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Variability Analysis and OC Curves for Assessing Contractor and Agency Risks Associated with Construction Materials Acceptance

Dimitrios G. Goulias
Associate Professor
Department of Civil and Environmental Engineering
University of Maryland
USA

Sahand Sasha Karimi
PhD Candidate
Department of Civil and Environmental Engineering
University of Maryland
USA

Athens Institute for Education and Research
8 Valaoritou Street, Kolonaki, 10671 Athens, Greece
Tel: + 30 210 3634210 Fax: + 30 210 3634209
Email: info@atiner.gr URL: www.atiner.gr
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Dimitrios G. Goulias
Associate Professor
Department of Civil and Environmental Engineering
University of Maryland
USA

Sahand Sasha Karimi
PhD Candidate
Department of Civil and Environmental Engineering
University of Maryland
USA

Abstract

Over the past two decades the role of Departments of Transportations (DOTs) has shifted from quality control (QC) of materials and placement techniques to quality assurance (QA) and acceptance. This has placed more responsibility for quality during production on the contractor, producer and supplier. 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 several materials acceptance specifications were revised. In some cases the revised specifications 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 complimentary testing and inspection from SHA to verify results (QA).

It was the objective of this study to identify typical material QC/QA procedures and a) examine their conformance in relation to the federal requirements for defining QA plans, b) identify potential improvements to existing SHA QA plans; c) assess product variability based on production QC data; and iv) evaluate risks related to the contractor and the owner based on material acceptance data. This paper presents the results from the variability analysis and the development of OC curves for evaluating the risks associated to the contractor and owner/ agency.

Keywords:
Corresponding Author:

Introduction

DOTs are responsible for materials QA. Over the years the role of agencies has shifted from quality control (QC) to quality assurance (QA) and acceptance (AASHTO 1996, Burati et. al. 2005, Karimi et. al., 2011). To adapt to such change several specifications and QA procedures were revised. It was the objective of this study to review current material QC/QA procedures to assess among other product variability and calculate risks to the agency and contractors (Goulias et.al., 2013). This paper presents (i) the variability analysis of selected concrete mixtures from the precast concrete production, and (ii) the risk analysis on granular aggregate base materials (GAB) using data from a typical construction project in the region.

Risk Analysis based on Operating Characteristic (OC) Curve

In developing the OC curves and calculating the risks to the agency and the contractor the following terms are defined (Goulias et.al., 2013, Burati et. al., 2006 & 2011, TRB Circular E-C037, 2002): Acceptable Quality Level (AQL) represents the minimum quality level for fully acceptable material. When quality is based on Percent Within Specification Limits (PWL), the AQL is the PWL value for which the material is considered fully acceptable; Rejectable Quality Level (RQL) represents the level of quality below which the material is considered unacceptable; OC Curve represents the relationship between the actual quality of a lot (PWL), and the probability of its acceptance; Seller's risk α (also referred to as Type I error) is the probability of rejecting an acceptable quality level (AQL) material. It is the risk that a producer takes in having AQL material rejected; Buyer's risk, β, (also called the Type II error) is the probability of accepting a lower quality (rejectable quality level - RQL) material. It is the risk that the highway agency takes in having RQL material accepted.

The development of risk analysis requires data form acceptance testing that are independent of the QC data collected by contractors. In these analyses field density data from a newly constructed highway were used. The histogram of Figure 1 shows the distribution of the field density values from this project. Considering that the lower specification limit for density is 97%, it can be observed that none of the values was below this limit.

A normality test was used to assess whether these values follow a normal distribution (MDOT, 2004 & 2008). The normality test used was based on the interquartile range (IQR) method. The standard deviation, s, for the samples was calculated and used to get a value of IQR/s = 1.16. According to this procedure the data are normally distributed (with a mean density value of 98.2%, standard deviation of 0.89 and a coefficient of variation of 0.9%) since this value is close to the value IQR/s≈1.3 for normally distributed data.

The density data were then used to develop the OC curves for calculating the risks to the agency and the contractor. The procedure followed by Villiers et al.

(2003) was followed using the standard error of the density data (i.e., representing the population characteristics) in order to relate PWL and probability of acceptance. Simulation analysis was then run for various sample sizes (n). Figure 2 shows four OC curves for different values of n.

Based on this OC curve, the resulting alpha (α) and beta (b) risks are evaluated in function of the sample size (n) of the measurements used for acceptance within a production lot, and in function of the selected upper quality level (AQL) and lower quality level (RQL). Typical values of AQL = 90% and RQL = 40% are used for civil engineering materials by highway agencies. As it can be seen from Figure 2 when two samples from each lot are used for acceptance (n=2) the alpha (α) and beta (b) are of the order of 4% and 37% respectively. Thus the agency bears a high risk of accepting lower quality material. In order to reduce such risk the agency needs to increase the number of samples used from each lot from 2 to eventually 4, 5 or even more samples for judging the quality of lots. The contractor risk is relatively lower in relation to the agency risk.

Based on the field density data variability and the development of the OC curves for the quantification of agency and contractor risks carried out in this study, the agency can select acceptable levels of risks by adjusting sample size and/or eventually adjusting specification acceptance limits.

Variability Analysis of Producers' Precast Concrete Quality

A variety of plants produce precast concrete elements for state projects. The plants report the compressive strength from a variety of concrete mixtures in their QC reports. It was the objective of this study to examine and assess the level of concrete variability for these concrete mixtures in terms of the 28 day compressive strength. As an example of the variability analysis used in this study for assessing the quality and uniformity of these mixtures the data and analysis results from a concrete mixture of a modern – fully automated precast concrete plant are presented herein.

For this concrete mix with a design strength of 27,579kPa (4,000psi), the average 28 day compressive strength was 35,197kPa (5,105psi) with a standard deviation of 2302kPa (334psi), providing thus a coefficient of variation (CV) of 6.5%. For the 26 strength data provided for this mixture quality control chart analyses was conducted for assessing the degree of randomness in concrete production. In order to assess whether the concrete production process is 'in control,' the 'theory of runs' was used as outlined in FHWA 'Statistical Quality Control of Highway Construction' (FHWA 1970). The control chart for this concrete mixture is shown in Figure 3.

As it can be observed from this control chart all the data fall within three standard deviation of their average. In terms of variability and randomness of the production process the guidelines of the "theory of runs" indicates that the process may be considered "out of control" when:

- Whenever, in 11 successive points on the control chart, at least 10 are on the same side of the central line.

- Whenever, in 14 successive points on the control chart, at least 12 are on the same side of the central line.

- Whenever, in 17 successive points on the control chart, at least 14 are on the same side of the central line.

- Whenever, in 20 successive points on the control chart, at least 16 are on the same side of the central line.

From these data sets it appears that the concrete production for this mixture in this plant does not fall under the ‘out of control’ category.

The last step of the analysis was to examine whether the concrete strength data follow a normal distribution so as to be able to develop probability statements on the expected number of concrete samples above, below or within the specification limits. In order to identify whether the 28 day strength values follow the normal distribution two descriptive methods were used to check for normality: i) develop a relative frequency histogram of the data, (if concrete strength values are approximately normal, then the shape of the histogram will be similar to the normal bell shape curve); and ii) use the interquartile range, IQR, and standard deviation, s, for the samples, and calculate the ratio IQR/s (as in the GAB density case, if the strength values are approximately normal, then IQR/s≈1.3).

Figure 4 shows the relative frequency histogram for the concrete mixture from this plant. Regarding the normality test based on the interquartile range (IQR) method, the standard deviation, s, for the samples was calculated and used to get a value of IQR/s = 1.2. Thus, according to this procedure the data are normally distributed since this value is close to the value IQR/s≈1.3 for normally distributed data.

Conclusion

It was the objective of this study to assess among other, product variability during production and evaluate risks related to the contractor and the owner/ highway agency based on material acceptance procedures. The analysis on the field density data for GAB indicated that these are normally distributed. The risk analysis on the field density indicted that the agency bares a significant risk on accepting lower quality material. Thus, potential adjustments are needed on the current state of practice for accepting GABs. Based on the field density data variability and the OC curves, the agency can select acceptable levels of risks by adjusting sample size and/or eventually adjusting specification acceptance limits. The variability analysis on the concrete strength data for precast concrete elements indicated that there is a very good process of production providing a low variability in strength, and overall the production process is “in control” based on the theory of runs. Furthermore, concrete strength values follow the normal distribution and thus probability statements on the expected number of concrete strength above, below or within specification limits can be developed in probabilistic terms. The methodologies followed in this study can be used from any highway agency wishing to examine their QA/QC procedures and assess the material quality and any potential adjustments needed to improve quality or reduce risks.

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Figure 1. *Field Density Data for a Newly Constructed Pavement*

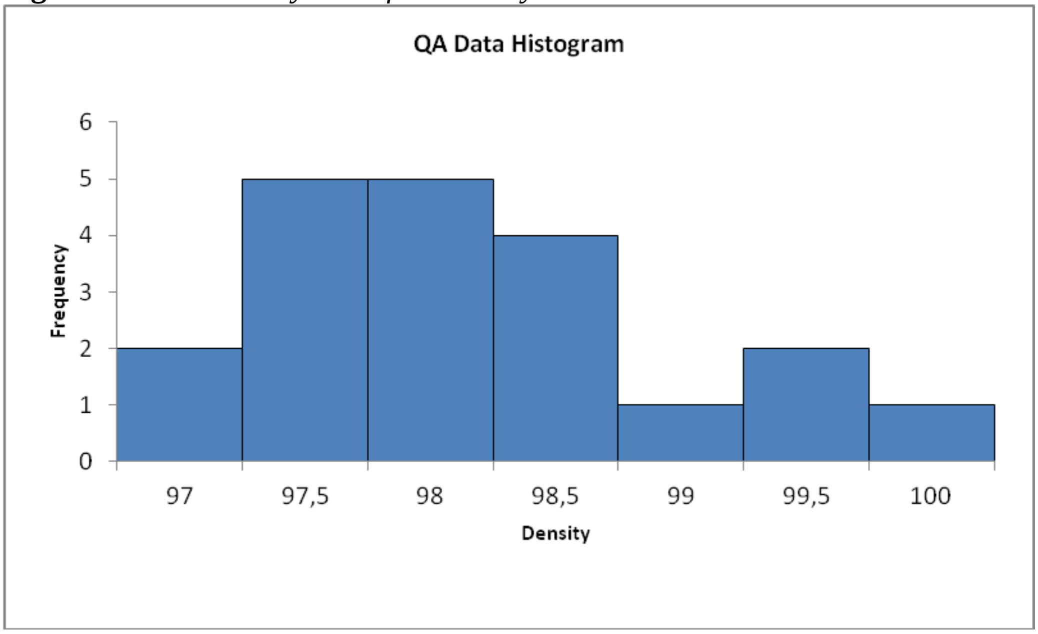

Figure 2. *OC for Field Density Data*

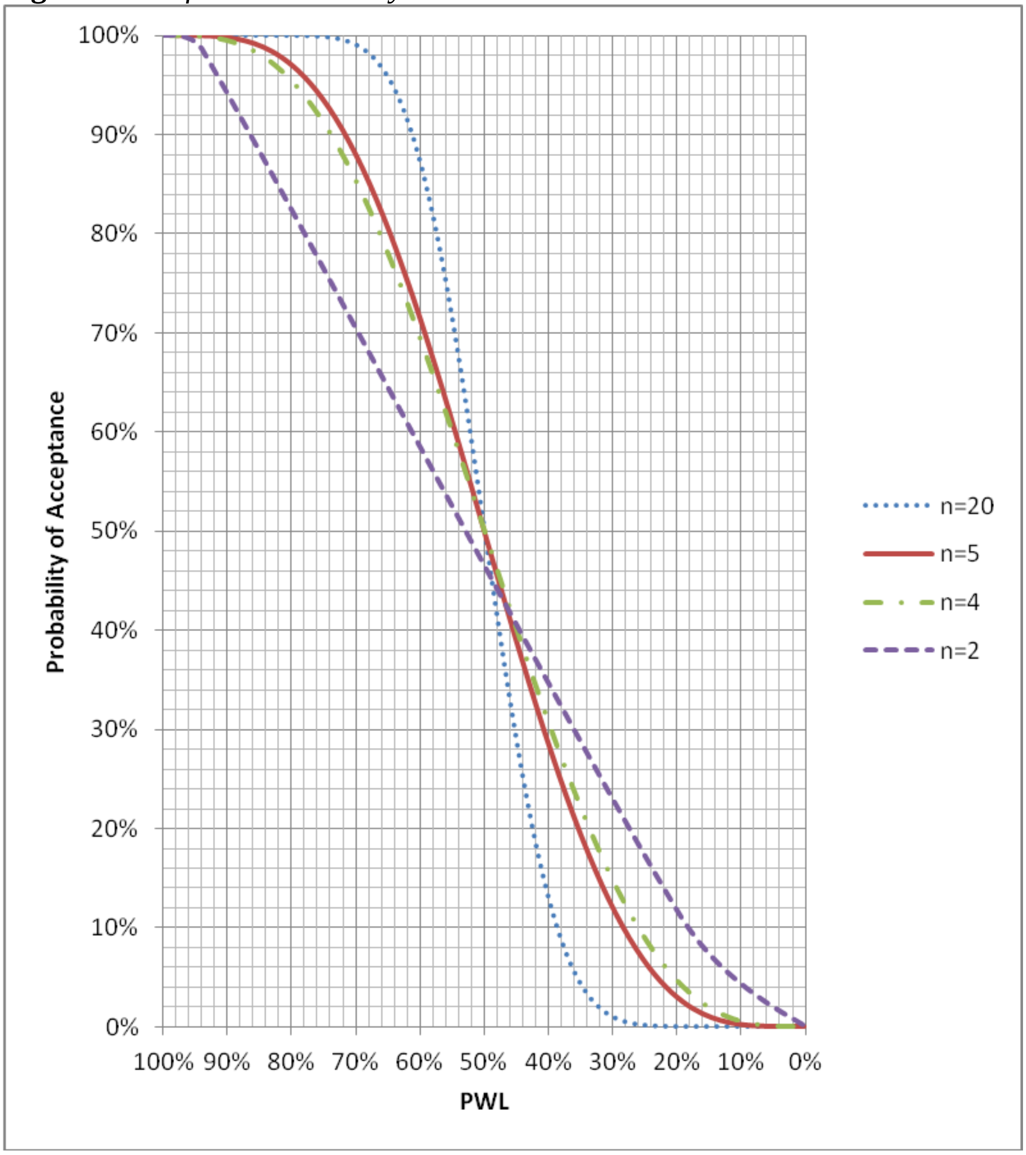

Figure 3. *Control Chart for Concrete Mix Production, 28 Day Strength Values*

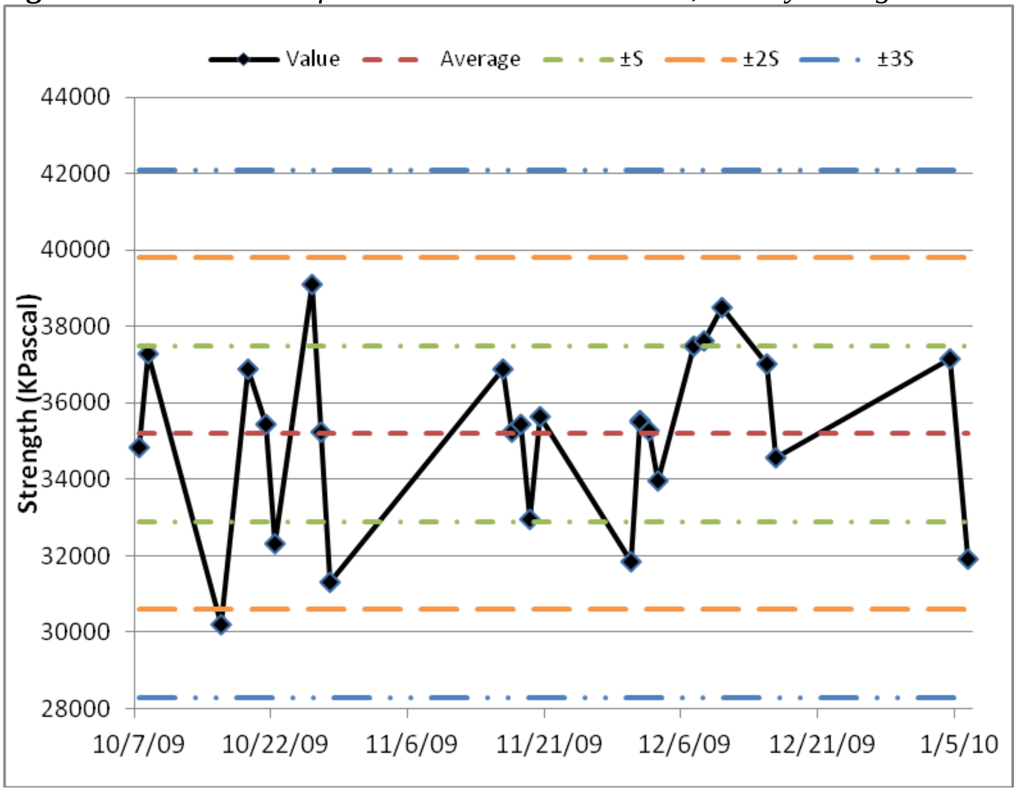

Figure 4. *Relative Frequency Histogram for the 28 Day Strength Data (n=26)*