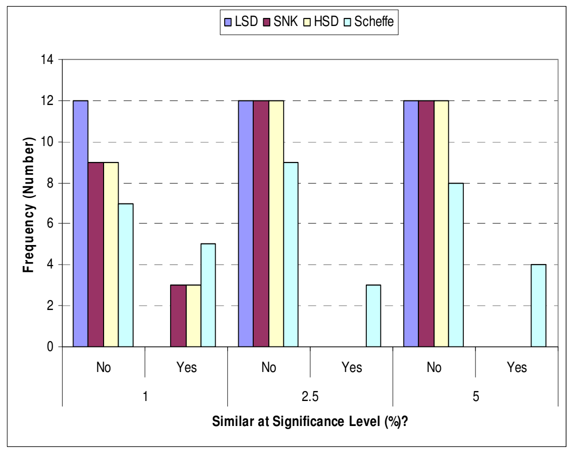
Figure 1: Moving average control chart for Superpave pavement and mixture parameters

7.2 Lot-Wise Mean Comparison

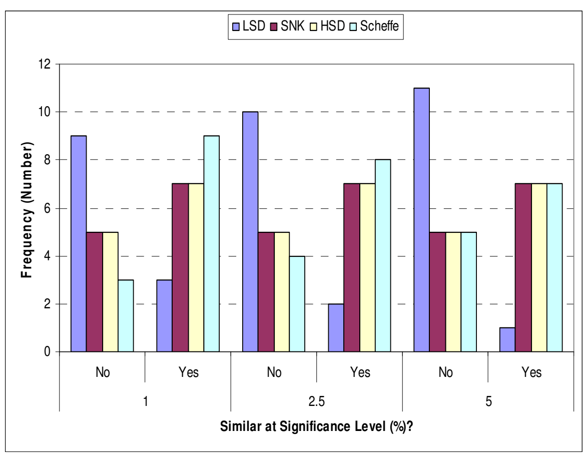
Figure 2 shows lot-wise comparison of QC/QA means. Student-Newman-Keuls (SNK) and Tukey's Honestly Significant Difference (HSD) tests show the same results at all significance levels. Figures 2(a) and 2(c) show there is no significant difference between lot means for QC air voids and QA density at all significance levels and for all methods except LSD. Figure 2(b) shows there are significant differences between lot means in most cases at all significance levels and for all methods for QC density. These results show that LSD and Scheffe tests are the strongest and weakest, respectively, in detecting significant difference in means.



(a) QC for Air Voids



(b) QC for Density



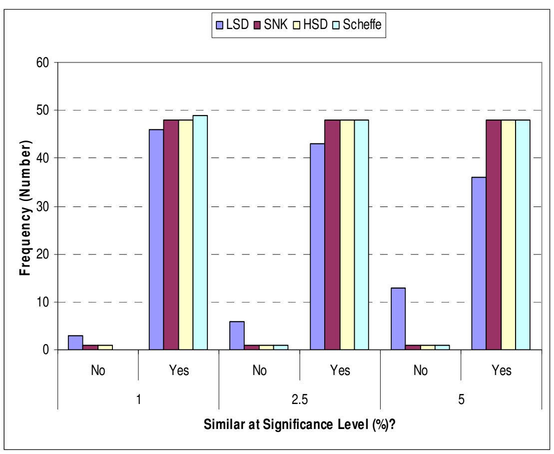
(c) QA for Density

Figure 2: Lot-wise means comparison for Superpave mixtures and pavements

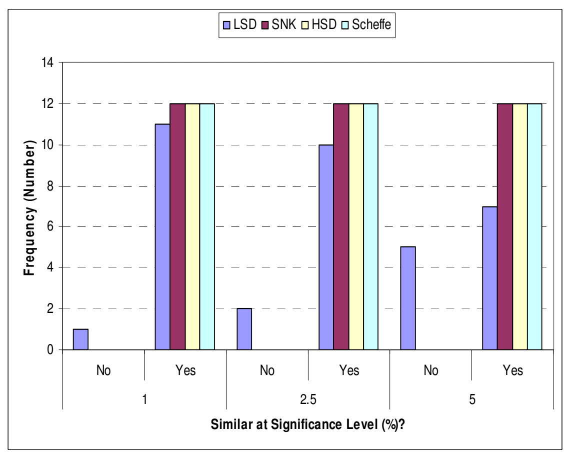
Lot-wise comparison shows that QC and QA means are significantly different in most cases. As a result, QC/QA comparison should be lot-wise instead of KDOT's current procedure that combines data from five successive lots for air voids. More sublot data may be taken for each lot so that enough data can be obtained for statistical analysis. Ten QC readings and five QA readings per lot, similar to current Superpave density data, will be enough for more robust statistical analysis. This result confirms the study by Benson (1995). It was suggested that within practical limitations of the type of job, lot size could be expanded tenfold to encompass an entire week's production. There would be considerable benefits in terms of reduced staff and equipment inventory if larger lot sizes are implemented. The increase in risk to buyers and sellers as a result of slightly higher within-lot variability are not unreasonable.

7.3 Sublot-Wise Mean Comparison

Figure 3 shows sublot-wise mean comparison for Superpave pavements using four mean comparison methods at three different significance levels. Sublot-wise QC/QA comparison for air voids has been done using four QC sublot readings and the QA reading as the fifth sub-lot reading in each lot. Sheffe method shows that there is no significant difference between the sublot means of QC/QA air voids at 1% significance level as shown in Figure 3(a). Sublot-wise QC/QA in-place density analysis has been done using 10 QC sublot data and five QA sublot data in each lot. There is no significant difference using all methods except LSD for QC in-place density and QC/QA in-place density as shown in Figures 3(b) and 3(d). Figures 3(a), 3(b), and 3(d) show that significant difference using the LSD method clearly increases with an increase in significance level. Currently KDOT uses 1% significance level and it is difficult to find significant difference at this level. It is recommended that 2.5% significance level be used as a compromise between 1 and 5% significance levels for both contractors and KDOT. Figure 3(c) shows that there is no significant difference using all methods.



(a) QC/QA for Air voids

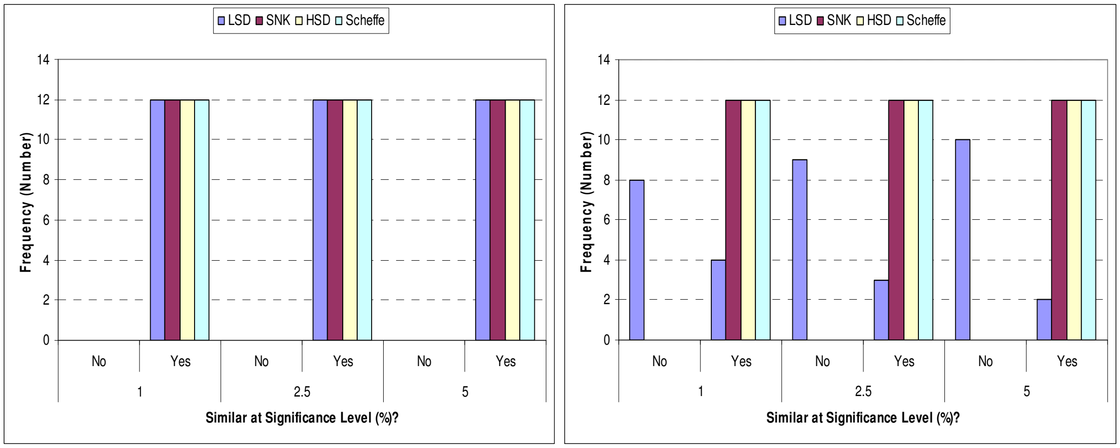


(b) QC for Density

7.4 Composite Index

Composite index (PD*) was developed in terms of air voids (VA), in-place density (DEN), asphalt content (AC), and voids in mineral aggregates (VMA). The coefficients were obtained using the data in Table 1. The magnitudes of the coefficients reflect the effect of the variables on the long-term performance of the pavements. The coefficients may be modified based on field performance and/or agency's experience. Composite index varies from zero to 100%. The final model developed is shown in Equation (2).

$$PD^* = 0.329PD_{VA} + 0.263PD_{DEN} + 0.219PD_{AC} + 0.188PD_{VMA} \quad (2)$$



(c) QA for Density (d) QC/QA for Density

Figure 3: Sublot-wise means comparison for Superpave pavements

7.5 Practical Performance Model

Practical performance was developed using data in Table 1. Different values of shape factors were tried and it was found that shape factor of 1.5 is the best. The model was checked whether it returns precisely the values used to develop it, which it did. It was also checked at extreme values (PD=0 and PD=100), and examined how extra quality in some variables can offset the deficient quality in other variables while still resulting in design life of 10 years. The model showed consistent results based on engineering judgment and experience. The model may be modified and/or validated using KDOT's experience and/or performance data in the future. The final performance model is shown by Equation (3). The model is used to better understand the consequences of either exceeding or falling short of the desired quality levels, and to provide a logical and defensible basis for the adjusted pay schedules that are an integral part of PRS.

$$EL = e^{2.49-0.0022PD_{VA}^{1.5}-0.0016PD_{DEN}^{1.5}-0.0013PD_{AC}^{1.5}-0.0010PD_{VMA}^{1.5}} \quad (3)$$

8 CONCLUSIONS

Based on this study, the following conclusions can be made:

- Moving average control chart does not clearly show any systematic bias in QC/QA data for Superpave mixtures and pavements in Kansas.
- Lot-wise comparison shows that QC/QA means are significantly different in most of the cases. Ten QC readings and five QA readings per lot will be sufficient for statistical analysis.
- Student-Newman-Keuls (SNK) and Tukey's Honestly Significant Difference (HSD) tests show similar results at all significance levels. LSD and Scheffe is the strongest and weakest test, respectively, in detecting significant difference in means.
- Composite index and practical performance models were developed using Superpave mixture data available in Kansas.

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