THE PERCENT WITHIN LIMITS APPROACH FOR ACCEPTANCE

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A fundamental concept of state transportation agencies' quality assurance (QA) specifications is the separation of the functions of quality control (QC) and acceptance, with the contractor responsible for QC and the agency or its designated representative responsible for obtaining and conducting verification tests and making acceptance decisions. However, a reduction in agency resources has resulted in many agencies accepting QC data as part of the acceptance decision. As such, an emphasis has been placed on improved contractor QC and process control. Agencies have initiated additional measures to enhance confidence in the products they accept, including the development and use of statistically based acceptance plans. Statistically based acceptance plans consider both agency and contractor risk, are related to performance, and are readily understood and applied. These plans also provide incentives for good-quality work and provide disincentives for poor-quality work. The percent within limits (PWL) approach is a commonly used form of statistically based acceptance and can provide advantages to agencies and industry when implemented. This technical brief provides an overview of PWL acceptance approaches and provides data supporting the potential advantages of the use of PWL approaches over conventional acceptance approaches.

Introduction

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Agencies have initiated additional measures to enhance confidence in the products they accept, including the development and use of statistically based acceptance plans. Statistically based acceptance plans consider both agency and contractor risk, are related to performance, and are readily understood and applied (Burati et al. 2003). These plans also provide incentives for good-quality work and provide disincentives for poor-quality work. The percent within limits (PWL) approach is a commonly used form of statistically based acceptance and can provide advantages to agencies and industry when implemented.

This technical brief provides an overview of PWL acceptance approaches and provides data supporting the potential advantages of the use of PWL approaches over conventional acceptance approaches.

Background

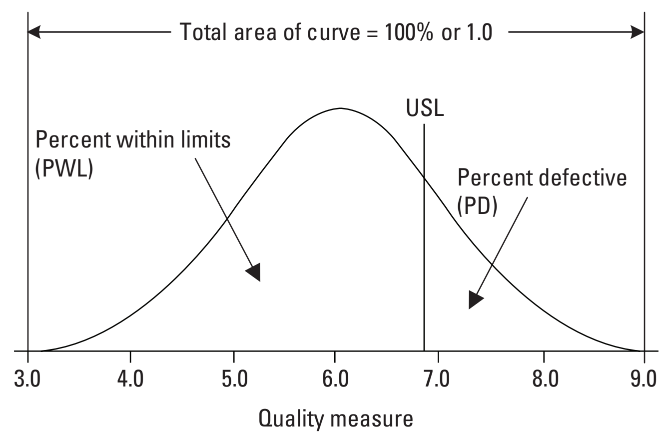
According to the *Glossary of Transportation Construction Quality Assurance Terms*, acceptance is "the process whereby all factors used by the agency (i.e. sampling, testing, and inspection) are evaluated to determine the degree of compliance with contract requirements and to determine the corresponding value for a given product" (TRB 2018). AASHTO R 9, Standard Practice for Acceptance Sampling Plans for Highway Construction, provides guidance to agencies on the development of acceptance plans that include separate functions QC and acceptance. For highway construction, acceptance plans should be statistically based on variables, not on a pass/fail basis, using attributes.

Since the variability resulting from most materials and construction is unknown, acceptance plans should measure both the product average and variability as estimates of a population. Many statistically based acceptance plans are developed in terms of the percent of material or constructed work within agency-determined limits. This approach, referred to as the PWL process, provides advantages because it incorporates both the sample mean and standard deviation, as well as the sample size, into the pay factor determination (Moulthrop et al. 2012). Another key advantage of the PWL process is that it considers the degree of variability within the population of test results. More broadly, the PWL approach recognizes the contractor's efforts toward controlling variability and, as a result, can be expected to improve the uniformity of pavement properties and performance (Russell and Frantzen 2008).

It is important to remember that sample results, whether used as part of the PWL process or as part of another acceptance approach, are always estimates of the population. Therefore, the estimate of the population is improved as the sampling frequency increases. Since small sample sizes (or relatively low sampling frequencies) are used in most construction testing, the distribution used is the noncentral t distribution, which converges with the normal distribution as the sample size n approaches infinity. Because the PWL method uses an estimate of the population, the measure of central tendency (often the mean, but possibly the median or mode of the data) and the variability are also estimates.

The Percent within Limits Process

In the PWL process, the PWL plus the percent deficient (PD) equals the whole (100%) of the material or work within a population. The relationship between PWL and PD is graphically shown in Figure 1.



Adapted from AASHTO R 9

Figure 1. Relationship between PWL and PD

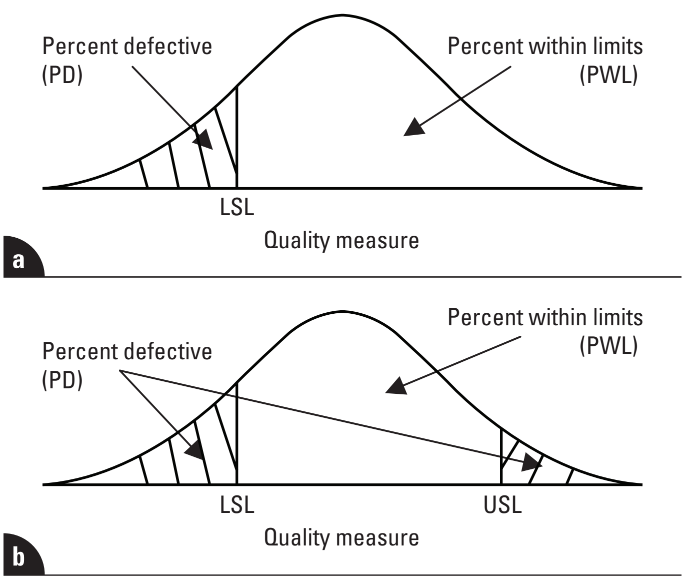
> "Intuitively, PWL is a good measure of quality because it is reasonable to assume that the more of the product that is within the specification limits, the better the quality of the product should be."
>
> AASHTO R 9

Also shown in Figure 1 is the upper specification limit (USL), though a lower specification limit (LSL) can also be used as appropriate. A single-sided or single-limit specification (Figure 2a) uses only a USL or an LSL. A double-sided or double-limit specification (Figure 2b) uses both a USL and an LSL. Quality measurements for concrete pavements that have been used by agencies in PWL procedures for pay, along with their appropriate specification limits, include the following (Russell and Frantzen 2008, Moulthrop et al. 2012):

- Pavement thickness, a one-sided LSL-only measure
- Compressive strength, a one-sided LSL-only measure
- Air content, a two-sided USL and LSL measure

Although the previous list provides only conventional concrete pavement quality measures that agencies have used for PWL acceptance in the past, the process is not limited to the use of only traditional measures. The Federal Highway Administration (FHWA) encourages agencies to consider the use of other performance-engineered mixture (PEM) tests in the PWL method of acceptance, including the following (Praul and Ahlstrom 2019):

- Water content
- Super Air Meter (SAM) number
- Surface or bulk resistivity
- Thickness via MIT-SCAN-T3
- Strength



Adapted from KDOT 2018

Figure 2. Specification limits: (a) single-limit specification and (b) double-limit specification

An example of the establishment of PWL limits for the SAM number (AASHTO T 395) is presented in Praul and Ahlstrom (2019).

Establishing PWL specification limits (USL or LSL) requires an agency to define the performance of material or work that is acceptable at a reasonable cost when that material or work is used for the intended purpose. In general, for quality characteristics with single specification limits, the limit can be set at a value that is an appropriate number of standard deviations above (or below) the desired value. For characteristics with double limits, there is a chance of a target miss, where the contractor fails to center the process directly on the target value, and the variability associated with both the target miss and the process variability must be considered in combination. AASHTO R 9 provides a procedure that can be followed to establish specification limits for double limits, while additional guidance for agencies developing new or modifying existing acceptance plans and quality assurance specifications is provided in *Optimal Procedures for Quality Assurance Specifications* (Burati et al. 2003).

Acceptable Quality Level and Rejectable Quality Level

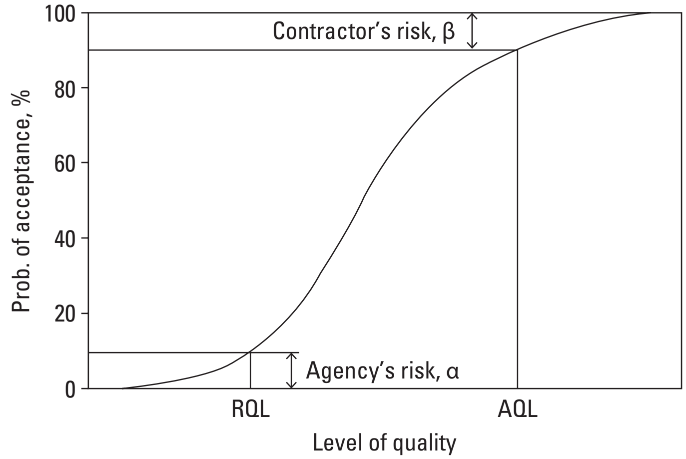
An acceptable quality level (AQL) and a rejectable quality level (RQL) of material or work must also be defined to support the use of the PWL procedure. According to AASHTO R 9, AQL is the "minimum level of actual quality at which the material or construction can be considered fully acceptable (for that quality characteristic)," and the material will receive an average pay over the long run of 100%. RQL is the "maximum level of actual quality at which the material or construction can be considered unacceptable (rejectable), and the required actions are often removal and replacement, corrective action, or a relatively lower pay factor."

For example, depending on the variability anticipated in a quality measure as well as an agency's risk tolerance, an AQL for a double-limit specification could be established at 90 PWL, indicating that 90% of the material or work must be within the specification limits to be completely acceptable. This approach results in 5% deficient material or work at the upper and lower ends of the curve. AASHTO R 9 recommends that AQLs be established no lower than 90 PWL to avoid the perception that lower quality levels are acceptable.

To establish an RQL, an agency often decides what constitutes a sufficiently large percentage of material outside of specification limits that warrants rejection of the lot.

For example, consider an instance where an agency decides that if 60% of material or work within a lot does not meet specification limits, it should be rejected. The RQL is then established as 60 PWL. AASHTO R 9 states that typical RQL values are between 30 and 70 PWL, although an RQL can also be determined based on historical data. It should be noted that in this approach, the PD may also include material that is not defective per se but is of lesser quality than that within the specification limits (AASHTO R 9).

Examples of AQL and RQL are shown in Figure 3. Also shown in Figure 3 are the buyer's risk, α, that an agency is accepting poor-quality (rejectable) material or work, and the seller's risk, β, that an agency is rejecting acceptable material or work.



Recreated from Burati et al. 2003

Figure 3. Example of AQL and RQL, along with agency's and contractor's risk

An acceptance limit can also be placed directly on a quality measure to establish a minimum or maximum allowable value that will permit acceptance of a lot. Many states have used an AQL of 90 and an RQL of 50 for statistically based tests (Russell and Frantzen 2008). Some agencies have established acceptance limits with pay adjustments, incentives, or disincentives that modify pay levels based on the level of quality of the material or work (Moulthrop et al. 2012, AASHTO R 9). Pay adjustments are discussed later in this section.

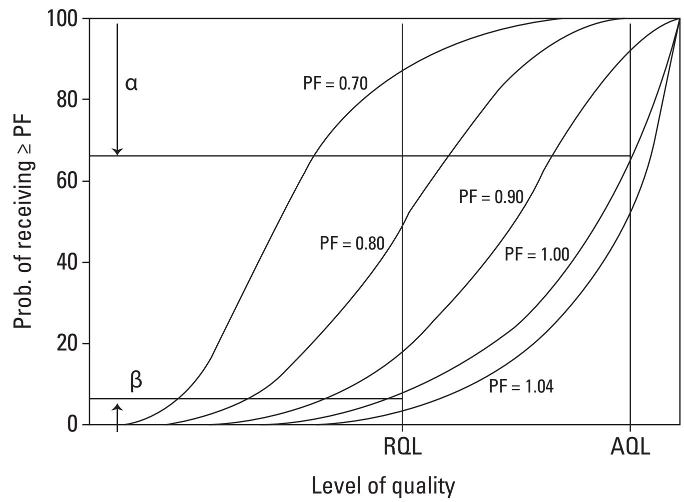


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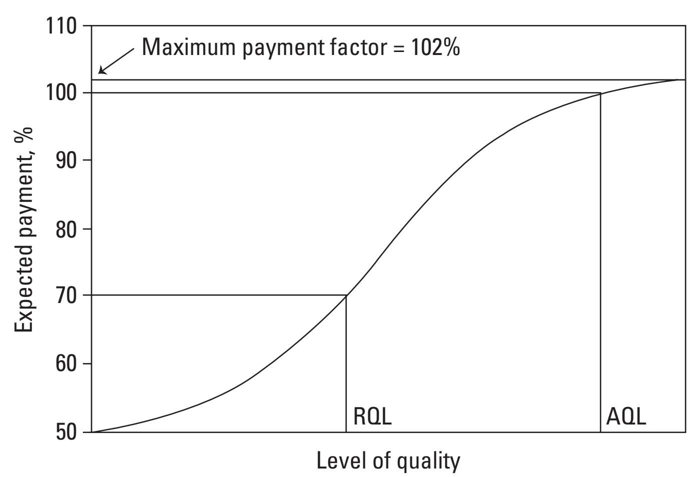
Figure 4. Example OC curve for a statistical test procedure

FHWA recommends that agencies establish their specification limits in a manner that supports the identification of an AQL using the PWL approach. Agencies also need to provide minimum expectations for QC test data analysis and associated action/suspension limits. There is no right or wrong way to establish the AQL and/or the RQL, but the buyer's and seller's risks should be considered.

Evaluation of Risk

Risks can be evaluated using an operating characteristics (OC) curve (Figure 4) and an expected payment (EP) curve (Figure 5). The OC curve plots the probability of acceptance against the actual quality level. The EP curve plots the average payment that the contractor can expect for a lot or population with a given level of quality (FHWA 2003). If payment adjustment provisions are provided by an agency, an OC must be prepared for each selected payment level (FHWA 2003). Guidance on developing OC and EP curves, including case studies on the development of these types of specifications by agencies, is presented in Burati et al. (2003).



Recreated from Burati et al. 2003

Figure 5. Example EP curve for a statistical test procedure

Acceptance Plans

Acceptance of materials or work is frequently based on QA testing performed in qualified laboratories by qualified personnel. Increasingly often, many agencies are also utilizing contractors' QCs test results as part of the acceptance decision. Per 23 CFR 637, a validation procedure is required if these results are used, and the procedure should adhere to the following recommendations in AASHTO R 9:

- The sampling and testing must be performed in qualified laboratories and by qualified sampling and testing personnel.
- The quality of the material must be validated by verification sampling and testing. The verification sampling and testing used in the acceptance decision is to be performed on samples that are taken independently from those taken by the contractor.

An independent assurance (IA) program provides a third-party evaluation of testing procedures, inspection procedures, and equipment, which enables results to be compared and deficiencies to be detected. This improves the reliability of testing results from both the acceptance and QC processes.

Pay adjustments and pay equations can be developed based upon the agency's risk tolerance. These can be based on a single quality measure or can include two or more quality measures, weighted to reflect the agency's preferences (Russell and Frantzen 2008, Moulthrop et al. 2012). Providing modest incentives for superior quality (such as 103% pay for 0 PD lots of materials or work), along with significant disincentives for poor quality (such as 50% pay for 50 PD lots of materials or work), has been shown to be a successful approach for agencies.

The use of incentives and disincentives has been shown to provide several advantages to agencies and, in many cases, contractors. The use of disincentives strongly encourages contractors to develop and use QC provisions to ensure that the finished product will meet or exceed the desired level of quality an acceptably high percentage of the time (Burati et al. 2003). Disincentives also allow an agency to recover some funds to help cover the costs of the likely deficient performance resulting from lower-quality materials or work.

Payment of incentives for superior-quality work has been shown to provide a number of advantages to both the agency and the contractor. The contractor has the ability and incentive to obtain additional pay for superior-quality work. For the agency, benefits include those associated with contractor motivation and improved QC, the potential for improved performance or increased service life for the constructed project, and an improved relationship with the contractor (Burati et al. 2003).

> Incentives also provide a means for an agency to differentiate between high-performing and low-performing contractors in a low-bid environment. When a PWL specification is used, contractors that are targeting their production, minimizing their variability, and consistently providing high-quality work will be successful.

When establishing pay equations, accounting for variability is important. Using limits and pay factors that account for variability, such as 100% pay for 10 PD lots of materials or work, is recommended (Burati et al. 2012). The primary reason for including positive pay adjustments is to ensure that the contractor receives 100% pay when material is delivered at the AQL. PWL is not an exact measure, since there is error due to variability in the statistical procedures. Even if a contractor produces material that is exactly 90 PWL, each lot-by-lot measure of PWL may not equal 90 due to this variability. If an agency only applies negative pay adjustments, a contractor could deliver material that deserves 100% pay overall but may not receive full compensation.

> Contractors should be familiar with an agency's acceptance plan and how their respective QC programs are integrated into it.

As states increasingly move towards PWL specifications, FHWA is encouraging agencies to establish clear guidance on what is expected of contractors' QC test results when an individual test result yields failing results, as well as trigger points and suspension limits for QC data. Action limits indicate when corrective action should be taken or processes should be adjusted, and suspension limits indicate when processes should be stopped and adjusted prior to continuing production. Many existing PWL specifications currently include defined action and suspension limits for QC. Agencies should also establish minimum expectations for the analysis of QC test data and associated action and suspension limits. Contractors will then be able to develop a sampling and testing plan that supports agency requirements. Contractors should include their QC sampling and testing frequencies in their QC plans so that agencies can consider these data in their acceptance process.

Acceptance plans should be revisited by agencies periodically and be revised as experience is gained, new technologies emerge, and improved quality processes are identified. AASHTO R 9 describes the seven steps an agency should take to develop a new acceptance plan (or revise an existing one):

- Initiation and planning
- Acceptance plan development steps
- QC procedures
- Acceptance procedures
- Risks and risk analysis
- Pay factors
- Implementation steps

Agencies are increasingly encouraged to consider risk in their acceptance testing. For example, a tiered approach can be utilized based on the type of element, the risk associated with that element, and/or the risks associated with the QC plan. Sampling and testing frequencies should be established to balance the need for an accurate estimate of the population, proper risk allocation, and practical considerations such as the time required to perform a specific test procedure. Means to reduce variability can also be incorporated, such as indicating that acceptance tests should be performed by the same technician for an entire lot.

Agencies should also establish dispute resolution procedures to help resolve conflicts that may arise due to discrepancies between agency results and contractor results, particularly when a pay reduction is at stake. Procedures should also be included in a QA program to help identify testing errors (AASHTO 2013). Additional guidance is presented in Burati et al. (2003).

Example: Comparing Strength Acceptance Using Conventional and PWL Approaches

FWHA's Mobile Concrete Technology Center (MCTC) has collected compressive strength test results at concrete pavement projects across the United States. The test data are limited to the data that could be collected during the timeframe the MCTC was able to remain at each project site. However, these data offer useful insights into the impact that the implementation of PWL acceptance approaches has had on the typical test results acquired from the concrete mixtures produced at the projects visited.

Table 1 shows the mean and standard deviation of 28-day compressive strength test data collected by the MCTC at concrete pavement projects in three states using PWL acceptance. The participating state agencies included the Michigan Department of Transportation (MDOT), which had a 28-day compressive strength requirement of 3,500 psi; the Arizona Department of Transportation (ADOT), which had a 28-day compressive strength requirement of 4,000 psi; and the Ohio Department of Transportation (ODOT), which had a 28-day compressive strength requirement of 4,000 psi. The 28-day compressive strength test data collected by the MCTC at concrete pavement projects in three other states that did not use PWL procedures for acceptance (designated A, B, and C) are also shown in Table 1. The target 28-day compressive strengths used by States A, B, and C were 3,000 psi, 3,500, and 4,000 psi, respectively. The normal distribution curves associated with these data are plotted in Figure 6.

Table 1. Mean and standard deviation of 28-day compressive strength test data collected by FHWA's MCTC at projects in selected states

MCTC Data from Project Site	State Agency					
	Michigan	Arizona	Ohio	State A	State B	State C
Mean 28-day Compressive Strength (psi)	4,507	5,977	6,095	5,855	6,317	6,695
Standard Distribution (psi)	173	236	164	615	456	792
Required 28-day Compressive Strength (psi)	3,500	4,000	4,000	3,000	3,500	4,000
Difference between Mean and Required 28-day Compressive Strength (psi)	1,007	1,977	2,095	2,855	2,817	2,695

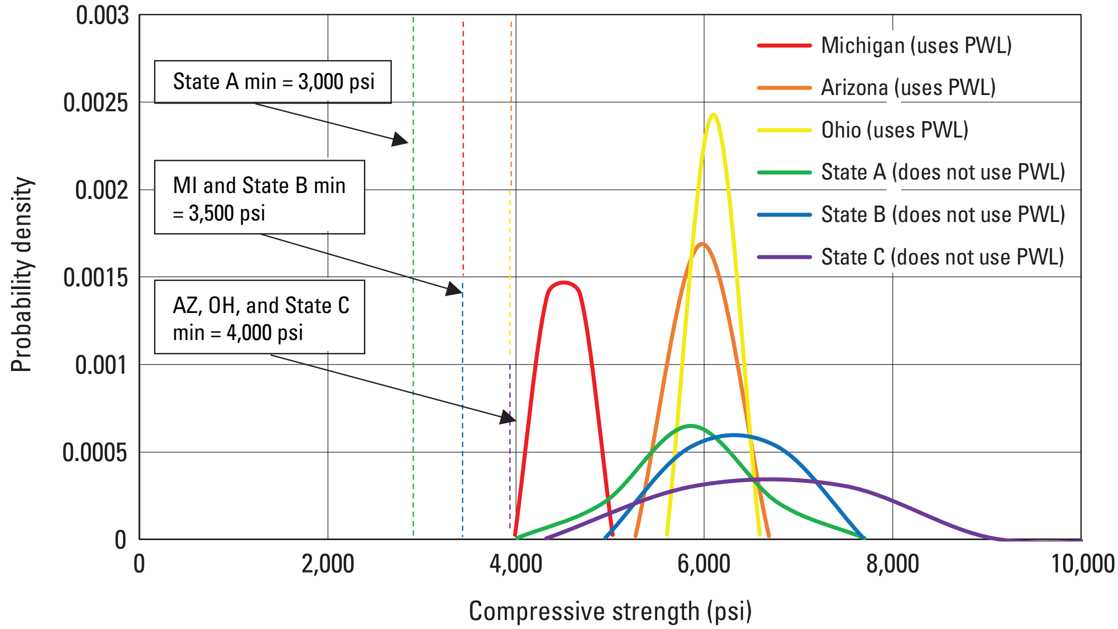


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Figure 6. Normal distribution curves computed from 28-day compressive strength test data collected by FHWA's MCTC at projects in six states

As can be observed in Table 1 and Figure 6, the standard distributions for data collected from projects in the three states using PWL acceptance approaches exhibit far lower standard deviations than the results for the data collected from projects in the three states not using PWL acceptance approaches. As described in this technical brief, agencies using a PWL approach reward contractors for using process control and QC techniques to control their production and reduce variability. As such, the data reveal that states using PWL approaches tend to have lower standard deviations and average compressive strengths closer to the production targets than states that are not using PWL approaches.

Additionally, the data for MDOT indicate that the contractor produced a mixture with a strength much closer to the minimum required 28-day compressive strength of 3,500 psi. The differences between the mean and required 28-day compressive strength test results for projects in the three states using PWL approaches are 1,007 psi, 1,977 psi, and 2,095 psi for Michigan, Arizona, and Ohio, respectively. These results are in contrast to the greater differences between the mean and required 28-day compressive strength test results for the three states not using PWL, which are 2,855 psi, 2,817 psi, and 2,695 psi for States A, B, and C, respectively. This contrast provides evidence that PWL acceptance approaches entice contractors to improve their process control and QC, improving the consistency of their mixtures. Additionally, when mixture production and placement activities are in control and strength targets are being readily and consistently met, contractors tend to reduce the amount of cement in their mixtures. This results in the placement of more economical and sustainable concrete mixtures and suggests that states not using PWL acceptance approaches may be missing opportunities to save money and reduce durability issues associated with higher cement content.

Closing

QA specifications and acceptance practices for concrete pavement projects vary across the United States and have evolved to meet agency goals, risk tolerances, and available resources. Specifications have changed to address substandard performance, to include new quality characteristics, and to incorporate performance approaches that provide benefits to both the agency and industry stakeholders. All agencies aim to use QA acceptance approaches that provide confidence that the work being accepted meets quality standards and will provide the desired performance over its service life.

Variability has historically exhibited a strong link to construction quality, with reduced variability associated with a higher-quality final product and a longer service life (Cavalline et al. 2021). PWL acceptance approaches incorporate variability into the acceptance decision. As such, PWL acceptance approaches encourage the contractor to use process control and QC to monitor and improve their operations and constructed products.

Data collected by the MCTC provide evidence that agencies using PWL acceptance approaches can expect that contractor efforts to meet these acceptance requirements (and associated incentives) are producing concrete mixtures that are more consistent (exhibit lower variability). These data also show that contractors constructing concrete pavements in states using PWL approaches are producing mixtures with a smaller difference between the required acceptance strength and the actual strength. This indicates that mixtures produced in states using PWL acceptance approaches may have lower cement contents, providing both improved durability performance and sustainability benefits.

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About the National Concrete Pavement Technology Center

The mission of the National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University is to unite key transportation stakeholders around the central goal of developing and implementing innovative technology and best practices for sustainable concrete pavement construction and maintenance.