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Risk Assessment for the Acceptance of Construction Materials

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ABSTRACT: Highway agencies deal with a variety of materials and construction processes where a wide spectrum of specifications and acceptance requirements exist. Over the past two decades the role of most of these agencies has shifted from quality control of materials and placement techniques to quality assurance and acceptance. In such scenario producers are responsible for monitoring quality test results (i.e., Quality Control, QC), and agencies collect and use quality assurance data (QA) for acceptance and rewards based on the quality at delivery. In the process of revising such quality and acceptance approach there is a need to consider the risks associated with the acceptance of materials and construction quality to both the agency and supplier. Objective of this study was to define a methodology for assessing the acceptance risks for construction materials. The case of granular base materials of highways was used with field density data from an important toll road in United States, so as to demonstrate the methodology. The proposed methodology is applicable to many construction materials that acceptance data are collected and is transferable to any region around the world.

Keywords: Risk Analysis, Quality Control, Quality Assurance, Construction Materials, Acceptance.

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I. INTRODUCTION

Transportation agencies are responsible for assuring that materials produced, supplied and placed on construction projects meet quality requirements set within material and construction specifications. Since the role of most of these agencies has shifted from quality control of materials and placement techniques to quality assurance and acceptance, this has placed more responsibility for quality during production on the contractor, producer and supplier. On the other hand, agency's role has been focusing towards assurance of material quality and oversight of contractor quality control operations. Such shift in responsibilities is attributed to the modern transition from method and end-results specifications towards performance specs, and the adoption of Design-Build practice in construction. This shift eventually allows higher level of innovation and flexibility from the contractor, and lower involvement and resources from the agency. To adapt to such environment many agencies have begun to revise their materials acceptance specifications. In some cases, the revised specs allow for the acceptance and payment of materials to be based on contractor, producer and/or supplier quality test results (QC and certification testing) with complementary testing and inspection from agency to verify results (QA). In other situations, QA data are used for acceptance and rewards based on quality at delivery. In addition, many specifications have been revised to assess material quality based on statistical basis (i.e., percent within specification limits, PWL) rather than individual or average test results. This allows for better incorporation of material variability in the acceptance and payment decision.

The desire to assess, and eventually balance, risks calls for: i) a requirement to identify robust statistical acceptance procedures, preferably based on historical data; ii) requirement to assess and quantify the actual risks taken by either the agency (Type I) or the contracting industry (Type II); iii) requirement to identify potential revisions to existing specifications for improving quality and acceptance; and iv) requirement to assign proper rewards for quality. The overall objective of this study was to propose a universal methodology for evaluating Type I and Type II risks and utilize the methodology for selected construction materials. The case of Graded Aggregate Base (GAB) is presented here in from data collected during the construction of a major toll road.

II. METHODOLOGY FOR EVALUATING RISKS

While the steps of the proposed methodology for evaluating acceptance risks are listed next, only a subset of those are described herein in some detail due to manuscript size limitations. Details of all these steps can be found in the research study report [1].

1. Review of current material QA/QC procedures;
2. Identification of key factors affecting the quality of material;
3. Determination of best statistical distribution to fit historic data of materials;
4. Build Operational Characteristic (OC) Curves to calculate Type I and Type II risks.
5. Identify effects of sample size and specification tolerances on Acceptance Risks.
6. Assess Pay Factors in relation to Acceptance Risks

A typical Quality Assurance process for graded aggregate base (GAB), Step 1, includes plant inspections and aggregate source approvals procedures while field density compaction is based on an acceptance program [1,2] Thus, several studies have examined the parameters affecting GAB quality and performance, Step 2 [2, 3, 4]. The National Cooperative Highway Research project 4-23, "Performance-Related Tests of Aggregates for Use in Unbound Pavement Layers," identified aggregate properties that influence the performance of base layers and thus pavements [5]. Most agencies measure the density of the graded aggregate base/subbase as the means of payment to the contractor, and define their own target density value for the specification based on the job in hand. As an example, Maryland State Highway Administration (MDSHA) has assigned 97% field density as the minimum average requirement for the Intercountry Connector (ICC) construction project used in this study for the development of the methodology. Even though, the density of the base/subbase is a good indication of the quality of the final product, the properties of coarse and fine aggregates used in base and subbase layers are very important to the performance of the pavement system in which they are used. Thus, based on this review [5], the single main parameter to measure the quality of GAB is its field density.

Based on historical data the distribution of each material parameter can be identified next, Step 3. In order to better identify the distribution of any given set of data it is essential to examine representative historical data. Histograms allow the user to narrow down the possible distribution that would be a good representative of the given set of data. Statistic tests are available for assessing normality or other type of distribution fitting the historical data. For example, among the simple and quick methods to perform normality of data is the use of the interquartile range, IQR, [6,7]. According to this descriptive method, the interquartile range (IQR) is used with the standard deviation (s) of the given data to calculate the ratio of IQR/s. If the data are approximately normal then $IQR/s \approx 1.3$. For the GAB field density data of the selected project analysed in this study the IQR/s was calculated to be equal to 1.16, which shows that the QA acceptance data do closely follow the normal distribution [8,9]. When the normality of a data set cannot be determined or it is concluded that a data set is not normally distributed, a goodness-of-fit method needs to be utilized in order to determine the proper distribution. Alternative normality tests include the Kolmogorov-Smirnov, the Shapiro-Wilk and the Anderson-Darling tests [9].

For the development of the operating characteristic (OC) curves, Step 4, several important definitions of statistical quality assurance parameters are needed. These include [10,11,12, 13]:

AQL - The minimum level of actual quality at which the material or construction can be considered fully acceptable;

RQL - the maximum level of actual quality at which the material or construction can be considered unacceptable (rejectable);

OC Curve - A graphic representation of an acceptance plan that shows the relationship between the actual quality of a lot and either (1) the probability of its acceptance (for accept/reject acceptance plans) or (2) the probability of its acceptance at various payment levels (for acceptance plans that include pay adjustment provisions);

Seller's risk (α)- also called type I error. The probability that an acceptable lot of material will erroneously be rejected even thought is at the acceptable quality level (AQL);

Buyer's risk (β)- also called type II error. The probability that a low quality lot will be erroneously fully accepted even thought it is of rejectable quality level (RQL).

Based on these terms the seller's risk (α) and the buyer's risk (β) are calculated at AQL and RQL respectively. In terms of acceptance plans, there are generally two types depending on the specific material and acceptance process used: the accept/reject plans, and acceptance plans that include pay adjustment provisions. In the case of acceptance plans with pay provisions, the AQL and RQL are the parameters that an agency can utilize to determine incentives and penalties. Using the OC Curves, this study examined with the current specification limits the impact of sampling sizes on the Type I and II risks. The AASHTO recommended levels for these risks are 1% and 5% for preventing substantial financial loss [14].

The construction of the OC curve is explained by illustrating the case of field density data in Figure 1. The area under the normal distribution curve within the specification limit for field density is the probability of acceptance. If the density distribution is shifted in relation to the specification limits, then alternative values of PWL is observed reflecting different levels of probability of acceptance. Several such probability-of-acceptance values can be calculated by simulating normal distribution curves at various mean values. This set of probability acceptance values versus the deviation of the mean from the target form the OC curve. This OC curve is created for a given sampling frequency and standard deviation. Several of these OC curves, as explained above, are created for different sampling frequencies (n), Figure 1. In this process the pooled standard deviation/variance is the method for estimating the standard deviation/variance given several different samples taken in different circumstances where the mean may vary between samples but the true or population standard deviation variance is assumed to remain the same [14]. In general standard deviation refers to the amount expected an individual measurement to vary from the average, and standard error of the mean is the expected value averaged from several measurements to vary from the true mean of the same measurements. The idea is that the more measurements are taken the closer the average should be to the real population average. These probabilities of acceptance values are the ordinates of the OC curve and the abscissa is the PWL values obtained from the actual standard deviation, both of which are for the same mean values [15]. Figure 1 represents a typical OC curve for the four sampling frequencies. As the sample size increases, the curve becomes steeper with a common intersection point at PWL of 50%. This indicates that as the sampling frequency increases, the probability of accepting bad quality material decreases at a faster rate as the PWL reduces or the quality drops. This is due to the fact that the sampling procedure becomes a more accurate way of estimating the true population characteristics as the sampling size increases. In other words, by increasing the sampling size, our judgment of whether a lot is acceptable or not is more accurate. This clearly illustrates that the amount of information obtained from each of these OC curves can be extremely useful in analysing the risk for a given sampling frequency, variability and specification limit.

Based on the characteristics of all the field density data (average of 98.2% and standard deviation of 0.89), simulation analysis was run for various sample sizes (n) and using the normally distributed QA data, Step 5. Figure 1 shows four OC curves for different values of n, while Table 1 provides a summary of the calculated risks at different sample sizes. As the sample size increases the risks decrease. Similarly, the effects of modifying specification tolerances can be examined for adjusting risks between the agency and the contractors. Finally, objective of the pay factor analysis, Step 6, is to assess if the levels of pay adjustments are appropriate in function to the impact of material quality and process variability on performance. To be able to perform such assessment performance models should be used and related to Expected Pay schedules. As expected the potential consequences from a poor quality material, or material failure, could be significantly different due to i) public safety and ii) cost implications to the agency in function of the importance and facility use (i.e., risks to the traveling public and the highway system overall). In terms of GAB field density, the following pay factor equation is used by the agency:

$$PF = \frac{f1*PWL1 + f2*PWL2 + f3*PWL3 + f4*MC + f5*FD}{\sum f} \quad [1]$$

where: f_1=weight of sieve No.30; f_2=weight of sieve No.200; f_3=weight of sieve 3/8 in; f_4=weight Moisture Content; f_5=weight of Field Density; PWL_1=Percent Within Limit of sieve No.30; PWL_2=Percent Within Limit of sieve No.200; PWL_3=Percent Within Limit of sieve 19mm (3/8”); MC = Moisture Content (%); FD= Field Density (%).

Initial analysis on PF are currently under way based on simulation analysis examining the impact of moving production quality from AQL to RQL and assessing the corresponding PFs and related levels of acceptance risks.

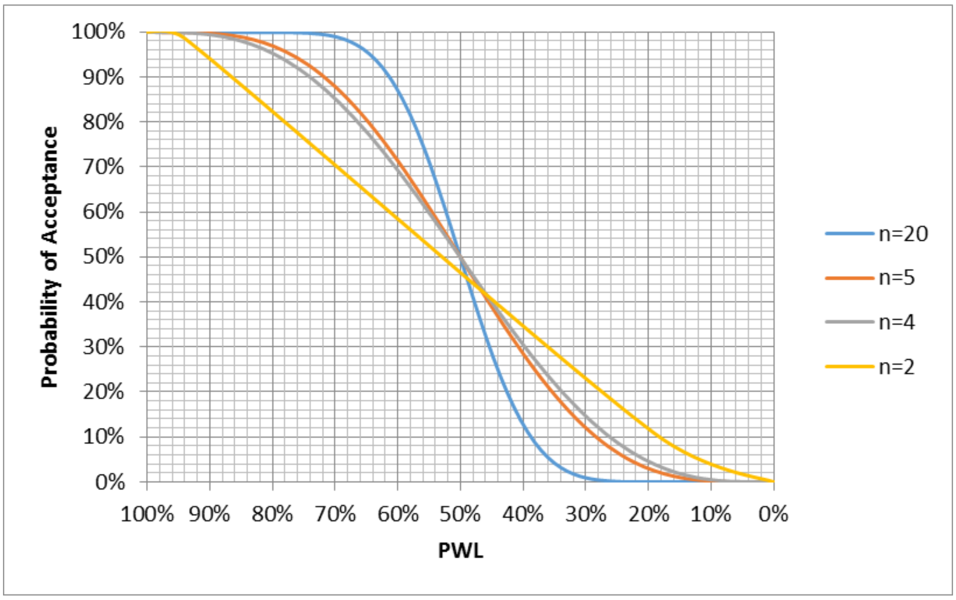

Fig 1. OC Analysis for the GAB Field Density Data.

Table 1. Risk Values for Field Density Data.

Sample size	Alpha (%)	Beta (%)
20	0	13
5	0	29
4	1	30
2	4	37

III. CONCLUSIONS

This paper presents a methodology for assessing acceptance risks for construction materials. The methodology requires the review of current QA/QC procedures for the specific material, identification of key factors affecting quality, determination of statistical distribution to fit the historic data of material properties, development of the operational characteristic Curves and assessment of acceptance risks, assessment of sample size and specification tolerances on risks, and relating risks to pay factors. Field density data for GAB of a major toll road were used to demonstrate the methodology and identify potential implications of sample size on risks. The proposed methodology is applicable to many construction materials that acceptance data are collected, and it is transferable to any region around the world.

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