National Cooperative Highway Research Program

Synthesis of Highway Practice 232

Variability in Highway Pavement Construction

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of interest to state DOT construction, materials, statistical, specification, and inspection engineers; DOT research staff; pavement construction material suppliers; highway construction contractors; and civil engineering consulting firms, including field and laboratory materials testing personnel. The synthesis describes the state of the practice for defining and measuring variability in highway pavement construction. Data obtained from a review of the literature, a survey of state departments of transportation (DOTs), and discussions with selected state DOT personnel and private materials producers are presented.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

This report of the Transportation Research Board defines several measures of variability but concentrates on the use of standard deviation as the usual measure of variability. The synthesis updates reported typical variabilities found in materials and construction specifications. Also included are discussions of current research activities as related to variability, how variability can be used in the development of specification limits, the use of incentives and disincentives in specifications, and the need for additional information on the variability of several materials and construction processes. The synthesis does not include detailed discussions of performance-related specifications (PRS) or of quality control measures.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the research in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

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The Principal Investigators responsible for the conduct of this synthesis were Sally D. Liff, Manager, Synthesis Studies, and Stephen F. Maher, Senior Program Officer. This synthesis was edited by Linda S. Mason.

Scott A. Sabol, Senior Program Officer, National Cooperative Highway Research Program, assisted the NCHRP 20-05 staff and the Topic Panel.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance are appreciated.

VARIABILITY IN HIGHWAY PAVEMENT CONSTRUCTION

SUMMARY

The quality of highways has always been a major concern to highway engineers and contractors. The *AASHTO Quality Assurance Guide Specification*, a publication of the American Association of State Highway and Transportation Officials, uses the variability of materials and construction processes as one of the measures to assess quality. It is sometimes thought that a more uniform product, one with less variability, is an indication of better quality.

Tests conducted between 1956 and 1962 by the American Association of State Highway Officials, known as the AASHO Road Test, revealed the magnitude of variabilities expected to be encountered in the construction of pavements. Since the Road Test findings were reported, many studies on typical variability in highway construction have been conducted by both the Federal Highway Administration and various state departments of transportation. DOTs and contractors now routinely use computers to accumulate data from materials quality control and acceptance testing, and have developed databases for quantifying material and construction variability and other important properties.

This synthesis of information defines several measures of variability but concentrates on the use of standard deviation as the most typical variability measure. The synthesis updates reported typical variabilities found in materials and construction processes.

In order to use variability data properly in specifications, it is important to understand the ways of measuring variability and the relationship of variability to the bell-shaped Normal Curve. Likewise, it is important to recognize the relationship between a sample and the population from which it was obtained. Finally, it should be recognized that several sources of variability make up the overall variability range used to establish specification limits.

Little up-to-date information was found on the variability of soils and embankments for this synthesis. The information reported for these materials is primarily for field compaction and is somewhat dated. More data were found for aggregate base and select material, particularly regarding gradation. Much of the recent variability data come from databases developed and used by aggregate producers. For asphalt concrete, recent data are reported for properties such as aggregate gradation, asphalt content, and volumetric properties. Asphalt concrete construction variability data include information for air voids in the compacted pavement and thickness and smoothness variability. Information was found for portland cement concrete materials, aggregate gradation, cylinder and beam strength, air content, slump, water/cement ratio, and permeability variability. The portland cement concrete construction data include the variability of properties for core strength, and pavement thickness and smoothness.

From the data gathered in this synthesis, variability has a relatively wide range of values for each test procedure and material and construction property. Factors that influence this variability include the period of time, distance, area, and quantity of material over which the variability is measured. Information on each of these factors was not always

available. If the data contained here are to be used in the development of a specification, they should be used prudently; verification of the variability under conditions of proposed usage is encouraged.

This synthesis summarizes the available information. Also included is a discussion of current variability research activities, and ways to identify research needs, and to use variability in the development of specification limits and the state of the practice of incentives and disincentives in specifications. There is a need for additional information on the variability of several material and construction processes.

CHAPTER ONE

INTRODUCTION

BACKGROUND

Although variability is well recognized both in nature and in manufacturing processes, in engineering, practitioners are often surprised when two test results from the same sample are not the same. When the test values differ, the assumption is often that one must be in error. Some questions that may arise are "How should variability be related to specification limits?" "Is there a relationship between the process capability and the specification limits?"

"Variability" is used in this synthesis to mean the quantification of typical variation found in materials and construction processes in highway pavement construction. The key word is "typical;" it may or may not apply to the variability of a process that targets a particular specification depending on the sources of variability operating in the acceptance plan for that specification. It is important to recognize that sources of variability are present and that these sources appreciably influence the magnitude found.

This synthesis addresses these variability questions and the importance of defining the variability of materials and construction processes. Also, for potential users of these measures of variabilities, an update of typical materials and construction variabilities and the use of incentive and disincentive pay schedules for acceptance are presented.

AASHO Road Test

Although the importance of the magnitude of variability has been recognized in the highway industry since the early 1950s (*1,2*), it was not until the analysis of the variabilities of materials and construction from the AASHO Road Test (1956–1962) that the magnitude and the effect of the variabilities on specifications limits made substantial impact. Virtually no materials or construction properties met the specifications 100 percent of the time and some met the specifications less than 50 percent of the time. Carey and Shook stated that "AASHO Road Test specifications were intended to represent typical specifications, the kind used every day for control of our large highway construction program." *(3)* The development of the specifications resulted from what a panel of engineers judged could typically be built. A conclusion by Carey and Shook emanating from the Road Test stated:

> Briefly summarizing, we want to show that with many more well-trained inspectors than could economically be used in normal construction, with high-speed testing techniques, with a large-scale materials laboratory on site, with the ability to control in detail the contractor's construction procedures, with a highly competent and cooperative contractor who was well paid for everything he was required to do, and the eyes of the highway fraternity on the back of our necks, we were still unable to meet the specifications for many of the construction items within a country mile (*3*).

Many specification limits used today have as little basis as those observed by Carey and Shook in the AASHO Road Test. And often, today's specification limits consider neither process capability nor the performance measures necessary to achieve an adequate product (*4*).

The information gained from the AASHO Road Test data analysis led to an appreciable research effort in the 1960s by the Bureau of Public Roads (BPR) and several state departments of transportation (DOTs). The resulting national conferences and research reports proved invaluable in developing magnitudes of variability from typical construction projects (*5–21*).

RELATIONSHIP OF VARIABILITY TO STATISTICAL QUALITY ASSURANCE SPECIFICATIONS

Specification limits used to control and accept a product are most appropriate when they relate to a measure of the variability typically found in the process that produces that product, particularly if the limits are used in a Statistical Quality Assurance (SQA) specification. This document adopts the American Association of State Highway and Transportation Officials (AASHTO) definition of an SQA specification found under Quality Assurance in the *AASHTO Quality Assurance Guide Specification (22)*. This definition is, "all those planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy given requirements for quality." This definition furthermore contains at least two parts (also taken from the Guide Specification)—a Quality Control (QC) function, defined as "the sum total of activities performed by the seller (producer, manufacturer, and/or contractor) to make sure that a product meets contract specification requirements;" and an Acceptance Program, defined as "all factors that comprise the agency's determination of the degree of compliance with contract requirements and value of a product." SQA specifications contain, among other elements, both Quality Control and Acceptance Limits that are based on a function of the expected or allowable variability of the particular process. As discussed in chapter 2, "Understanding Variability," it is important that the specification limits be established under sampling, testing, and process conditions similar to those to which they will be applied.

RELATIONSHIP TO NATIONAL QUALITY INITIATIVE

A unique partnership, the National Quality Initiative (NQI), was formed by AASHTO, the Federal Highway Administration

(FHWA), and various highway industry associations to monitor and encourage continuous quality improvement within the highway industry *(24)*.

Under the auspices of the NQI, the "National Policy on the Quality of Highways" was developed by the members of the NQI Steering Committee (Appendix A). One of the principles of the National Policy is

> . . . a continuing commitment for quality products, information, and services through proper design, construction specifications related to performance, adherence to specifications, use of quality materials, use of qualified personnel, and sufficient maintenance, . . . *(23)*

Knowledge and application of variability is essential to this. To help ensure that the objectives of the National Policy on the Quality of Highways are met, the NQI Long-Range Plan was developed in June 1994 *(24)*. This synthesis embodies one of its objectives, which is to "promote and disseminate information on quality enhancement practices throughout the highway community."

PURPOSE OF SYNTHESIS

Scope

The quality of highway construction has always been a major concern of highway engineers and contractors. One of the advances made in the 1960s was to increase emphasis on the use of SQA specifications. At that time, the use of these specifications was not completely understood by the construction community. This situation has improved over the last several years and SQA is now widely used by many states and is emphasized in the *AASHTO Quality Assurance Guide Specification,* the National Quality Initiative (NQI), and various FHWA and DOT initiatives.

Giving proper consideration to construction variabilities is an essential element of SQA. In 1969, FHWA's *Public Roads* published a six-part article that summarized results from research studies measuring the typical variability associated with highway materials and construction, and the components of such variability *(12)*. These research studies confirmed the presence of the large magnitude of variability that was first revealed a decade earlier in the AASHO Road Test.

New research by DOTs and the creation of DOT and contractor/supplier databases since 1969 address the typical construction variabilities encountered. With numerous changes in construction procedures, test methods, materials, and the loss of experienced personnel, it is inevitable that today's typical construction variabilities differ from 1969 standards.

The synthesis does not include detailed discussions of performance-related specifications (PRS) or QC measures.

Need for Updated Variability Information

Several studies of typical variability were undertaken and reported in the 1960s on soils, asphalt concrete, portland cement concrete, and properties of pavement layers constructed with these materials. The references cited provide a perspective on not only the materials and construction activities investigated, but also on the wide geographical scope of the studies *(7–21)*. In the intervening years, several additional studies have been reported, as discussed in chapters 3, 4, and 5 on the particular materials. Due to improvements in technology, process capability, testing equipment and procedures, and increased recognition of the existence of variability, the variability of some processes has been reduced *(25–27)*. There is also concern that possibly offsetting these positive effects are the negative effects brought about by the loss of experienced personnel which can result in increased variability in some products because of the lack of experience or training in sampling and testing techniques. No synthesis documenting more recent typical variabilities has been published.

Organization of the Synthesis

Chapter 2 discusses variability and the ways it can be measured. This chapter also discusses sources of variability and explains Precision Statements. Chapter 3 contains variability data on soils and on aggregate base material and construction. Chapter 4 has information on asphalt concrete materials and construction processes, including some information on the variability of recent procedures such as those developed during the Strategic Highway Research Program (SHRP) study. Chapter 5 contains variability of portland cement concrete with emphasis on paving concrete. Chapter 6 discusses the proper use of variability in the development of specifications and provides an update on the DOTs' uses of incentive and disincentive pay factors. Chapter 7 suggests ways of obtaining data needed by the highway community to develop more realistic specification limits and draws conclusions based on the review of the literature.

Caution in Using Data Contained in the Synthesis

The following discussion on using the data in this synthesis with caution is in no way intended to dissuade the reader from trying to use or understand the information. As explained in chapter 2, it is important to understand the sources of variability that make up the magnitude of variability presented for each material and construction process. If not, the magnitude may be used erroneously. For example, the seemingly straightforward use of the measure of the variability of the gradation of aggregate base material has its pitfalls. Is the gradation open-graded or dense-graded? Is the material from a natural deposit or is it manufactured? If it is manufactured, is it a run from the crusher or is it pug-mill mixed? Additionally, the type of aggregate may influence the magnitude of variability.

The time frame over which the variability is defined is also important. For example, the variability of portland cement concrete strength will not be the same measured daily as if compiled monthly. The conditions from which the variabilities were obtained are documented in chapters 3, 4, and 5. Although many references do not contain information regarding period of time measured or the method used to obtain data, this should not detract from its usefulness. Instead, it is important to use these data as a starting point for verifying the magnitude of variability dictated by the conditions the user encounters.

CHAPTER TWO

UNDERSTANDING VARIABILITY

THE NORMAL CURVE

An appropriate starting point in understanding variability is the use of the bell-shaped Normal Curve or Normal Distribution. Figure 1 shows a typical Normal Curve for a distribution of Asphalt Contents. A Normal Curve that has more spread than another, for the same property, also has more variability than the other, narrower curve (Figure 2). This spread often relates to a function of a measure of variability. The Normal Curve represents a population such as the strength of 186 concrete cores from a highway paving project (*28*). Figure 3 shows a histogram of the 186 core strengths with the Normal Curve superimposed over the histogram. The strengths range from a minimum of 13 000 kPa (1885 psi) to a maximum of 38 000 kPa (5511 psi) for a spread of 25 000 kPa (3626 psi).

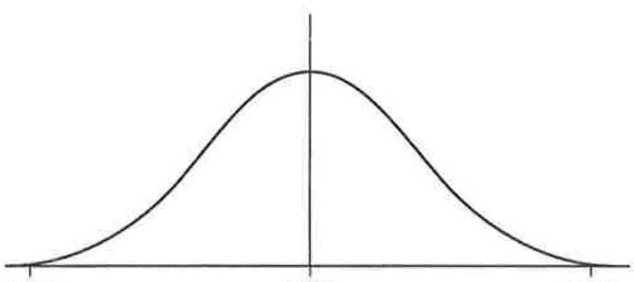

FIGURE 1 Familiar bell-shaped normal curve for asphalt.

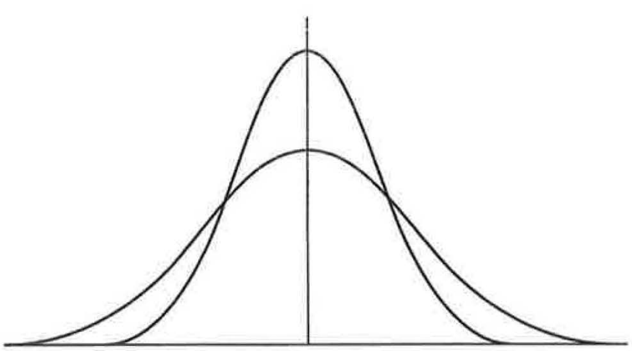

FIGURE 2 Two normal curves with different variabilities (28).

This concept of variability is easily understood and the Normal Curve can provide a perspective on the variability of most highway material and construction properties. However, once the concept is described in statistical terms, some people find it harder to grasp. The following discussion presents the statistical terms related to variability in a simple manner.

RELATIONSHIP OF POPULATION TO SAMPLE

One of the most difficult concepts to understand in statistical calculations is that population parameters are rarely known. There is rarely enough information available to know what the true central tendency and variability of the population is. In the Figure 3 example of concrete core strengths, 186 core strengths define the population. The data defining the population were compiled after the project was completed. Most highway materials and construction decisions relating to quality control and acceptance are made on a short-term basis, such as a day's production or a mile of pavement, called a "lot." These decisions involve small sample sizes (rarely more than 10). Thus, sample statistics are almost always used in highway materials and construction to estimate the population parameters. The sample statistics used are only *estimates* of the true population values, not the true values themselves.

MEASURES OF VARIABILITY

Although, as will be explained, the standard deviation is the most often used measure of variability, the variance is the basic measure of variability and understanding this measure is the first step in understanding variability.

Variance

The basic mathematical measure of variability is the variance. For a known population, i.e., a situation in which many values are available from which a true variance can be calculated, the population variance σ^2 is equal to the mean-squared deviation of the variable from the population mean μ,

$$\sigma^2 = \frac{\Sigma(x-\mu)^2}{n}$$

where

σ^2 = the variance,
x = the individual values,
μ = the population mean, and
n = the number of values in the population.

Using the 186 core strengths as an example, the variance would be calculated as shown in Table 1 and the equation that

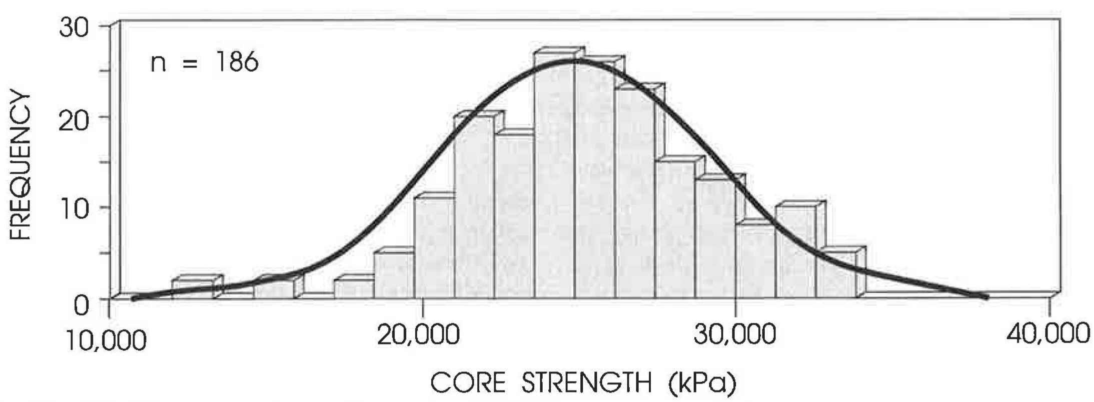

FIGURE 3 Histogram and normal curve for 186 PCC core strengths *(28).*

follows. The population average is the sum of the individual values divided by 186 and equals 26 027 kPa (3772 psi).

TABLE 1

PARTIAL CALCULATION OF σ^2 FOR 186 CORE STRENGTHS (kPa)

x	μ	$(x - \mu)$	$(x - \mu)^2$
28,360	26,027	2,333	5,442,889
30,910	26,027	4,883	23,843,689
26,010	26,027	-17	289
23,940	26,027	-2,087	4,355,569
28,910	26,027	2,883	8,311,689
.	.	.	.
.	.	.	.
.	.	.	.
Σ			2.82789 (10^9)

1 psi = 6.9 kPa

$$\sigma^2 = \frac{\Sigma(x-x)^2}{n-1} = 2.82789(10^9)/186 = 15{,}203{,}715 \text{ kPa}^2.$$

As mentioned above, all that is usually available for statistical measures in practice is a sample from the population and it is necessary to *estimate* the population parameters from the same statistics. The variance of a sample is designated as s^2 to distinguish it from the variance of the population. To calculate the sample variance, the sample data are used to determine the sample mean x is an *estimate* of the population mean; to provide an *unbiased* estimate of the population variance, n-1 (called "Degrees of Freedom") is used in the denominator of the equation for the variance. Thus,

$$s^2 = \frac{\Sigma(x-\bar{x})^2}{n\text{-}1}$$

where:

s^2 = the variance,
x = the individual values,
$\bar{x}$ = the sample mean, and
n-1 = the Degrees of Freedom.

Using a sample size of 4 core strengths (the first strengths in Table 1) as an example, the variance would be calculated as shown in Table 2 and the equation that follows. The sample average is the sum of the individual values divided by 4 and equals 27 305 kPa (3957 psi).

TABLE 2

CALCULATION OF s^2 FOR 4 CORE STRENGTHS (kPa)

x	$\bar{x}$	$(x - \bar{x})$	$(x - \bar{x})^2$
23,360	27,305	1,055	1,113,025
30,910	27,305	3,505	12,996,025
26,010	27,305	-1,295	1,677,025
23,940	27,305	-3,365	11,323,225
Σ			27,109,300

1 psi = 6.9 kPa

$$s^2 = \frac{\Sigma(x-x)^2}{n-1} = 27{,}109{,}300/3 = 9{,}036{,}433 \text{ kPa}^2.$$

One reason the variance is the basic measure of variability is that variances are additive and other measures of variability are not. This is an important point because if a number of different variances affect a measurement, the variance of the measurement is equal to the sum of the individual variances. This concept is extremely important when determining the sources or components of variability. However, the disadvantage of the use of the variance is that the units of variance are the square of the units of the measurement involved; this is a difficult measure of variability to work with. It is customary, therefore, to use the square root of the variance (the standard deviation) as the measure of variability.

Standard Deviation

Several methods can be used to measure variability. Since the units of standard deviation are the same as those in the measurement, it is easier to use than the variance. The same general discussion (presented above) concerning the relationship between sample and population of the variance, with only a subtle statistical difference, also applies to the standard deviation. The overall standard deviation is cited most in the references and is used in this synthesis unless otherwise identified. The use of the standard deviation has no disadvantages as a measure of variability, although there are some who feel that the equation and the need for adjusting for the "Degrees of Freedom" is too complicated. Pocket calculators make obtaining a standard deviation from a data set no more difficult than adding or subtracting. Most pocket calculators with statistical functions easily provide both the population standard deviation and sample standard "s" values. It is important, especially for small sample sizes, to use the proper key to calculate the appropriate value. Care must also be taken when using computer programs that generate standard deviations to ascertain whether the standard deviation is s and, if necessary, to convert to the appropriate value.

Using the above example of concrete core strengths, the population standard deviation, $\sigma = \sqrt{\sigma^2} = \sqrt{15{,}203{,}715}$, = 3899 kPa (565 psi) and the sample deviation, $s = \sqrt{s^2} = \sqrt{9{,}036{,}433}$ = 3006 kPa (436 psi). As the calculations indicate, the two standard deviations are not the same and the sample standard deviation is only an estimate of the population standard deviation. If many sets of samples of size n = 4 were obtained from the population, and the sample standard deviation were calculated for each, a distribution of sample size standard deviations would be obtained in which the average standard deviation would be close to the true population standard deviation of 3899 kPa (565 psi).

Range

Range is the simplest measure of variability; it is an important measure. It is obtained by subtracting the smallest value from the largest value in a data set. It represents the absolute value of the spread of the data and includes all the data points in the range. For this reason, it is sometimes used for control charts on assembly-line and in field QC applications. Its disadvantage is that because the range is calculated from only two of the data points in a set, it may not provide as accurate an estimation of the population standard deviation as the sample variance or standard deviation, both of which use all the data *(29)*.

Coefficient of Variation

The coefficient of variation, C.V., is sometimes used as a relative measure of variability. It is calculated by dividing the standard deviation by the average and expressing the result as a percent. The C.V. is most often used for portland cement concrete (PCC) strength as can be seen in chapter 5. Using strength as an example, field-produced PCC with a strength C.V. of 10 percent or less is considered to have been produced under well-controlled conditions.

An example of the use of the C.V. for the PCC core strengths above with a population standard deviation of 3899 kPa (565 psi) and the average population strength of 26 027 kPa (3772 psi) would produce a C.V. of 3,899/26,027 × 100 = 15.0 percent.

Relationship Between the Standard Deviation and Areas Under the Normal Curve

The Normal Curve has important features that make it useful in writing specifications for typical materials and construction processes found in highway construction. Each Normal Curve is symmetric about its average and the total area under the curve is 100 percent. Furthermore, the area falling within any interval under the curve can be determined. Since the curve is symmetric about its average, it follows that 50 percent of the area will be below the average and 50 percent above the average. In addition (as illustrated in Figure 4), it is a characteristic of the Normal Curve that approximately 67 percent of the area under the curve will be between the average plus and minus one standard deviation ($\mu \pm 1\sigma$), 95 percent will be between $\mu \pm 2\sigma$, and 99.7 percent will be between $\mu \pm 3\sigma$. As a simple example of how this relationship has been used in specifications, plus and minus two standard deviations have been often used to establish tolerances for specification limits. Thus, for a specification for asphalt content that may have a standard deviation of 0.25 percent, the limits might be the Job Mix Formula (JMF) plus and minus 0.50 percent. There are better ways of establishing specification limits (see chapter 6).

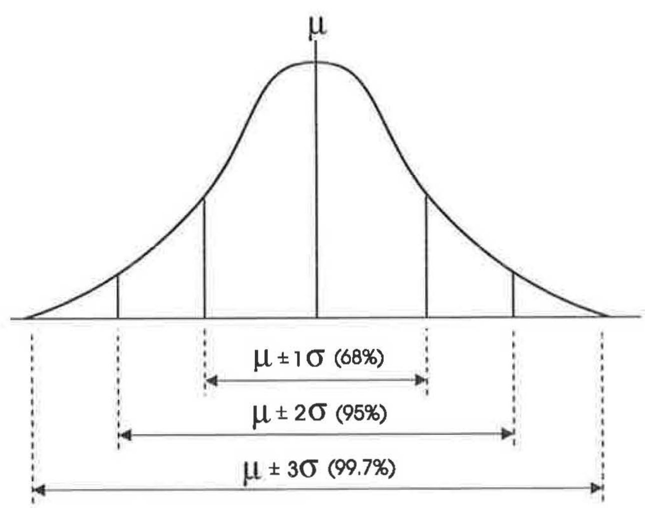

FIGURE 4 Relationship between standard deviation and areas under the normal curve.

IMPORTANCE OF RANDOM SAMPLING WHEN MEASURING VARIABILITY

Since samples are used to estimate population parameters, it is important that the properties of the sample represent the properties of the population. Proper sample selection is essential. An important concept in the selection process is the use of random sampling. Random Sampling is a procedure in which any individual measurement in the population is as likely to be included as any other, e.g., every portion of a compacted roadbed has an equal chance of being sampled for testing. The alternative to random sampling is based on selective sampling in which the person doing the sampling uses "judgment" in selecting where or when to take the sample. Judgment sampling may be biased, either underestimating or overestimating the true variability, depending on how the sampling is done. If the true variability is underestimated and specification limits are based on the underestimated value, the specification limits will be tighter than appropriate. If the true variability is overestimated, the specification limits will be more liberal than they should be. In either case, the true variability will not be as accurately estimated as when done using a random sample. Using a variability obtained under nonrandom sampling conditions for establishing specification limits will likely result in limits that are not desirable.

Stratified random sampling is a variation of random sampling in which the population to be sampled is divided into equal subpopulations, usually called sublots, and a random sample is taken from each subpopulation. This is a valid method of obtaining a random sample.

There are occasions in production quality (process) control activities in which systematic or selective sampling is a valid procedure. An example of the use of selective sampling as a quality control technique is the validation or check of a test result indicating that the process is out of control or nearly so. Rather than wait for the next random sample (which may be several hours away), it is often prudent to select a sample quickly to determine if the process is truly out of control or if an extraneous source of variability caused the aberration. The results of this test should be useful to the quality control technician in deciding whether some modification of the process should be made or not. However, measurements obtained under these conditions should *not* be used to estimate the variability of the population.

SOURCES OF VARIABILITY

As mentioned above under variance, variability has many sources or components. When the standard deviation of a population is measured, it is the overall standard deviation σ_0 that is obtained. This is the sum of all the individual "internal" standard deviations discussed below. The overall standard deviation is the primary value that should ultimately be related to the specification limit, within the time frame defined by the lot. The lot is defined as the time, area, volume, or length over which the material or construction is judged for acceptance or over which the quality control limits are established. The individual sources of variability should never be used by themselves to determine the specification limit.

The explanation of Components of Variability is covered very well by Willenbrock in *A Manual for Statistical Quality Control of Highway Construction (30)*. A shortened version of Willenbrock's discussion is quoted below and applies to construction processes as well as to materials.

> There are five components of variation of material characteristics that should be discussed. An understanding of the relationship and interaction between them will indicate how the overall variation (i.e., the variation that must be considered when specifications for a particular material are being developed) may be determined. The types of variation discussed are:
>
> 1. Inherent variation,
> 2. Sampling and testing variation,
> 3. Within-Batch variation,
> 4. Batch-to-Batch variation, and
> 5. Overall variation.

In the development of a specification, each component should be examined for 1) the number of other methods of analysis and 2) good judgment to ensure that each individual component does not bias the overall variation and ultimately the specifications. If the components are excessively variable, every effort should be made to reduce the variability. On the other hand, if the variability of the components is small, they may cause the specification to be too restrictive. In all cases, these components should be identified and quantified in order to determine the source and magnitude of the variation.

Inherent Variation

The inherent variation is the true random variation of the material. It is a function of the characteristics of the material itself. It may vary in magnitude and it may be surprising to realize that it is one of the smallest sources of variation. This source of variation cannot, however, be used by itself as the specification limit. Inherent variation, like other sources of variation, can only be determined by the process of sampling and testing, and it should be recognized that this sampling and testing will introduce additional sources of variation.

Sampling and Testing Variation

The sampling and testing components are actually separate sources of variation. However, they are often combined into one source of variation.

Sampling variation is a function of sampling technique and is detected when a sample increment taken from one part of a batch will not indicate the same test result as one taken from another part of the same batch.

Testing variation is the lack of repeatability of test results between test portions, which may include the effects of reducing sample increments to test portion size. Operators, equipment condition, and calibration and test procedure are a few of the factors that can cause high testing variations.

Sampling and testing variations are sometimes difficult to separate from other sources of variation because samples have to be taken and tests have to be made on a material to determine the variations. As a result, they become an integral part of the overall variability.

Within-Batch Variation

Variation within a batch depends on the magnitude of the difference in the measurements between two increments that are taken from the same batch. It should be noted that the same thing was said about sampling variation. Sampling variation is a function of sampling technique; within-batch variability is a function of the consistency of the process. Classic examples of within-batch variation are aggregate segregation, slump change from the front of a load to the back, and variation in core depths of a concrete pavement for adjacent cores in the same location.

Batch-to-Batch Variation

This is usually the largest source of variation in any process. It represents the difference in test results from one batch to other batches of the same material from the same process. It is always caused by the process and is greatest when the process is called "out of control." To detect this type of variation it is necessary to expose the process to sampling for a long period of time.

Overall Variation

The sum of all the individual sources of variation is called the overall variation. It becomes the primary consideration when establishing specification limits. It is very important to remember that all the sources of variation must be included in order to determine specification limits.

It is important to reiterate that the overall variation has a source of variability due to time. Since all the sources of variability must be contained in the overall variation, the time frame over which the variation is measured is important when establishing the specification limits. The standard deviations contained in the following chapters are overall variations unless otherwise noted. However, the time frame over which the overall variation is measured often is often not stated in the references and therefore not known.

An example of the relationship of the inherent (material), testing, sampling, and overall variation with the variances being additive is shown below for PCC strength. The addition of the variances allows the standard deviation to be calculated. This example is taken from *Quality Assurance in Highway Construction (12)*.

$$\sigma_0^2 = \sigma_t^2 + \sigma_s^2 + \sigma_m^2 = 1173^2 + 1628^2 + 2140^2$$

$$\sigma_0^2 = 1{,}375{,}929 + 2{,}650{,}384 + 4{,}579{,}600$$

$$\sigma^2_0 = 8{,}605{,}913 \text{ kPa}^2$$

$$\sigma_0 = 2{,}932 \text{ kPa}$$

where

σ_0^2 = the overall variance,
σ_t^2 = the testing variance,
σ_s^2 = the sampling variance,
σ_m^2 = the inherent (material) variance, and
σ_0 = the overall standard deviation.

The geometric relationship among the sources of variability are shown in Figure 5.

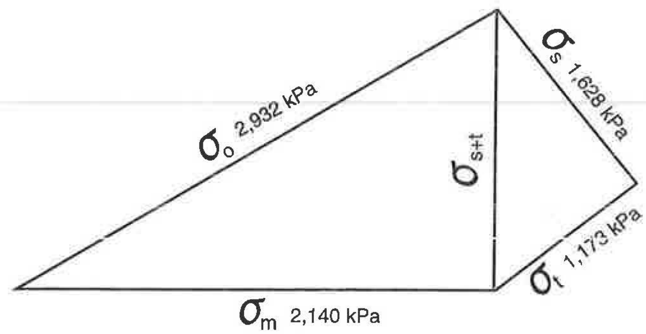

FIGURE 5 Relationship among testing, sampling, inherent, and overall variation.

As Stroup-Gardiner et al. rightly emphasized, it is important to maintain a consistent sampling and testing program so that the sampling and testing variation does not unduly increase the estimates of the within-batch, batch-to-batch, or overall variations *(4)*.

PRECISION STATEMENTS

Precision statements for test procedures are very useful in helping practitioners know the magnitude of variability to expect between test results when the test method is used in one or more laboratories. ASTM E 177 "Standard Practice for Use of the Terms Precision and Bias in ASTM Test Methods" discusses the concepts below in greater detail.

The *precision* of a measurement process relates to the closeness of agreement between test results obtained under prescribed *like conditions* from the measurement process being evaluated. The precision of the measurement process will depend on what sources of variability are purposely included in the establishment of the precision data. For instance, time may be a factor that affects the test result. The experimental design used to establish the precision statement must stipulate over what time period the test results must be obtained. The precision statement would then be appropriate for this time period. For this reason, it is rare that a precision statement contains sufficient sources of variability to be used as the basis for establishing specification limits *(5)*.

Often, the term *accuracy* is confused with precision. Accuracy relates to the closeness of agreement between the average of one or more test results and an accepted reference value. Accuracy may be thought of as an absence of *bias*, which is related to a consistent or systematic difference between a set of test results from a process and the true value, or reference value, of the property being measured.

A bull's-eye target is often used to explain precision, accuracy, and bias. The series of targets shown in Figure 6 illustrates the differences between them.

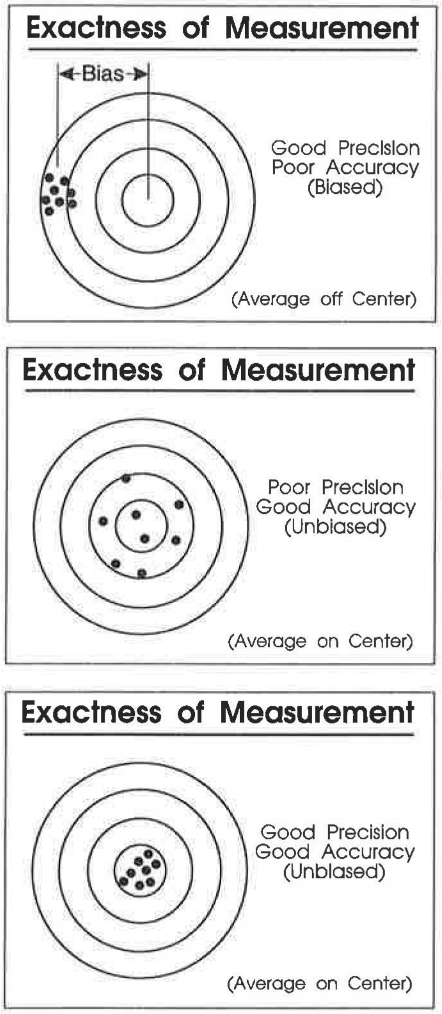

FIGURE 6 Precision, accuracy, and bias.

Within-Laboratory Precision

Within-laboratory precision is sometimes called single-operator-day-apparatus precision. Variability is established using one well-trained operator on one set of equipment. Two or more test results are obtained in a short period of time during which neither the equipment nor the environment is likely to change appreciably. The variability is intended to be due primarily to small changes in equipment, calibration, reagents, environment, and/or operator procedure, and possibly to some heterogeneity in the material tested. The last variable is intentionally kept small by the use of test specimens from material that is reasonably uniform. This information is typically obtained under what is often called "split sample" conditions.

In order to obtain the *repeatability* of the test method, a pooled (combined statistically) within-laboratory precision is obtained using one operator, one day, one set of equipment, and one material in each of several laboratories in an interlaboratory study.

Difference Two-Standard-Deviation Limit (d2s) is also sometimes found in association with within-laboratory precision. This difference is the magnitude of the largest difference (not to be exceeded more than 1 out of 20 times) between the two test results obtained on the same day by one operator using the same equipment from the same material. In other words, approximately 95 percent of all pairs of test results under the above-mentioned conditions can be expected to differ by no more than this amount. This value is of particular use when determining the ability of an operator to repeat results or when determining whether the testing device is in calibration.

Between-Laboratory Precision

A larger variability exists between laboratories testing reasonably uniform samples of the same material because each laboratory has its own operator, apparatus, and environmental conditions. The variability of the test results is used to calculate the between-laboratory precision which, when based on a single test result from each laboratory, is also called the *reproducibility* of the test method. It is important to keep in mind that this definition refers to the testing of nearly identical samples of the same material.

Similar to the above Within-Laboratory Precision discussion is a *Difference Two-Standard-Deviation Limit* (d2s), sometimes found in association with between-laboratory precision. This difference is the magnitude of the largest difference (not to be exceeded more than 1 out of 20 times) between two test results obtained by two operators using two pieces of the same type of equipment from the same material. In other words, approximately 95 percent of all pairs of test results under the above-mentioned conditions can be expected to differ by no more than this amount. This value will always be as large as, and generally larger than, that obtained from the within-laboratory d2s value because the between-laboratory value contains not only the within-laboratory variability but also additional sources of variability. This value is of particular use when comparing test results from the same material from two different laboratories, such as within the same testing agency or between a DOT laboratory and a contractor laboratory.

An example of a precision statement is shown in Table 3, ASTM D 2041 "Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures."

Round-Robin Testing

ASTM undertakes an interlaboratory study whenever a precision statement is developed (discussed in detail in ASTM E-691 "Conducting an Interlaboratory Study to Determine the

TABLE 3

PRECISION STATEMENT FOR ASTM D 2041 "THEORETICAL MAXIMUM SPECIFIC GRAVITY AND DENSITY OF BITUMINOUS PAVEMENT MIXTURES"

Test and Type Index	Standard Deviation (1s)	Acceptable Range of Two Results (d2s)
Single-operator precision	0.0040	0.011
Multilaboratory precision	0.0064	0.019

Precision of a Test Method"). This standard suggests that at least 30 laboratories be used to establish the necessary information although this is often impractical. Round-robin testing is another term for interlaboratory testing and is a desirable practice for any agency with multiple laboratories. This allows the determination of the typical variability for the laboratories involved in the testing and identifies any laboratory that may exceed the typical or standard variability established by the agency.

POTENTIAL CHANGES IN VARIABILITY RELATED TO TECHNOLOGICAL IMPROVEMENTS

Variabilities have been measured for many materials and construction procedures since the 1960s. Technological and testing improvements for the last several years makes it reasonable to expect that the overall variability of many products and processes has decreased. Another possible reason that the magnitude of the overall variability may have decreased is the highway community's increased awareness and recognition of variability. For example, in 1968 the Virginia DOT found that the typical standard deviation of asphalt content determined through the Reflux extraction test was 0.25 percent *(26)*. Studies done more recently indicate that the typical standard deviation using the same test is now about 0.20 percent; resulting in a 20-percent reduction in the overall variability *(27,28)*. Possible reasons for this reduction in variability are:

- Improvement in asphalt mix production due to updated plants and automated weighing systems;
- Awareness of the importance of variability which was emphasized by asphalt content acceptance programs that included standard deviation.

STATISTICAL TESTS TO COMPARE SAMPLE DATA SETS

It is often desirable to compare sample statistics from two sources. The National Quality Improvement Task Force on Quality Assurance developed an *AASHTO Implementation Manual for Quality Assurance* to provide guidance for implementing SQA specifications (*31*). One suggestion was to use the greatest number of test results available to ensure making the best decision regarding specification compliance. This allows the DOT to combine contractor and DOT test results under certain stipulated conditions. These conditions state that the tests must be performed on the same type equipment using the same test procedure, and that the contractor test results should be validated. One way of validating the test results is to determine if the contractor and DOT tests performed on the same material indicate comparable sample statistics. In other words, what is the probability that the two sets of data come from the same population? This can be done by using two statistical tests: one for comparing the two variabilities, as measured by the sample variances; and one for comparing the two averages, as measured by the samples averages. The first statistical test is the F-test, and the second is the t-test. The details of these statistical tests are beyond the scope of this synthesis, but a computer program developed for FHWA Demonstration Program 89, and the procedures contained in the above mentioned report provide this information (*31,32*).

RELATIONSHIP AMONG VARIABILITY, SPECIFICATION LIMITS, AND PERFORMANCE

Two relationships among variability, specification limits, and performance are of particular importance. The first is the relationship between an acceptable process variability and the specification limits governing that process. The second is the relationship between the process variability, the ensuing specification limits, and performance (when one exists). In this instance, one measure of performance that is often used is life-cycle costs.

Many specification limits have been developed according to the principle that tighter limits will force contractors to produce better products. This is a probable misconception and may lead to claims and/or continuous arguments between the contractor and DOT. It is far better to determine an acceptable process variability and use that variability in establishing the appropriate specification limits. The variability used in establishing the limits must come from data obtained in a random sampling procedure. The location and specific method of taking the sample must be constant. The test method must be stated and followed closely in all the samples that are used to establish the variability. In making decisions regarding the acceptability or unacceptability of the product (lot) in the specification, it is desirable to test by lot size. These decisions are often best accomplished in a special study involving a representative number of contractors/suppliers in order to determine an acceptable range in the process variability. The variability will vary from contractor to contractor, from plant/site to plant/site, and from time to time. It is the specification writer's responsibility to establish an acceptable magnitude of variability. Many of the considerations listed below become irrelevant if the relationship between variability and performance has been established. Until that time, the decision regarding what magnitude of variability to use should consider the following:

- Has the process sampled produced acceptable production? If not, variability measured from unacceptable production should not be included in the analysis.
- Are some of the variability data from one or two projects appreciably different from the majority? If so, the reason for the difference should be sought and, if appropriate, these data may be excluded.
- Can the contractors with the higher variability be expected to reduce their variability in an economic way?

Once the variabilities have been compiled, the specification writer should choose a "typical" variability on which to establish the specification limits. This variability is often chosen slightly below the median variability. This determines that the most variable contractors will have to improve their process capability to the industry norm. On the other hand, if the specification is properly written, there is still a strong incentive to encourage the contractors with excellent control to continue to operate at that level.

Different viewpoints exist on the importance of determining the process variability in some types of specifications, which are addressed in detail in chapter 6. It is considered good practice to obtain a realistic measure of the variability of the process over the time frame in which it will be applied, in the specification, regardless of what type of specification is used.

Establishing the process capability and the resultant specification limits is not a one-time procedure. A database should be established to accumulate the variabilities and should be reviewed periodically to determine whether any significant changes in the variability are taking place. If any changes in the sampling location, test procedure, or other factors that relate to the sources of variability are made, the variability related to the new sampling/testing scheme should be measured.

The second relationship addresses many products for which a relationship exists between the variability and performance. Although there are other important relationships in Performance Related Specifications (PRS), the relationship between performance and variability cannot be ignored. An example of this is the asphalt content of an asphalt concrete mixture. If the asphalt content is too low, the mix will not be sufficiently durable; if the asphalt content is too high, it will not resist permanent deformation. With a material such as this, maintaining a reasonable variability is important to performance. Using this variability as a basis for the specification limits, which in this case are related to performance, will provide all parties involved with a better understanding of the specification limits and the "comfort zone" will be improved.

PRESENT PRACTICE OF DETERMINING TOLERANCES FOR SPECIFICATION LIMITS

A questionnaire was sent to all state departments of transportation requesting information on variability data obtained over the last 20 years, and on several related subjects. A copy of the questionnaire is in Appendix B. Forty-seven states and the District of Columbia responded to the questionnaire. One of the questions asked was, which of several procedures are used for setting specification limits? Of the 48 replies, only three did not respond to this question. The response by number of DOTs replying to each procedure is shown in Table 4.

TABLE 4

PRESENT DOT PRACTICES OF SETTING SPECIFICATION LIMITS (45 of the 48 respondents replied to this question)

DOT Practice	Number of DOTs Using
Experience	42
Engineering Judgment	40
Variability From Research Studies	26
Variability From Pilot Projects	24
Variability From Typical Contracts	27
Tolerances From Other Agencies	42
AASHTO/ASTM Precision Statements	32
Other	1

The tendency discernible from these data is that the DOTs use experience, engineering judgment, tolerances from other agencies, and standard precision statements more often than they use variability data from studies or projects. While this result is not surprising, it indicates that many specification limits are still being set the same way as the ones used in the AASHO Road Test almost 40 years ago. This reinforces the belief that the tolerances set in this manner do not properly relate to process capability. The questionnaire wording did not make it possible to determine whether the AASHTO/ASTM precision statements were the only values used to determine the tolerances. The use of precision statements cannot be faulted *if* the statements are used as a guide and the tolerances accommodate process variability and sampling and testing variability. *However, if the precision statements are used by themselves to establish the specification limits, they are being misapplied and a specification developed using only this value has little chance of being met.*

Use of Questionnaire Responses

Other questions asked what recent studies have been done to quantify typical variabilities of materials/construction, what materials/construction characteristics need updating and which characteristics are the respondents uneasy about, and whether incentive and disincentive pay schedules are used and if so, how large is each. The responses from the questionnaire provided the updated information in the chapters that follow. Other research and established databases also contributed.

CHAPTER THREE

TYPICAL VARIABILITY FOR SOILS AND AGGREGATE BASE

SOILS

The variability of soils and embankments is more difficult to quantify than most highway materials. Published variability data on soil properties, for instance, are so sketchy and the magnitude so large that they were of little value in this synthesis; recent variability data could not be found. Compaction is the soil property that has received the most attention from the standpoint of quantifying the variability. As McMahon indicates in one part of *Quality Assurance in Highway Construction*, the variability of the material itself impedes the use of overall standard deviation as a measure of contractor performance (*12*). As the composition of the material becomes more variable, results of the compaction process also become more variable. Data from a California report indicate how the variability can differ from soil to soil; standard deviations of relative compaction on three projects were 2.44, 3.09, and 5.52 percent for a homogeneous, fine-grained soil, a soil with intermediate variable properties, and an extremely heterogenous soil respectively (*13*).

In an Indiana study, Williamson found that the standard deviation for relative compaction on three projects varied from 5.7 to 7.5 percent depending on soil type and method of test (*14*). An Alabama report contains a standard deviation for relative compaction of 3.7 percent and a standard deviation for moisture content of 3.6 percent (*15*). In a report from Utah, the sampling and testing variability, as well as overall standard deviation, are provided for relative percent compaction (*16*). The sampling and testing standard deviation for the sand cone method on embankments was 1.9 percent and the overall standard deviation was 4.5 percent. Calculating the source of variability due to sampling and testing relative to the overall variability by using the respective variances, the sampling and testing variability is determined to be 17 percent of the overall variability. For the nuclear density gauge, the sampling and testing variability (standard deviation of 1.5 percent) is determined to be 11 percent of the overall variability (standard deviation of 4.6 percent).

AGGREGATE BASE

Gradation

Many DOTs and aggregate producers have established databases that accumulate population parameters for several products. The information listed below is for aggregate base material from several sources and for various sieve sizes. The standard deviations apply to the percent passing the particular sieve listed.

PennDOT Aggregate Study

In 1984, the Pennsylvania Transportation Institute conducted a study for PennDOT to determine acceptance criteria for aggregate gradation. As part of this study, the variability of PennDOT 2A aggregate, which is used as unbound aggregate subbase, was determined (*33*). The typical standard deviations found in this study are shown in Table 5, but this report is also a good source of information for other aggregate sizes.

TABLE 5

TYPICAL STANDARD DEVIATIONS FOR PENNDOT SUBBASE AGGREGATE GRADATIONS (*16*) (Percent Passing)

Sieve Size	19 mm (3/4")	9.5 mm (3/8")	4.75 mm (#4)	1.2 mm (#16)	75 µm (#200)
Gravel	6.8	8.3	6.2	3.6	1.2
Limestone	3.5	5.6	5.2	3.4	1.4

Virginia 1994 Aggregate Base Data

In 1995, Virginia revised its SQA Aggregate Base Gradation Specification, originally developed in 1970. To do this, statewide 1994 aggregate base data were analyzed for variability memorandum from C.S. Hughes to R.D. Horan, VDOT Assistant State Materials Engineer. "Tolerances for Quality Index Specification for Aggregate Base Gradation," February 2, 1995). The data in Table 6 are for the material designated as #21B, which requires pug-mill mixing; these data were taken from 58 plants and 8,532 samples. The trend was for the standard deviations to decrease from those obtained at the time of the original specification development.

TABLE 6

TYPICAL VDOT STANDARD DEVIATIONS FOR THE GRADATION OF AGGREGATE BASE MATERIAL

	Percent Passing				
Sieve Size	25 mm (1")	9.5 mm (3/8")	2.0 mm (#10)	425 µm (#40)	75 µm (#200)
Design Range	85–95	50–69	20–36	9–19	4–7
Standard Deviation	1.9	4.2	2.8	1.7	0.9

Data From Aggregate Producers

Vulcan Materials is a national aggregate producer; two of its divisions (one in the Southeast and one in the Midwest) were contacted in an effort to obtain typical variability under a variety of conditions and materials. The data shown in Table 7 were collected by Vulcan Materials in late 1993 and 1994 under the conditions and for the materials indicated (personal

TABLE 7

PRODUCER'S VARIABILITY DATA ON AGGREGATE GRADATION (Percent Passing)

		Standard Deviation					
Sieve Size	n	19 mm (3/4")	4.75 mm (#40)	2.3 mm (#8)	2.0 mm (#10)	250 µm (#60)	75 µm (#200)
Granite, Not Pug-mill Mixed	106	3.9	3.3	3.7	3.7	3.1	1.2
Limestone, Not Pug-mill Mixed	65	1.8	2.3	1.7	1.6	1.5	1.0
Limestone, Pug-mill Mixed	53	0.9	2.8	2.0	1.7	1.0	0.7
Limestone, Not Pug-mill Mixed	163	–	6.7	2.7	1.5	–	–
Glacial Gravel, Pit-run, rounded	25	–	7.7	3.3	0.9	–	–
Glacial Gravel, Pit-run, crushed	2	–	6.8	2.5	1.2	–	–

TABLE 8

AGGREGATE BASE GRADATION VARIABILITY DATA FROM THE PLANT AND FROM THE ROADWAY FOR A NORTH CAROLINA PRODUCER (Percent Passing)

		Standard Deviation					
Sieve Size	n	25 mm (1")	12.5 mm (1/2")	4.75 mm (#4)	2.0 mm (#10)	4.25 µm (#40)	75 µm (#200)
Plant Samples	169	2.2	4.3	3.4	3.0	3.2	1.0
Roadway Samples	180	1.8	4.3	4.2	4.3	3.3	1.3

TABLE 9

VIRGINIA PRODUCER'S VARIABILITY DATA ON SELECTED GRADATION

		Standard Deviations				
Sieve Size	n	4.75 mm (#40)	2.0 mm (#10)	4.25 µm (#40)	75 µm (#200)	L.L.
Design Range (% Passing)	–	–	25–55	16–30	4–14	25 Max.
Granite	30	4.3	3.4	1.9	1.1	1.0
Limestone	21	4.5	3.0	1.7	1.4	1.2
Traprock	68	4.6	3.0	1.7	0.9	1.2

communication with Kelly Fikes, Vulcan Materials, Georgia Division, January 12, 1995; and Chuck Sanders, Illinois Division, March 6, 1995). The first three materials are aggregate base from the southeastern United States; the last three are clean stone (no fines) from the Midwest. The last two aggregates are natural glacial aggregates.

Another aggregate producer, Martin Marietta, provided variability data on aggregate base gradation obtained in 1994 from samples taken by NCDOT inspectors at the plant and also from samples taken by the DOT from the same production period from the roadway. The data shown in Table 8 are for a granite aggregate that was not pug-mill mixed (personal communication with Sam Johnson, Martin Marietta, North Carolina Division, January 13, 1995).

A Virginia aggregate producer provided variability data obtained in 1994 from three plants producing Select Material (CBR-30 Material) (personal correspondence with Randy Weingart, Luck Stone Co., Richmond, Va., January 12,1995). This material is used primarily as a foundation for subbase material. The standard deviations are shown in Table 9.

As the above variability data show, there are ranges in standard deviations and general tendencies from material to material and process to process. Using these data indiscriminately increases the possibility of arriving at standard deviations of the material and process that are different from the data given above. Any agency undertaking the development of an SQA specification could safely use the variability data shown above as a starting point. However, the applicable variability data should be verified under the particular conditions of use.

Compaction

Relative compaction variability data were obtained for aggregate bases and subbases from the same Utah study mentioned above under soils (*16*). The sampling and testing standard deviation for the sand cone method on aggregate base was 1.5 percent. By using the sampling and testing variance and overall variance, and by calculating the source of variability due to sampling and testing, this source of variability is determined to be 25 percent of the overall variability, represented by a standard deviation of 2.9 percent. For the nuclear density gauge, the sampling and testing standard deviation was 1.1 percent, which is determined to be 16 percent of the overall standard deviation of 2.9 percent.

CHAPTER FOUR

TYPICAL VARIABILITY FOR ASPHALT CONCRETE

The largest use of SQA specifications in the United States has been in the area of asphalt concrete. This probably results from a perception that SQA specifications for asphalt concrete are easier to implement because the test results can be obtained in a more timely manner than for portland cement concrete. To establish realistic specification limits, several DOTs started in the 1960s to measure the variability of such asphalt concrete properties as asphalt content and gradation (*7,8,10,17–21,25,34*). More recently, the variability of laboratory volumetric properties, air voids after roadway compaction, and asphalt content have been measured frequently (*26,27,35–38*). Several states are following a suggestion in the *AASHTO Implementation Manual for Quality Assurance* to use both DOT and contractor test results in the acceptance decision. At least two DOTs have already issued reports that follow this suggestion. (*27,39*).

ASPHALT CONCRETE MATERIALS

Gradation

Many of the variability studies on gradation for asphalt mixtures were performed in the 1960s (see Table 10). However, more recent results from Washington (1993) and Pennsylvania (1982), and information on the questionnaire, show that the typical standard deviations of aggregate gradation taken from extraction tests have not changed appreciably (*40,41*). The WSDOT data are drawn from a single project (n = 81) on which a newly developed SQA specification was used. The PennDOT data were obtained on one project (n = 49) which, combined with several other projects, served as a basis for establishing specification limits for an SQA specification. The Indiana DOT data, provided in the response to the questionnaire, summarizes the results over the 3-year period from 1987 to 1989.

It first appears that the variability of gradations from the extraction test may have decreased slightly over the 20-year period covered in Table 10, but it is more likely that the differences are related to geography rather than time.

The variability information from the Indiana DOT contains data from both mixtures with virgin aggregate and mixtures with approximately 20 percent recycled asphalt pavement (RAP). There is no significant difference in the standard deviations of the two types of mixtures.

Cold Feed Gradation

With the current emphasis placed on Quality Control, one of the high priority control points for asphalt mixtures is the plant cold feed. Hudson and Waller reported in NCHRP Report 69 cold feed variability data for four plants (*42*). The standard deviations for these plants are given in Table 11. Plants number 1, 2, and 3 produced surface mixtures and plant number 4 produced a binder mixture. [These data from plants 1 through 4 were obtained in 1969. The standard deviations appear to be excessively large in some cases. These data should be used with caution.] More recent data were sought from a Midwest asphalt contractor who supplied the cold feed data obtained in 1993; plant 5 results are from a binder mix and plant 6 results are from a surface mix. (personal correspondence from

TABLE 10

TYPICAL AGGREGATE GRADATION VARIABILITY FROM EXTRACTION TESTS (Percent Passing)

Agency: Source	Agency: Year	Standard Deviation: 19 mm (3/4") or 12.5 mm (1/2")	9.5 mm (3/8")	6.33 mm (1/4") or 4.75 mm (#4)	2.3 mm (#8) or 2.00 mm (#10)	850 µm (#20) or 600 µm (#30)	425 µm (#40) or 300 µm (#50)	80 µm (#40) or 300 µm (#50)	75 µm (#200)
Surface Mixtures									
Arkansas*	1993	1.7	2.6	2.8	1.7	1.3	1.3	1.1	0.6
Washington *(40)*	1993	1.6	2.5	3.0	2.4	–	1.6	–	0.5
Pennsylvania *(41)*	1982	2.3	4.4	3.4	2.5	1.9	1.5	1.2	1.0
BPR *(34)*	1969	1.4	2.5	3.5	2.8	2.1	1.6	1.2	0.9
Virginia *(25)*	1968	–	1.9	3.3	3.2	2.1	1.6	1.2	0.9
Binder or Base Mixtures									
Indiana*	1989	3.8	–	3.0	–	1.3	–	–	0.4
BPR *(34)*	1969	4.3	4.9	3.9	2.5	2.2	1.7	1.2	0.9

*Data from questionnaire responses.

TABLE 11

TYPICAL AGGREGATE GRADATION VARIABILITY FROM COLD FEED SAMPLES

		Standard Deviation, Percent Passing							
Plant	n	9.5 mm (3/8")	4.75 mm (#4)	2.3 mm (#8)	1.2 mm (#16)	600 μm (#30)	300 μm (#50)	150 μm (#100)	75 μm (#200)
1s (*42*)	36	1.1	8.4	9.6	9.2	6.9	3.6	2.4	1.5
2s (*42*)	36	0.8	3.9	4.7	5.7	4.3	3.9	2.8	1.5
3s (*42*)	36	2.3	6.5	5.8	4.9	4.1	2.6	1.4	0.9
4b (*42*)	36	9.4	8.4	7.9	6.1	4.6	2.9	1.5	0.5
5b	32	3.2	3.3	3.2	3.3	1.8	1.0	0.6	0.6
6s	21	2.4	2.1	1.8	1.3	1.0	0.7	0.6	0.5

s is a Surface Mix and b is a Binder Mix

Jack Weigle, Payne and Dolan, Inc. Waukesha, Wisconsin, April 3, 1995).

Table 11 shows that the standard deviations from the recent contractor Quality Control results (Plants 5 and 6) are generally lower than those obtained in 1969, with the exception of the #200 sieve results of Plant 4. This reduction in variability may be partly attributable to recent increases in responsibility and control for contractors in SQA specifications.

Asphalt Content

Many studies done until recently have involved the variability of asphalt content using extraction tests (*25, 34, 35, 41, 43*). The use of chlorinated solvents has become an environmental concern and emphasis has shifted to the use of nuclear gauges (*27,44–46*) for determination of asphalt content; the most recent test method is the use of a muffle furnace that removes the asphalt through burning.

The Center for Construction Materials Research at the University of Nevada-Reno did a study of the precision of ASTM D 2172 "Test Method for Quantitative Extraction of Bitumen from Bituminous Paving Mixtures," and ASTM D 4125 "Test Method for Asphalt Content of Bituminous Mixtures by the Nuclear Method" (*44*). The study compared precision statements from ASTM, AASHTO Material Reference Laboratory (AMRL) databases and a Round-Robin study. One of their findings was that

> The within- and between-laboratory standard deviations presented in the ASTM D2172 precision statement for the extraction methods are 0.18 and 0.29 percent, respectively. The same standard deviations for the AMRL data were 0.20 and 0.22 percent, respectively. The nuclear asphalt cement content gauges produce within- and between-laboratory standard deviations of 0.16 and 0.23 percent, respectively. The nuclear gauges appear to reduce the within-laboratory standard deviations. The between-laboratory standard deviation for these gauges is virtually identical to that for extractions (AMRL) (*44*).

This close agreement in testing variability is also reflected in the close overall variabilities.

The National Center for Asphalt Technology recently completed a preliminary study of the determination of asphalt contents by three methods: the ignition method using a muffle furnace, a nuclear asphalt content gauge, and an extraction process using the centrifuge method. The muffle furnace used in this study was a prototype that has since been refined (*46*). This study also included a round-robin test using an advanced version of the prototype in 12 laboratories; the "within-lab" standard deviation was 0.04 percent and the "between-lab" standard deviation was 0.06 percent. The standard deviations for this procedure are appreciably lower than those of the other methods mentioned above. Table 12 shows some typical standard deviations from several different sources.

TABLE 12

TYPICAL ASPHALT CONTENT VARIABILITY

Source	Year	Test	Std Dev, %
Arkansas*	1994	Extraction	0.21
Virginia (*27*)	1994	Extraction	0.18
Virginia (*27*)	1994	Nuclear	0.21
NCAT (*45*)	1994	Nuclear	0.19
NCAT (*45*)	1994	Centrifuge	0.44
NCAT (*45*)	1994	Ignition	0.30
Washington (*40*)	1993	Extraction	0.24
Colorado (*35*)	1993	Extraction	0.15
Kansas (*46*)	1988	Nuclear	0.27
Virginia (*26*)	1988	Extraction	0.19
Pennsylvania (*43*)	1980	Extraction	0.25
BPR (*34*)	1969	Extraction	0.28
Virginia (*25*)	1968	Extraction	0.25

*Data from questionnaire responses

It appears that the variability of this property decreases over time when the same test method is used. It is interesting to note that some of the overall standard deviations shown in Table 12 are lower than those given in the above mentioned ASTM Precision Statements. This should not be surprising, because the round-robin testing used to develop the variability in the Precision Statement is a pooled standard deviation of many different operators using many different pieces of equipment. Thus, for the sources listed above with lower overall standard deviations, the testing variability is well within the level of precision of the measurement process itself.

Two studies mentioned above that have compared DOT and contractor test results have been done by Alabama and Virginia. One of the properties compared is asphalt content. The Alabama report, which was instrumental in developing specification limits for their SQA specification, found for 1992 data a pooled standard deviation of nuclear asphalt content for

TABLE 16

AVERAGE STANDARD DEVIATIONS FOR ASPHALT CONCRETE PAVEMENT THICKNESS FROM NEW JERSEY *(57)*

Design Thickness mm (in.)	Average Thickness, mm (in.)	Standard Deviation, mm (in.)	C.V., %
Surface, 40 (1.5)	44 (1.73)	6.6 (0.26)	15.0
Surface/Binder, 50 (2.0)	57 (2.25)	8.4 (0.33)	14.7
Surface/Binder, 75 (3.0)	85 (3.37)	10.7 (0.42)	12.5
Base, 100 (4.0)	100 (4.00)	14.2 (0.56)	14.0
Base, 150 (6.0)	150 (5.99)	14.2 (0.56)	9.3

quality is very important. Often, only one measurement is made over a given distance and the single value is used as *the smoothness* value. Variability often is not determined. NCHRP Project 20-7, Task 53 assessed the state of the practice using profilographs to measure pavement smoothness *(58)*. In the discussion of results, it is pointed out that the method of reducing the data obtained with a profilograph is very important. "Since trace reductions are dependent upon operator skill and training, and upon the specifications by which reduction is performed, it is difficult to compare results from different studies." *(58)*

A literature survey done in Task 53 revealed the variability of computerized profilographs typically ranges between a standard deviation of 0.008 m/km to 0.016 m/km (0.5 to 1.0 in/mi).

One study was conducted by FHWA Central Federal Lands Highway Division using a California-type Profilograph *(59)*. A section of asphalt pavement that contained 19 sublots was sent to 25 individuals for data reduction. For analysis purposes, the 19 sublots were separated into the 9 smoothest sublots and the 10 roughest sublots. Standard deviations were measured on the 9 smoothest sublots with the values ranging from 0.027 m/km to 0.038 m/km (1.7 to 2.4 in./mi). It is interesting to note that the standard deviations generated by operator data reduction in this study are higher than those of the Task 53 summary.

An analysis was performed in 1994 by FHWA Western Federal Lands Highway Division on data obtained using a California-type Profilograph on 0.16 km (0.1 mi) segments. The pooled standard deviation of new construction dense-graded asphalt pavement was 0.030 m/km (1.9 in./mi); the pooled standard deviation of multi-lift overlay dense-graded asphalt pavement was 0.035 m/km (2.2 in./mi). It was concluded that no difference was found in the variability of the two types of construction. (personal communication with Bruce Wasill, FHWA Western Lands Highway Division, April 4, 1995).

A study conducted by the Center for Transportation Research at the University of Texas using the Ames and McCracken California-type profilographs found standard deviations of from 0.03 m/km to 0.026 m/km (0.2 to 1.6 in./mi) for the average of two results from the same profilograph (one from each wheel path) *(60)*. The report states that the two profilographs have similar repeatability and that the variability in roughness is related to the variance resulting from operator-profilograph interaction, operator-profilograph repeatability, and interpreter variability.

Another smoothness measuring device that has been used is the Mays Ride Meter. This device, typically mounted in a car, is purported to determine relative pavement smoothness quickly and inexpensively *(61)*. New Jersey conducted a study to determine, among other characteristics, the reliability of the device. This study found an overall standard deviation of 0.054 m/km (3.35 in./mi) and a standard deviation from day-to-day of 0.031 m/km (1.96 in./mi) *(61)*.

ERES Consultants analyzed initial pavement smoothness from several projects. One project of interest contained data from Arizona using the Mays meter to measure smoothness on a conventional asphalt pavement. The standard deviation was 0.034 m/km (2.1 in./mi) on 1-mile segments of a 22.5 km (14 mi) project constructed in 1973 (personal correspondence from Kurt Smith, ERES Consultants, Urbana, Illinois, March 24, 1995).

CHAPTER FIVE

TYPICAL VARIABILITY FOR PORTLAND CEMENT CONCRETE

Although SQA specifications for portland cement concrete (PCC) are not used by as many states as they are for asphalt concrete, some DOTs have established valuable databases and have implemented SQA specifications for PCC. In fact, New Jersey's specification for PCC pavement and structural concrete is the only performance-related specification presently being used (*62-64*). A 1994 survey found that 40 DOTs use smoothness specifications for PCC pavements and smoothness specifications for asphalt concrete pavements have been adopted by 24 DOTs (*65*).

Some engineers think that the variability of PCC used for paving may be different from that used in structural applications. Apparently, this is due to the widespread use of portable plants for the former and stationary plants for the latter. While the main emphasis of the variability information is on paving concrete, data were also found and are included for structural concrete.

PORTLAND CEMENT CONCRETE MATERIALS

A thorough study of PCC for paving was done in the mid 1970s by Arizona DOT (*66*). The data from this study are referenced throughout this section. One of the interesting aspects of this report is that two different methods of data accumulation were used; one consisted of a statistically designed experiment from which parameters for various specifications of paving concrete were measured; the other was the analysis of historical measurements on paving concrete obtained without random sampling. The data reported below for Arizona used random sampling, unless otherwise noted.

Most other recent variability data for PCC come from databases and unpublished variability studies done by DOTs and contractors. Much of the information was attached to the questionnaire for this synthesis.

Gradation

Coarse Aggregate

The Arizona data from the designed experiment of the report mentioned above analyzed sources of variability due to material (σ_m), sampling (σ_s), and testing (σ_t). For coarse aggregate, the σ_t for the top size sieve is appreciably larger than both σ_m and σ_s and also appreciably larger than σ_t for other sieve sizes. The larger the coarse aggregate, the larger the relative magnitude of σ_t. For example, for the coarse aggregate with a 50 mm (2-in.) top size, σ_t is about 66 to 67 percent, σ_s is 5 to 12 percent and σ_m is 22 to 27 percent depending on whether percent passing or percent retained is used to define the gradation. For the coarse aggregate with a 25 mm (1-in.) top size, the σ_t is about 27 to 29 percent, σ_s is 5 to 14 percent and σ_m is 56 to 65 percent, depending on whether percent passing or percent retained is used. One of the conclusions of the report is that because of the higher testing variation of the 50 mm (2-in.) top size aggregate, a larger sample, (i.e. a larger volume of material) should be taken.

One of the observations from this analysis states that "based on percent passing, the variations on any one sieve have a cumulative effect on the variations of all smaller sieves. On the basis of percent retained, the variations of material do not directly affect the subsequent sieves." The data come from both historical information and a statistically designed experiment to measure sources of variability.

Table 17 contains data on the variability of coarse aggregates used in PCC from Arizona and Florida (*66,67*). The Florida data come from a 1991 report of aggregates from selected concrete plants. The report contains data from both the mines (quarries) and from the plants; only the data from the mines were used (*67*).

Comparing the standard deviations obtained from random sampling with those obtained from project (non-random)

TABLE 17

VARIABILITY OF COARSE AGGREGATE FOR USE IN PCC MIXES (Percent Passing Sieve Size)

Source	Aggregate Size	Sieve No.	Standard Deviation,%
Arizona (*66*)*	Coarse	19 mm (3/4in.)	0.65–2.45*
Arizona (*66*)*	Coarse	12.5 mm (1/2in.)	2.30–6.14*
Arizona (*66*)*	Coarse	9.5 mm (3/8in.)	1.20–3.84*
Arizona (*66*)*	Coarse	4.75 mm (1/4in.)	0.95–1.64*
Florida (*67*)	57	12.5 mm (1/2in.)	5.5
Florida (*67*)	57	75 µm (#200)	0.2
Florida (*67*)	67	12.5 mm (1/2in.)	1.5

*Historical data

sampling indicated that the standard deviations for six of the seven sieve sizes for coarse aggregates were lower for those samples taken in a non-random manner compared to those taken randomly. No statistical test was used to determine if the magnitude of differences is statistically significant.

Fine Aggregates

The Arizona data from the designed experiment analyzed the same sources of variability for the fine aggregate as those mentioned above for the coarse aggregate. For the fine aggregate, the σ_t for the top size sieve (No. 4) is less than σ_m but larger than σ_s. However, the magnitude of σ_t is relatively constant for all sieves, 4.75 mm to 75 µm, (from the No. 4 to the No. 200) varying only from about 15 to 47 percent for percent passing and 10 to 40 percent for percent retained.

Table 18 contains data on the variability of fine aggregates used in PCC pavement construction in Arizona and Florida (*66,67*).

The following results were noted in the analysis of fine aggregate data from Arizona: when random sampling is used to obtain standard deviations, the standard deviations are lower for five of six sieve sizes than when non-random samples are used. The results were reversed when analyzing coarse aggregate.

Cylinder Strength

The data in Table 19 are from reports from Arizona, Illinois, and Pennsylvania (*66,68,69*) or from databases and variability studies on 28-day cylinder strength studies provided with the completed questionnaire. A result is reported for PCC strengths as the average of two cylinder strengths. The main emphasis of this material property is paving concrete, but data for structural concrete were found in the compilation and are included. The Arizona data were obtained from the random sampling portion of the study, which produced a slightly lower standard deviation than from data acquired in a non-random manner. The Georgia data are for cylinders from three paving projects paved in 1992 and 1993. The result is a pooled standard deviation of 304 single cylinders taken from the three projects. (personal correspondence from Wouter Gulden, Georgia DOT, June 5, 1995). Results are shown in Table 19.

Richard Weed, NJDOT, provided an additional perspective on these strength values, by stating on the questionnaire that a typical standard deviation associated with a lot is about 2070 kPa (300 psi). In this instance, a lot would be a day's production or less. The influence of time as a source of variability is apparent from the data in Table 19, which generally represent from several months to a year's production. There is also a

TABLE 18

VARIABILITY OF FINE AGGREGATE USED IN PCC MIXES (Percent Passing Sieve Size)

Source	Aggregate Size	Sieve Size	Standard Deviation,%
Arizona (*66*)*	Fine	4.75 mm (#4)	0.50–2.38*
Arizona (*66*)*	Fine	1.2 mm (#16)	0.96–2.28*
Arizona (*66*)*	Fine	300 µm (#50)	0.64–1.64*
Arizona (*66*)*	Fine	150 µm (#100)	0.32–0.91*
Florida (*67*)	Screenings	1.2 mm (#16)	1.86
Florida (*67*)	Screenings	75 µm (#200)	0.24
Florida (*67*)	Sand	600 µm (#30)	0.42
Florida (*67*)	Sand	75 µm (#200)	0.09

*Historical data

TABLE 19

TYPICAL STANDARD DEVIATIONS FOR 28-DAY PCC CYLINDER STRENGTHS (kPa)

Source	Year	Class	Average	Std Dev.	Coefficient of Variation, %
Georgia	1993	Paving	32896	3351*	10.2
New York	1993	Gen Structural	30428	5213	17.3
New York	1993	Thin Structural	33275	5364	16.3
New York	1993	Pumping	34744	5392	15.8
Illinois (*68*)	1992	Gen Structural	30807	2689	8.7
Maine	1992	Gen Structural	35661	4054	11.4
Maine	1991	Gen Structural	34123	4551	13.3
Virginia	1988	Gen Structural	33399	4551	13.6
Virginia	1988	High Strength	39763	4371	11.2
Arizona (*66*)	1974	Paving	30159	4151	13.8
Pennsylvania (*69*)	1972	Gen Structural	32062	4826	15.1

1 psi = 6.9 kPa

*Standard deviation based on single 28-day cylinders.

(All unreferenced data are from questionnaire responses) considerable difference in variability among standard deviations that represent lengthy production periods. Furthermore, from the limited data of 28-day cylinder strength for PCC used in paving, it appears that the variability of both paving and structural concrete can vary widely. This emphasizes the need to establish a typical variability under the conditions of anticipated usage.

Beam (Flexure) Strength

This measurement of PCC beam strength is controversial for several reasons; one is that the difference in variability depends on such factors as beam size, aggregate size, moisture content, and method of loading (*70*). Riley refers to a Midwestern state that uses a mid-point loading obtained an average flexure strength of 5633 kPa (817 psi) and a standard deviation of 717 kPa (104 psi), resulting in a coefficient of variation (C.V.) of 12.7 percent; and another Midwestern state that uses third-point loading that obtained an average flexure strength of 4690 kPa (680 psi) and standard deviation of 480 kPa (70 psi) resulting in a C.V. of 10.4 percent. The moisture content of the beams has also been stated as a source of variability (*71*).

The Pennsylvania study found an average flexural strength of 5450 kPa (790 psi) and standard deviation of 690 kPa (100 psi) for a C.V. of 12.7 percent (*69*).

An Indiana contractor provided both quality control tests and DOT acceptance tests for flexure strength on one contract. The results are based on the average of two beam breaks. The quality control tests produced an average strength of 4523 kPa (656 psi) and standard deviation of 228 kPa (33 psi) for a C.V. of 4.97 percent. The Indiana DOT data on the same 26 lots of material had an average of 32 103 kPa (656 psi), a standard deviation of 262 kPa (38 psi) for a C.V. of 5.76 percent. (personal communication from Pete Capon, Rieth-Riley Company, Goshen, Indiana, April 19, 1995).

Air Content

Both of the next two properties have traditionally been measured as screening tests for determining whether the plastic concrete should be placed on the basis of its having adequate durability and consistency properties (*72*). Table 20 shows air content data and the Rieth-Riley listings are from contractor quality control test results. In addition to the data from Arizona (*66*), Illinois (*68*), and BPR/New York (*72*), data were provided in the questionnaire responses. The data from Arizona indicated virtually identical standard deviations for both the random and non-random samples.

TABLE 20

TYPICAL STANDARD DEVIATIONS FOR AIR CONTENT (Percent)

Source	Year	Method	Standard Deviation,%
Illinois (*68*)	1993	Pressure	0.75—1.11
Rieth-Riley	1993	Pressure	0.53
New Jersey	1993	Pressure	0.75
Virginia	1988	Pressure	0.74
Arizona (*66*)	1974	Pressure	0.97
BPR/New York (*72*)	1969	Pressure	0.71–1.60
BPR/New York (*72*)	1969	Chace	0.76–1.60

Slump

This property is often used as a screening test to determine if the concrete is of the proper consistency (*72*). Information contained in Table 21 is from questionnaire responses or from the sources referenced. The Arizona data indicated a lower standard deviation for the random samples than for those taken non-randomly.

TABLE 21

VARIABILITY OF PCC SLUMP

Source	Year	Standard Deviation, mm (in.)
Illinois (*68*)	1993	25.1-31.2 (0.99–1.23)
New Jersey	1993	12.7 (0.5)
Virginia	1988	15.2 (0.6)
Arizona (*66*)	1974	15.2 (0.6)
BPR (*72*)	1969	12.7-22.9 (0–5-0.9)
Louisiana (*9*)	1966	30 (1.18)

Water/Cement Ratio

Very little data on the variability of water/cement ratio were found. Preliminary information obtained by the Construction Technology Laboratory, which is evaluating the Troxler Water/Cement 4430 gauge, indicates a "within-batch" standard deviation, using two replicates, of 0.009 (*73*). Additional work has been done by Troxler Electronic Laboratories and the National Ready Mix Concrete Association. On 12 batches of transit-mixed concrete, each with three replicate tests, the "within-batch" standard deviation was 0.026 and the overall standard deviation of all 36 individual tests was 0.035. (personal communication from Lawrence H. James, Troxler Electronic Laboratories, Research Triangle Park, North Carolina).

Permeability

Permeability has long been recognized as an important measure of durability. ASTM 1202 "Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration" is a method used to provide a rapid indication of durability and has been correlated to the long-term chloride ponding procedure (AASHTO T 259). Two studies, one by the Virginia Transportation Research Council (VTRC) and one by the VDOT Materials Division, were undertaken in Virginia in 1993 and 1994 using this method. (Personal correspondence from Celik Osyildirim, VTRC, April 4, 1995). The results, in Coulombs, are shown in Table 22.

CHAPTER SIX

PROPER USES OF VARIABILITY TO ESTABLISH SPECIFICATION LIMITS

The Introduction noted that a relationship should exist between the typical variability found in a process and the specification limits or tolerances used to control and accept the product from that process. This is good engineering practice and applies to all types of written specifications. The two types of SQA specifications described below are discussed in relation to the variability to the specification limit(s).

VARIABILITY KNOWN SPECIFICATIONS (CONTROLLING THE AVERAGE)

SQA specifications developed during the 1960s and 1970s were for the most part what are called Variability Known or Variability Assumed Specifications. These specifications concentrated on controlling the average of the product or process. Because a population has two important properties, the average and the standard deviation, a well-written specification should address both. Some SQA specifications did control not only the average variability, but also additional variability, many, however, did not. Because the industry was wary of statistics, these specifications were used for their apparent simplicity and ease of implementation. It was general practice in the development of these specifications to use a tolerance based on two standard deviations, or in the case of a multiple-sample plan (sample size $n > 1$), two standard deviations of the mean to establish the specification limit(s). In the case of a single-limit specification, such as PCC Strength, 97.5 percent of the product was expected to meet the specification if it were produced with the average and standard deviation intended (Figure 7). In the case of a double-limit specification, such as air voids in an asphalt mixture, 95 percent of the product would be expected to meet the specification (Figure 8). Thus, it was very important to determine an applicable variability. As discussed in chapter 2, many specifications only used the variability determined from the Precision Statement for the test method and not the overall standard deviation. This error made the specification difficult, if not impossible, to meet.

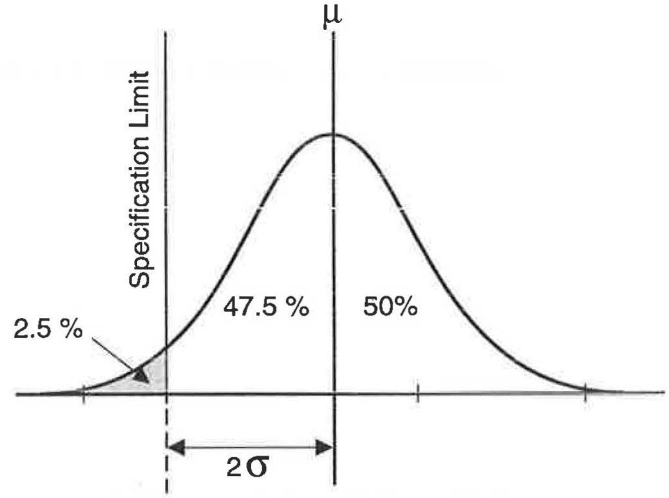

FIGURE 7 Example of a single-limit specification.

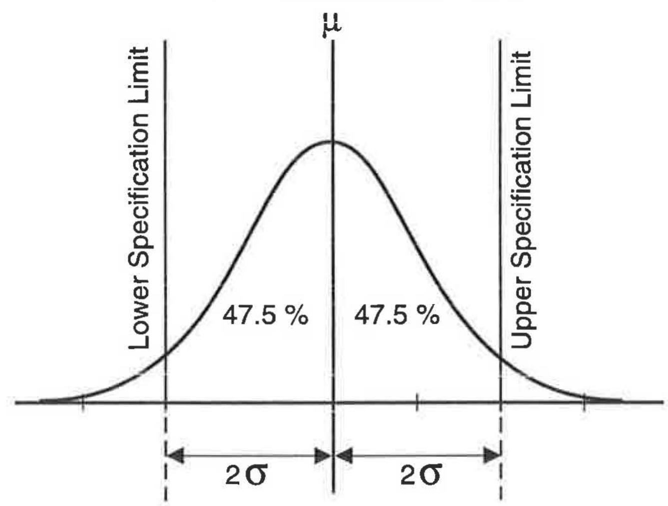

FIGURE 8 Example of double-limit specification.

VARIABILITY UNKNOWN SPECIFICATIONS (CONTROLLING THE AVERAGE AND VARIABILITY)

The evolution of SQA specifications from the 1980s to the present, finally revealed flaws in the Variability Known Specifications and the state-of-the-practice specification became the Variability Unknown Specification. This type specification uses both the lot average and standard deviation and is the type suggested for use with the Quality Level Analysis in the *AASHTO Quality Assurance Guide Specification* (*22*). The acceptance plans for this type of specification are based on procedures found in Military Standard 414 (*78*). Contrary to the terminology, it is good practice also to know the typical variability of the desired product when developing the specification limits for this type specification, especially for double-limit specifications. The terminology, Variability Unknown, derives from the fact that in the acceptance plan, the variability is determined on a lot-by-lot basis and is not assumed, unlike the previous type of specification. Once the applicable overall variability is determined, the specification limits are based on a function of the standard deviation to establish the allowable Percent Within Limits (PWL) or Percent Defective (PD) (Figure 9).

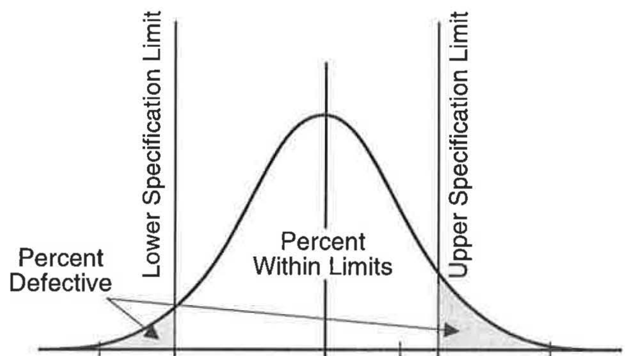

FIGURE 9 Relationship of percent defective and percent within limits to specification limits.

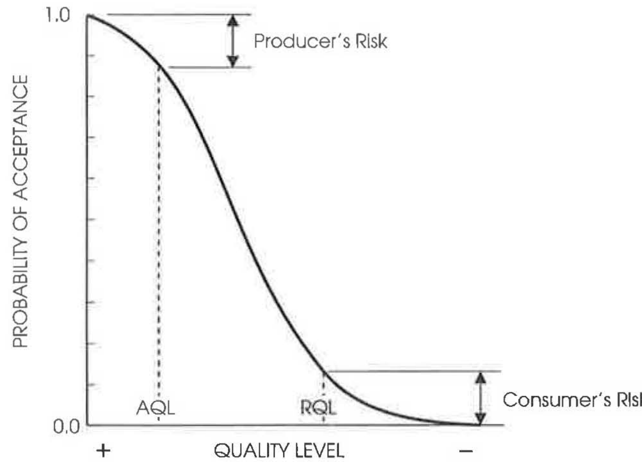

FIGURE 10 Conventional accept/reject OC curve *(62)*.

DEFINING THE AQL AND THE RQL

When developing an SQA specification, it is necessary for the specification to communicate precisely what is desired. This is accomplished by defining an acceptable quality level (AQL), usually stated in terms of PD or PWL, that corresponds to satisfactory performance. This is best accomplished when based on known performance relationships. But in the absence of these relationships, historical data and engineering judgment are often used.

To protect against seriously defective work, a rejectable quality level (RQL), also usually stated in terms of PD or PWL, must also be defined. This represents a level of quality that is known to lead to serious performance problems. This provides the DOT with a decision point at which to exercise its option to require removal and replacement, corrective action, or the assignment of a minimum pay factor for the lot.

OPERATING CHARACTERISTIC (OC) CURVES

When an acceptance plan is designed or analyzed, the AQL and RQL are important points of interest in evaluating the effectiveness of the acceptance plan. When the product is at the AQL, it should almost always be accepted or receive an average pay factor of 100 percent, depending on whether an accept/reject or pay adjustment procedure is used. When the work is at the RQL, it should almost always be rejected or receive a pay reduction commensurate with the anticipated cost of future repairs.

The analysis consists of constructing the OC curve. An example of a conventional accept/reject OC curve is shown in Figure 10 *(62)*. Probability of acceptance is indicated on the y-axis and is associated with a measure of the quality level indicated schematically on the x-axis. The risk to the consumer (buyer, owner, DOT, etc.) of accepting poor (RQL) product and the risk to the producer (seller, contractor, supplier, etc.) of having good (AQL) product rejected are both illustrated in this figure.

The OC curves for an acceptance plan with an adjustable pay schedule are similar to the OC curve for a conventional accept/reject acceptance plan except that a set of OC curves is needed to reflect the various payment options (Figure 11).

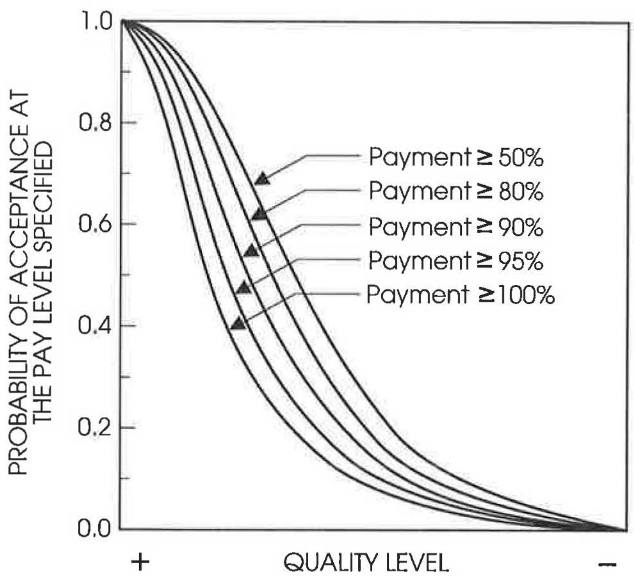

FIGURE 11 OC curves for adjustable payment acceptance plan *(62)*.

Another useful tool for evaluating the acceptance procedure, a variation of the standard OC curve, is the expected payment curve, which relates the actual quality of a lot to its mathematically expected payment value. In the example shown in Figure 12, work performed at the AQL can expect to receive 100 percent payment over the long run, while work at the RQL can expect to receive only 70 percent over the long run *(62)*.

For a variability known specification, or an acceptance plan based on the sample average, OC curves of the type shown in Figure 10 can be computed directly or constructed with the aid of special mathematical tables. For acceptance plans based on PD or PWL, and especially those with adjusted pay schedules, a computer program using simulation techniques may be necessary to develop the type of expected payment curve shown in Figure 12. The user's manual and software necessary to accomplish this task were developed by Richard Weed as part of the ongoing Quality Assurance work of FHWA Demonstration Project 89 *(79)*.

CHAPTER SEVEN

CONCLUSIONS

An effort has been made in the preparation of this synthesis to address the variability found in highway materials and construction. To achieve this goal, a thorough understanding of variability was necessary before quantifying the variability of soils and aggregate base, asphalt concrete, and portland cement concrete.

The following general conclusions are drawn from the literature reviewed, from statements of practice obtained from highway agencies and contractors, and from the consultant responsible for collecting the data and writing the draft reports.

- The variability of some material and construction properties has decreased over the last 20 years while others appear to be unchanged. Few, if any, were found to increase.
- It is likely that the decrease in variability of processes can be attributed to one or more of the following: contractor quality control, specifications that require a measurement of variability, improved industrial technology (e.g., computer driven plants), and improved test methods.
- It is apparent from the range of variabilities found for each material and construction property included in this synthesis that the use of a particular variability value may be useful as a starting point in the development of a specification, but it is prudent to verify the value under the particular conditions that the specification will be applied.

In reviewing the literature and practice of highway agencies and contractors, it is apparent that useful information either does not exist or is not readily available. The questionnaire provided input regarding the need for additional research on some items. The following suggestions are offered to add to the literature and improve the databases.

- Establish databases for those material and construction processes not currently captured in databases and review data of those that have been established by DOTs and contractors.
- Establish Precision Statements for new test methods as quickly as possible.
- Conduct a synthesis on the use of Incentive/Disincentive Pay Schedules, including the basis on which they were established.
- Conduct research to establish better relationships between variability and performance.
- Examine variability as a function of optimal lot size.

It was apparent in compiling the data in this synthesis that for many materials and construction processes, little recent variability information has been published, although there do appear to be many databases in existence that may contain this information. There are also many new tests that have come out of the SHRP studies, for which protocols have only recently been established. Sufficient time has not elapsed to do more than determine preliminary estimates of the variability. There are other new tests such as the Ignition test for Asphalt Content and the PCC Water/Cement Ratio Gauge that have also lacked time for sufficient variability data to be quantified.

The questionnaire replies allowed the respondents to indicate materials and construction processes for which they felt more variability information was needed. Data were found for some of these and have been included in the appropriate chapter. Other areas that lack data are listed below by material. However, there were two areas in which several respondents felt additional data were needed. One was the establishment of a better relationship between variability and performance, the need for which this synthesis has discussed. The other was a better measure of the variability of ride quality, especially as related to the AASHTO Quality Assurance Guide Specification (*22*).

Several areas lacking additional information are:

General Information

- Variability as a function of lot size,
- Ride quality bonuses related to long-term performance,
- Variability of Pavement Response; e.g., deflection, stress-strain,
- Variability of pavement loading, and
- Environmental variability.

Information on Subgrade and Subbase

- Subgrade material variability and
- Variability of compaction of subbase material.

Information on Asphalt Concrete

- Variability of compaction temperature,
- Variability of aggregate angularity and particle shape,
- Variability in smoothness data,
- Asphalt cement tolerances as related to grading, and
- Relationship between voids in the mineral aggregate and performance.

Information on PCC

- Variability of recycled concrete,
- Variability in the use of PCC admixtures,
- AASHTO-type Precision Statements for all PCC tests,
- Variability of voids (size and/or distribution),
- Variability of Portland Cement with High Hydrofluoric Acid Residue,
- Water demand specification for fine aggregate, and
- Variability of transit-mix air content and water/cement ratio.

REFERENCES

1. Odasz, Frank B., Jr. and Donald R. Nafus, "Statistical Quality Control Applied to an Asphalt Mixing Plant," *Proceedings of the Association of Asphalt Paving Technologists*, Vol. 23, 1954, pp. 78–96.
2. Warden, W.R., "Quality Control on the Garden State Parkway," *Proceedings of the Association of Asphalt Paving Technologists*, Vol. 23, 1954, pp. 296–310.
3. Carey, W.N., Jr. and J.F. Shook, "The Need for Change in Construction Control Procedures," *Proceedings, National Conference on Statistical Quality Control Methodology in Highway and Airfield Construction*, Charlottesville, VA, May 1966, pp. 105–116.
4. Stroup-Gardiner, Mary, David E. Newcomb, and David Savage, "Defining Specification Limits with Respect to Testing Variability," *Journal of the Association of Asphalt Paving Technologists*, Vol. 63, 1994, pp. 561–592.
5. *Highway Conference on Research and Development of Quality Control and Acceptance Specifications*, U.S. Department of Commerce, BPR, Office of Research and Development, Washington, D.C., April 1965, 504 pp.
6. *Proceedings, National Conference on Statistical Quality Control Methodology in Highway and Airfield Construction*, Charlottesville, VA, May 1966, 664 pp.
7. Oglio, Edward R. and Joseph A. Zenewitz, *A Study of Variability of Asphalt Concrete*, Bureau of Public Roads, Materials Division Office of Research and Development, January 1965, 16 pp.
8. Hammitt, G.M., II, *Statistical Analysis of Data From a Comparative Laboratory Test Program sponsored by ACIL*, U.S. Army Engineers Waterways Experiment Station, Corps of Engineers, Vicksburg, MS, January 1966, 4 pp.
9. Shah, S.C., *Quality Control Analysis—Part III—Concrete and Concrete Aggregates*, Research Reprint No. 24, Louisiana Department of Highways, Baton Rouge, LA, November 1966, 33 pp.
10. *Statistical Parameters Research Quality Control Study on Asphalt Pavement*, HPR 1 (3) Final Report, Colorado Department of Highways, Denver, CO, April 1967, 14 pp.
11. Jorgenson, James L., *The Statistical Approach to Quality Control in Highway Construction*, No. 16, Engineering Experiment Station Series, North Dakota State Highway Department, Fargo, ND, November 1968, 41 pp.
12. McMahon, Thurmul F., Woodrow J. Halstead, Wesley W. Baker, Edwin C. Granley, and James A. Kelly, "Quality Assurance in Highway Construction," initially compiled Feb.–Dec. 1969, *Public Roads*, Vol. 35, No. 6-11, 1969, reprinted in FHWA-TS-89-038, October 1990, 60 pp.
13. Sherman, George B., Robert O. Watkins, and Roget Prysock, *A Statistical Analysis of Embankment Compaction*, State of California, Department of Public Works, Division of Highways, Sacramento, CA, May 1966, 23 pp.
14. Williamson, T.G. and E.J. Yoder, *An Investigation of Compaction Variability for Selected Highway Projects in Indiana*, Purdue University, Indiana State Highway Commission, Lafayette, IN, December 1967, 20 pp.
15. David, J. H., *Quality Control of Construction by Statistical Tolerances*, Alabama Highway Department, Montgomery, AL, May 1967, 14 pp.
16. VanHouten Frank C., *Characteristics of Compacted Embankment*, Utah State Highway Department, Salt Lake City, UT, August 1967, 26 pp.
17. Afferton, Kenneth C., "A Statistical Study of Asphaltic Concrete," New Jersey State Department of Transportation, *Highway Research Record 184*, National Research Council, Washington, D.C., 1967, pp. 13–24.
18. *Determination of Statistical Parameters for Highway Construction*, Research Project No. 18, State Road Commission of West Virginia, by Materials Research and Development, Inc., Miller Warden Associates Division, Raleigh, NC, July 1966, 64 pp.
19. *Statistical Approach to the Quality Control of Plant Mix Pavement*, Wyoming State Highway Department, June 1968, 30 pp.
20. Adam, Verdi and S.C. Shah, *Tolerances for Asphaltic Concrete and Base Courses*, Louisiana Department of Highways, Baton Rouge, LA, November 1966, 27 pp.
21. *Variations in Bituminous Construction in Nebraska*, Nebraska Department of Roads, Lincoln, NE, September 1968, 19 pp.
22. *AASHTO Quality Assurance Guide Specification* (draft), AASHTO Joint Construction/Materials Quality Assurance Task Force, Federal Highway Administration, Washington, D.C., June 1995, 29 pp.
23. *National Policy on the Quality of Highways*, Federal Highway Administration, Washington, D.C., November 1992, 1 pp.
24. *National Quality Initiative, Long-Range Plan*, FHWA-SA-94-038, Federal Highway Administration, Washington, D.C., June 1994, 35 pp.
25. Dillard, Jack H., *Field Experiment with Statistical Methods*, Virginia Highway Research Council, Charlottesville, VA, September 1968, 16 pp.
26. Hughes, C.S., *Field Management of Asphalt Concrete Mixes*, VTRC 89-R6, Virginia Transportation Research Council, Charlottesville, VA, August 1988, 17 pp.
27. Hughes, C.S., *Results from VDOT's Pilot Project Using Volumetric Properties and Asphalt Content for Acceptance of Asphalt Concrete*, VTRC95, Technical Assistance Report 9, Virginia Transportation Research Council, Charlottesville, VA, January 1995, 7 pp.
28. *A Short Course on Statistical Quality Assurance*, Course Notebook, Virginia Transportation Technology Transfer Center, Charlottesville, VA, March 1991, 140 pp.
29. Snedecor, George W., *Statistical Methods*, 5th ed., Iowa State College Press, Ames, IA, 1956.
30. Willenbrock, Jack H., *A Manual for Statistical Quality Control of Highway Construction*, Volume II, FHWA,

National Highway Institute, Washington, D.C., September 1975, 265 pp.
31. *National Quality Improvement Task Force Report on Quality Assurance Procedures for Highway Construction*, FHWA-SA-94-039, Federal Highway Administration, Washington, D.C., April 1995, 28 pp.
32. Weed, R., *Quality Assurance Software for the Personal Computer, User's Manual*, FHWA Demonstration Project 89, Federal Highway Administration, Washington, D.C., May 1996, 185 pp.
33. Anderson, D.A., Z. Siddiqui, R.G. Shaw, and C.E. Antle, *Acceptance Criteria for Aggregates*, FHWA/PA 84-021, Washington, D.C., May 1985, 254 pp.
34. Granley, Edwin C., "Quality Assurance in Highway Construction—Part 4—Variations of Bituminous Construction," FHWA, *Public Roads*, Vol. 35, Nos. 6-11, 1969, reprinted in FHWA-TS-89-038, Federal Highway Administration, Washington, D.C., October 1990, pp 30-44.
35. Brakey, Bud A., *HBP QA/QC Pilot Projects Constructed in 1993*, Second Interim Report, Materials Branch, Colorado Department of Transportation, Denver, CO, May 1994, 24 pp.
36. Aguirre Engineers and PCS/Law Engineering, *An Investigative Study of the Colorado Department of Transportation Asphalt Mixture Design Procedure*, Executive Summary Report, CMS ID No. 023-91, Denver, CO, September 1993, 64 pp.
37. Benson, Paul E., "Comparison of End-Result and Method Specifications for Managing Quality," *Transportation Research Record 1491*, Transportation Research Board, National Research Council, Washington, D.C., 1995, pp. 3–10.
38. Hughes, C.S., "Incentive and Disincentive Specification for Asphalt Concrete Density," *Transportation Research Record 986*, National Research Council, Washington, D.C., 1984, pp. 38–42.
39. Parker, Frazier, Jr. and Md. Shabbir Hossain, "Hot-Mix Asphalt Mix Properties Measured for Construction Quality Control and Assurance," *Transportation Research Record 1469*, National Research Council, Washington, D.C., December 1994, pp. 9–17.
40. Markey, Stephen J., Joe P. Mahoney, and Robert M. Gietz, *An Evaluation of the WSDOT Quality Assurance Specification for Asphalt Concrete*, Final Report, Research Project T9903, Task 3, Subtask 3, Special Programs, Washington State Transportation Center, Seattle, WA, October 1993, 75 pp.
41. Cominsky, Ronald J. and Prithvi S. Kandhal, *Statistical Acceptance of Bituminous Paving Mixtures*, Research Project 79-28, Commonwealth of Pennsylvania Department of Transportation, Harrisburg, PA, May 1982, 232 pp.
42. Hudson, S.B. and H.F. Waller, "Evaluation of Construction Control Procedures," *NCHRP Report 69*, Transportation Research Board, National Research Council, Washington, D.C., 1969, 58 pp.
43. Kandhal, Prithvi S., Ronald J. Cominsky, Dean Maurer, and John B. Motter, "Development and Implementation of Statistically Based End-Result Specifications for Hot-Mix Asphalt in Pennsylvania," *Transportation Research Record 1389*, National Research Council, Washington, D.C., 1993, pp. 9–16.
44. Stroup-Gardiner, Mary, David E. Newcomb, and Jon A. Epps, "Precision of Methods for Determining Asphalt Cement Content," *Transportation Research Record 1228*, National Research Council, Washington, D.C., 1989, pp. 156–167.
45. Brown, Elton R., Nicholas E. Murphy, Li Yu, and Stuart Mager, "Historical Development of Asphalt Content Determination by the Ignition Method," *Journal of the Association of Asphalt Paving Technologists*, Vol. 64, 1995, pp. 241–277.
46. Fager, Glenn A., *Variations of Asphalt Percentage in Bituminous Mixes From Drum Dryer Mixes*, Kansas Department of Transportation, Topeka, KS, November 1988, 22 pp.
47. Carey, Donald E. and Harold R. Paul, *Quality Control of Recycled Asphalt Concrete*, Lousiana HPR Study No. 81-1B(B), Research and Development Section, Louisiana Department of Transportation and Development, Baton Rouge, LA, July 1982, 82 pp.
48. Harman, Thomas P., John D'Angelo, John Bukowski, and Theodore Ferragut, "Evaluation of SUPERPAVE Gyratory Compactor in the Field Management of Asphalt Mixes," *Transportation Research Record 1513*, National Research Council, Washington, D.C., 1995, pp. 1–8.
49. *Draft Quality Control Plan, Version No. 1*, NCHRP 9-7 Field Procedures and Equipment to Implement SHRP Asphalt Specifications, Brent Rauhut Engineering, Inc., Austin, TX, April 1995, 32 pp.
50. Stevenson, J.D. and Tim Aschenbrener, *Comparison of Test Results from Laboratory and Field Compacted Samples*, Report No. CDOT-DTD-R-94-3, Colorado Department of Transportation, Denver, CO, February 1994, 92 pp.
51. D'Angelo, John A. and Ted Ferragut, "Summary of Simulation Studies from Demonstration Project No. 74: Field Management of Asphalt Mixes," *Journal of the Association of Asphalt Paving Technologists*, Vol. 60, 1991, pp. 287–309.
52. Robson, Gary L., "A Report of the Determination of Marshall Test Data on Selected Projects in West Virginia," Research Report No. 1240829, Charleston, WV, 1989, 22 pp.
53. Elkin, B.L., "An Investigation of Bituminous Highway Materials and Methods of Production and Construction Control Based on Statistical Procedures," Phase IV—Quality Control Research Project, HPR-1(8), Part II, Indiana Department of Transportation, December 1971, 128 pp.
54. Hughes, C.S., *NCHRP Synthesis 152: Compaction of Asphalt Pavement*, Transportation Research Board, National Research Council, Washington, D.C., October 1989, 42 pp.
55. Weed, R., "Development of Air Voids Specification for Bituminous Concrete," *Transportation Research Record*

1491, Transportation Research Board, National Research Council, Washington, D.C., 1995, pp. 33–39.

56. Aurilio, V. and C. Raymond, "Development of End Result Specification for Pavement Compaction," *Transportation Research Record 1491*, Transportation Research Board, National Research Council, Washington, D.C., 1995, pp. 11–17.
57. Afferton, Kenneth C., "New Jersey's Thickness Specification for Bituminous Pavement," New Jersey Department of Transportation, *Transportation Research Circular 172*, Transportation Research Board, National Research Council, Washington, D.C., October 1975, 19 pp.
58. Scofield, Larry A., *Profile Limitations, Correlations, and Calibration Criteria for Effective Performance-Based Specifications*, NCHRP Project 20-7, Task 53, Transportation Research Board, National Research Council, Washington, D.C., 1994, 167 pp., (unpublished).
59. Budwig, Jerry L., *Bituminous Pavement Smoothness*, paper presented to 1994 TRB Annual Meeting, Washington, D.C., January 1994, 27 pp.
60. Goulias, Dimitrios G., Terry Dorsey, and W. Ronald Hudson, *End-Result Specifications for Rigid and Flexible Pavements in Texas*, FHWA/TX-93+1167-2F, Austin, TX, October 1992, 46 pp.
61. Croteau, Jack, *Ensuring Reliability of Mays Roughness Measurements*, Final Report, New Jersey HPR Study #7776, Trenton, NJ, March 1976, 46 pp.
62. Chamberlin, William P., *NCHRP Synthesis of Highway Practice 212; Performance-Related Specifications for Highway Construction and Rehabilitation*, Transportation Research Board, National Research Council, Washington, D.C., 1995, 48 pp.
63. Weed, Richard M., *Statistical Specification Development*, 2nd ed., FHWA/NJ-88-017, New Jersey Department of Transportation, Trenton, NJ, March 1989, 313 pp.
64. *Standard Specifications for Road and Bridge Construction*, Section 914, "Portland Cement Concrete, Mortar and Grout," New Jersey Department of Transportation, Trenton, NJ, 1989.
65. Ksaibati, Khaled, Rick Staigle, and Thomas M. Adkins, "Pavement Construction Smoothness Specifications in the United States," *Transportation Research Record 1491*, Transportation Research Board, National Research Council, Washington, D.C., 1995, pp. 27–32.
66. Gonsalves, George F.D. and John F. Eisenberg, *Implications of Statistical Quality Control of Portland Cement Concrete*, Report No. 7, Materials Services (Research), Arizona Department of Transportation, Phoenix, AZ, January 1975.
67. Ho, Robert and Don Hendricks, *Aggregate Study at Selected Concrete Plants*, Materials Office, Florida Department of Transportation, Gainesville, FL, March 1991.
68. *Evaluation of Potential Applications of End-Result and Performance-Related Specifications*, IHR-425, White Paper Presentations—Part II, Chapter V—Portland Cement Concrete Pavements (draft), Illinois Department of Transportation, Urbana–Champaign, IL, April 1994, 83 pp.
69. *Determination of Statistical Parameters* Phase II, Concrete Pavement and Structures, Interim Report, Materials, Research and Development, Inc., PennDOT, Harrisburg, PA, 1972.
70. Riley, Orrin, "Time to Rein in the Flexure Test," *Concrete International*, American Concrete Institute, Vol. 17, No. 6, June 1995, pp. 42–44.
71. Davis, Clayton L., *Factors Affecting Compressive and Flexural Strength*, presented to Pittsburgh Area Chapter, American Concrete Institute, Pittsburgh, PA, September 1967.
72. Baker, Wesley W. and Thurmul F. McMahon, "Part 3—Quality Assurance of Portland Cement Concrete," FHWA, *Public Roads*, Vol. 35, Nos. 6–11, 1969, reprinted in FHWA-TS-89-038, October 1990, 21-29 pp.
73. Whiting, David A., *Study of Troxler 4430 Water/Cement Ratio Gauge*, Construction Technology Laboratories Monthly Progress Report for February, 1995 to Highway Innovative Technology Evaluation Center, Washington, D.C., 1995, 12 pp.
74. Whiting, David and Philip D. Cady, *Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion Vol. 7 Method for Field Measurement of Concrete Permeability*, SHRP-S/FR92-109, Strategic Highway Research Program, Washngton, D.C., 1993, 87 pp.
75. Meininger, R.C., F.T. Wagner, and K.W. Hall, "Concrete Core Strength -- The Effect of Length to Diameter Ratio," *Journal of Testing and Evaluation*, Vol. 5, No. 3, ASTM, 1977.
76. Weber, W.G., Jr., R.L. Grey, and P.D. Cady, "Rapid Measurement of Concrete Pavement Thickness and Reinforcement Location," *NCHRP Report 168*, Transportation Research Board, National Research Council, Washington, D.C., 1976, 68 pp.
77. Harrison, Rob, Carl Bertrand, and W.R. Hudson, "Measuring the Smoothness of Newly Constructed Concrete Pavement for Acceptance Specifications," *Proceedings 4th International Conference on Concrete Pavement Design and Rehabilitation*, Purdue University, Lafayette, IN, 1989, pp. 601–614.
78. *Sampling Procedures and Tables for Inspection by Variables for Percent Defective*, Military Standard 414, U.S. Department of Defense, Washington, D.C., 1957.
79. Weed, R., "OCPLOT: PC Program to Generate Operating Characteristic Curves for Statistical Construction Specifications," *Transportation Research Record 1491*, Transportation Research Board, National Research Council, Washington, D.C., 1995, pp. 18–26.
80. *Proceedings Statistical Quality Assurance Workshop*, Bureau of Public Roads, Washington, D.C., October 22–24 1968, 114 pp.
81. Afferton, Kenneth C., Jack Freidenrich, and Richard M. Weed, "Managing Quality: Time for a National Policy," *Transportation Research Record 1340*, Washington D.C., 1995, pp. 3–39.

APPENDIX A

National Policy on the Quality of Highways

The National Transportation Policy charts a course for leading the United States' transportation system into the 21st century. The Nation's highway network is an essential element of our transportation infrastructure and its quality is critical to America's economic growth and its ability to compete in the world marketplace.

The United States is a world leader in providing quality highways to the customer, the highway user. To maintain this leadership role, this policy is intended to fulfill the requirements of the highway user by providing a durable, smooth, safe, aesthetically pleasing, environmentally sensitive, efficient, and economical highway system, in balance with other modes of transportation.

In support of these principles, therefore, the National Policy on the Quality of Highways is to make a continuing commitment for quality products, information, and services through:

- Proper design, construction specifications related to performance, adherence to specifications, use of quality materials, use of qualified personnel, and sufficient maintenance;
- Constant improvement of highway engineering technology by increasing emphasis on cooperative research, implementation, and technology sharing;
- Flexibility, coupled with responsibility, for designers, contractors, workers, and suppliers;
- Adequate assurances of quality achievement in planning, design, and construction, by owner agencies;
- Incentives that reward achievements and innovations in providing a demonstrated level of value-added quality; and
- Cooperative development of quality management systems and specifications between Federal, State, and local agencies, academia, and industry.

The development and preservation of a high-quality highway system requires a close partnership between all stakeholders; therefore, the undersigned organizations have cooperatively developed this national policy and will strive to fulfill its principles. In witness whereof, it is sealed and signed at Dallas/Fort Worth Airport, Texas, this 10th day of November, 1992.

American Association of State Highway and Transportation Officials

Federal Highway Administration

American Road & Transportation Builders Association

Associated General Contractors of America

American Concrete Pavement Association

National Asphalt Pavement Association

American Consulting Engineers Council

National Ready Mixed Concrete Association

APPENDIX B

Survey Questionnaire

APPENDIX B

Questionnaire

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
Project 20-5, Topic 26-02

Variability of Highway Pavement Construction

QUESTIONNAIRE

The completion of this questionnaire is being requested to update the literature on typical levels of variability encountered in the construction of highway pavements. The information requested pertains to any studies your agency may have done. As an adjunct to this information the method(s) used to establish tolerances for specification limits and whether incentive/disincentive provisions are used are also requested.

Date: ____________

AGENCY RESPONDING: ____________

Person: ____________

Title: ____________

Address: ____________

Phone No.: ____________

PERSON TO WHOM QUESTIONS ABOUT THE RESPONSE SHOULD BE DIRECTED:

Name: ____________

Title: ____________

Phone No.: ____________

Fax No.: ____________

PLEASE RETURN THE COMPLETED QUESTIONNAIRE AND SUPPORTING DOCUMENTS TO:

(Mail) *C.S. Hughes, P.E.*
318 Miller School Road
Charlottesville, VA 22903

(Fax) (804) 823-1797

PLEASE FEEL FREE TO CALL CHUCK HUGHES ON (804) 823-1797 IF YOU WISH TO DISCUSS THE QUESTIONNAIRE.

NCHRP PROJECT 20-5, TOPIC 26-02
AGENCY: ____________

Part I Variability

1. Has your agency done any studies (formal or informal) on materials or construction variability since 1974?

____ Yes ____ No

If no studies have been undertaken during this period, please go to Part II, Tolerances.

2. If you have done studies on materials or construction variability, were the studies in any of the following areas?

<u>Please check all that are applicable.</u>

TYPICAL VARIABILITY FOR SOILS AND AGGREGATE BASE

<u>Materials</u>

-Soil Properties ____
-Aggregate Gradation ____

<u>Construction</u>

-Embankment Compaction ____
-Embankment Moisture Content ____
-Aggregate Base Compaction ____
-Aggregate Base Moisture Content ____

TYPICAL VARIABILITY FOR ASPHALT CONCRETE (AC)

<u>Materials</u>

-Aggregate Gradation ____
-Asphalt Content ____
-Volumetric Properties ____
-Aggregate Characteristics
(Particle shape, texture, etc.) ____

<u>Construction</u>

-Compaction ____
-Thickness/Application Rate ____
-Ride Quality ____

TYPICAL VARIABILITY FOR PORTLAND CEMENT CONCRETE (PCC)

Materials/Structural Concrete

- -Aggregate Gradation _____
- -Slump _____
- -W/C Ratio _____
- -Strength _____
- -Air Content _____
- -Permeability _____
- -Admixtures _____
- -Pozzolins (Fly ash, slag, etc.) _____
- -Aggregate Characteristics (Particle shape, texture, etc.) _____

Materials/Paving Concrete

- -Aggregate Gradation _____
- -Slump _____
- -W/C Ratio _____
- -Cylinder or Beam Strength _____
- -Air Content _____
- -Admixtures _____
- -Pozzolins (Fly ash, slag, etc.) _____
- -Aggregate Characteristics (Particle shape, texture, etc.) _____

Construction/Paving Concrete

- -Ride Quality _____
- -Core Strength _____
- -Thickness _____

Any other typical variabilities studied not mentioned in question 2 above. (Please specify)

____

____

____

PLEASE INCLUDE IN THIS REPLY ANY PAPERS, REPORTS, OR ORGANIZED DATA THAT HAVE EMANATED FROM THE ABOVE STUDIES.

NCHRP PROJECT 20-5, TOPIC 26-02
AGENCY:________________________

3. Please describe any research currently underway on variability of the above listed materials/research.

____

____

____

4. Please list any material or construction characteristics for which you feel the variability data need to be determined or updated.

____

____

____

Part II Tolerances

1. Which of the following procedures do you typically use to determine tolerances for setting specification limits? (Please check all that apply.)

- Experience _____
- Engineering Judgment _____
- Variability from Research Studies _____
- Variability from Pilot Projects _____
- Variability from Typical Production/Construction Contracts _____
- Tolerances Used by Other Agencies _____
- AASHTO/ASTM Precision Statements _____
- Other (please specify) _____

2. Please list any materials/construction characteristics that you feel uncomfortable with the tolerances used or that you would like to see tolerances more scientifically developed? If the same as in question 4 above, please so state.

____

____

____

NCHRP PROJECT 20-5, TOPIC 26-02
AGENCY:____________________

Part III Incentives/Disincentives

1. Does your agency use incentives (price increases) or disincentives (price decreases) for materials/construction acceptances?

____Yes (GO TO NEXT PAGE) ____No (END)

THANK YOU FOR YOUR PARTICIPATION IN COMPLETING THIS SURVEY!

NCHRP PROJECT 20-5, TOPIC 26-02
AGENCY:____________________

2. If you use incentives/disincentives, for which of the items listed below are they used?

MATERIAL PROPERTY	Incentive			Disincentive		
	No	Yes	Max	No	Yes	Max
Base Course, Gradation						
AC, Aggregate Gradation						
Asphalt Content						
AC, Volumetric Properties						
P.C.C., Aggregate Gradation						
P.C.C., W/C Ratio						
P.C.C., Beam Strength Cylinder Strength						
P.C.C., Air Content						
P.C.C., Permeability						
(Other)						
CONSTRUCTION						
Embankment, Compaction Moisture Content						
Aggregate Base, Compaction Moisture						
AC, Compaction						
AC, Thickness						
AC, Ride Quality						
P.C.C., Core Strength						
P.C.C., Thickness						
P.C.C., Ride Quality						
Other						

THANK YOU FOR YOUR PARTICIPATION IN COMPLETING THIS SURVEY!