Research

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE 65

QUALITY ASSURANCE

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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QUALITY ASSURANCE

RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

AREAS OF INTEREST:

CONSTRUCTION
GENERAL MATERIALS
(HIGHWAY TRANSPORTATION)
(PUBLIC TRANSIT)
(RAIL TRANSPORTATION)
(AIR TRANSPORTATION)
(OTHER)

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. OCTOBER 1979

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.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the National Academy of Sciences, or the program sponsors.

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PREFACE

There exists a vast storehouse of information relating to nearly every subject of concern to highway administrators and engineers. Much of it resulted from research and much from successful application of the engineering ideas of men faced with problems in their day-to-day work. Because there has been a lack of systematic means for bringing such useful information together and making it available to the entire highway fraternity, 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 the useful knowledge from all possible sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series attempts to report on the 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 they are utilized in this fashion will quite logically be tempered by the breadth of the user's knowledge in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of special interest and usefulness to construction engineers, materials technologists, and others concerned with control and assurance of quality in highway construction. Detailed information is presented on quality assurance philosophies, programs, practices, and procedures.

Administrators, engineers, and researchers are faced continually with many highway problems on which much information already exists either in documented form or in terms of undocumented experience and practice. Unfortunately, this information often is fragmented, scattered, and unevaluated. As a consequence, full information on what has been learned about a problem frequently is not assembled in seeking a solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended 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 synthesizing and reporting on common highway problems. Syntheses from this endeavor constitute an NCHRP report series that collects and assembles the various forms of information into single concise documents pertaining to specific highway problems or sets of closely related problems.

Many factors influence the performance of highways and bridges. This report of the Transportation Research Board reviews these factors and outlines the major components of quality assurance systems used by state highway agencies to ensure compliance with specifications. A number of states have reported favorable experience in basing their testing and inspection procedures on end-result or performance type specifications. Use of statistical probabilities in quality control and assurance programs is also discussed in this report.

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 researchers in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records 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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QUALITY ASSURANCE

SUMMARY

The literature review and survey of states conducted for this synthesis reveal few data to relate highway facility performance to specification requirements or inspection and testing activities conducted by the states to assure that specifications are being met. However, most highway engineers believe that specific instances of poor performance result from poor construction techniques or failure to comply completely with specifications. Many highway engineers know of performance problems related to lack of compliance with good construction practices, but often such difficulties are not publicly documented.

Performance is affected by many factors. These may be environmental, such as the range of ambient temperatures, the cycles of freezing and thawing, and the amount of rainfall, or they may be load-related, such as the frequency, speed, and weight of traffic using the facility. The highway planner attempts to predict the extremes of such factors, and the designer attempts to design a facility that will resist destructive environmental and load factors for an adequate period of time.

However, the designer is faced with a number of constraints. In some cases, certain routes or locations are unusable because of prior or planned land use. Economics are a major consideration. It is often necessary to build more, but less durable, facilities at a lower unit cost in order to accommodate more traffic. Availability of materials is also a factor. If high-quality materials are not readily available, the cost of bringing them to a job site can be prohibitive. Consequently, less suitable, locally available materials must be employed.

Once these factors have been considered and a design agreed upon, the desired level of quality has been established. How well this level of quality is attained during construction then depends on another series of factors, among which are how well the requirements of the plans and specifications define the needed characteristics of the finished project, the workmanship of the contractor, and how well the finished project complies with the specifications.

Opinions differ as to what constitutes a quality assurance system. Before 1950, a recipe system was most frequently used. The buyer (the state) spelled out in detail what was to be built and how it was to be done. Under these conditions, the buyer was obligated to accept the project at the bid price.

In more recent years, end-result or performance specifications have been emphasized. The trend is to define what is wanted or what performance is expected, but to give greater leeway to the contractor (seller) in how it is to be built. The ultimate end-result system has been defined as one that employs specifications and acceptance procedures based on random sampling and statistical probabilities.

The procedures being used by most states lie somewhere in between the two approaches. Recognizing that detailed descriptions of how to build an entire project are unnecessary, most states have adopted an end-result approach by establishing

the desirable characteristics of intermediate materials or products. For example, requirements applying to the density characteristics of the compacted pavement have replaced requirements for types and weights of rollers.

In many cases, requirements are intuitively established by experience. In such cases, it is customary to use representative sampling and testing. A sample is considered to represent the total lot, and most often, unless noncompliance is indicated, only one sample will be tested. Retests are normally made after a noncomplying result is attained, and if the retest results are in compliance with the specification, the material or product is accepted.

Those adopting statistical quality assurance techniques assign the responsibility for process control to the seller (contractor). However, they review and approve the control procedures in advance and observe the degree of compliance. Limited numbers of acceptance tests are usually made, because the tests run by the seller for control are the same as those run by the buyer for acceptance. Complete duplication of testing, therefore, is considered a waste, and means are sought to avoid it.

Because the natural materials used for highway construction are variable and sometimes unpredictable, flexibility is needed to permit immediate adjustments in construction techniques or material requirements based on the knowledge and judgment of the engineer. Many believe that a formal system of acceptance and testing based on statistical probabilities prevents the exercise of proper judgment in such cases, and they are therefore reluctant to separate completely the process of control and acceptance. On the other hand, more uniformity is expected for manufactured materials, and most states have proceeded to an end-result specification for these products. For steel, guard rails, etc., some inspection is made at the fabrication plants, but composition analyses, etc., are usually accepted by certification. Many states are also accepting asphalts and portland cements by certification, with only occasional spot checking of production on either a regular or random basis. Small hardware items are also being accepted by certification.

Over-all, this synthesis emphasizes that under present circumstances there is no single, ideal quality assurance system for all highway (buying) agencies. There appears to be a general desire to move toward end-result specifications. However, the size of the job, the skill of the contractor, and the training of the inspectors vary from job to job and state to state. These differences, then, control the extent to which it is feasible to establish ultimate end-result requirements.

The general review and discussion of the problems presented in this report aim to eliminate much of the controversy relating to quality assurance; this should permit cooperative efforts among all concerned—buyer and seller agencies, political interests, and the public—with the ultimate result of improved performance of transportation facilities at reduced costs to society.

CHAPTER ONE

INTRODUCTION

The performance of a highway facility is a function of a number of independently operating factors, some of which are not controlled by the activities normally associated with quality assurance. However, performance can be significantly influenced by the system employed to assure quality. A number of recorded cases show that failure to conform to either material or construction specifications can result in failures of highway components. On the other hand, the materials being used may have inherent deficiencies that are not measured by the specifications so that even the most rigid adherence to requirements will not assure satisfactory performance. Normally, however, the selection of quality control and acceptance procedures and specification limits will affect the performance of a given project.

HISTORICAL DEVELOPMENT OF SPECIFICATIONS

It is important to remember that procedures, specifications, and tests for highway construction and materials were developed by evolution. Early road building was a "cut and try" operation, with success depending greatly on the skill and ingenuity of the engineer. Successes generally led to specifications aimed at duplicating them in other projects. This in turn led to empirical tests and requirements. These served well for the normal situation but did not necessarily apply to all conditions because they did not measure directly the characteristic most responsible for good or bad performance.

More recently, research has been conducted to discover and measure those characteristics most directly responsible for performance, and considerable progress has been made. Unfortunately, many of the procedures used to establish these relationships are time-consuming and require sophisticated equipment for data collection and analysis. Such procedures are not suitable for quality control of materials and construction. Thus the highway engineer still must monitor product quality with tests that are often indirectly related to performance. In fact, many of the properties of portland cement concrete that relate most directly to performance—strength, good surface texture, and abrasion resistance—do not exist at the time control must be exercised.

Two events in the early 1960s led to a realization by the U.S. highway community that changes in the manner of specifying requirements for highway materials and construction were needed. The first event was the AASHTO road test, which showed a considerably larger portion of the materials and finished pavements deviating from specifications than was considered normal by most highway engineers. At about the same time, several highway failures attracted the attention of Congress, which led to the establishment of the House Committee on Oversights and Investigations ("Blatnik Committee") to investigate the quality of highway construction. According to the 1962 report of that committee, test data often showed relatively large proportions of materials outside the stated specification limits and records were often inadequate to demonstrate whether or not the proper materials had been used.

These failures to comply fully with established limits have not been shown to result in serious pavement deficiencies. Highway engineers properly pointed out that the specifications were often the desired construction target and that "normal" deviations were expected and could be tolerated. Whether or not a given deviation was serious enough for rejection was considered a matter of engineering judgment.

As a result of the criticism, most states and the Federal Highway Administration (FHWA) revised their specifications to establish a "doctrine of reasonably close conformity" or "substantial compliance" with the specifications. New specification language made clear that 100 percent compliance was not always possible and that deviations would be dealt with on a case-by-case basis. When engineering judgment indicated that no serious defect in the final pavement would result from the deviations, the work would be accepted. In other cases, deficiencies might be ruled insufficient to remove the material or section of pavement from the highway. In such cases, agreements for reduction of payment might be reached.

As pointed out by McMahon and Halstead (*1*):

> When traditional specifications are combined with the skills of engineers, the complete cooperation of contractors, and the desire of everyone to do a good job, there is no doubt that a good highway can be built. However, inspectors and engineers must be capable of recognizing good materials and construction without relying solely on quality measurements.

The traditional procedure is difficult to define and very difficult to defend when the engineering judgment is challenged. Thus, FHWA established a research program to develop the so-called "statistical specification." Unfortunately, this terminology and some of the early presentations led to misunderstanding by many in the highway community regarding the intent and scope of the program. Despite major efforts by FHWA, TRB, and a number of state transportation departments to correct these misunderstandings, some of them still persist.

A number of factors inhibit the universal application of statistical probabilities to all elements of quality control and quality assurance in the highway construction field. Consequently, this synthesis was undertaken to look at the factors affecting performance and review principles of the various current quality assurance systems to establish, if possible, those procedures most important to good performance. Data on the cost of quality assurance in relation to its payoff in better performance and reduced maintenance costs were also sought.

The question of the degree to which statistical probabilities can be applied to highway quality assurance must also be addressed. *NCHRP Synthesis 38* (*2*) reviewed the fundamentals of statistically oriented specifications (those which employ the principles of statistical probability as the basis for decisions concerning the acceptability of a product). That report also discussed some of the major problems in implementing such specifications. The adverse reaction of some highway community elements to the report indicated a need to review the problems in the wider context of the total quality assurance program—including design considerations, the tests needed, and the limits applied, regardless of whether or not statistical probability theory is being employed as a part of the system.

In order to provide information concerning states' procedures and use of specific tests, a questionnaire was directed to all state transportation departments. The replies, summarized in Chapter Four, reveal significant agreement with respect to the major test procedures being employed for quality control and acceptance. Although the data are not sufficient to establish specific relationships, the summary of viewpoints hopefully will assist state transportation departments in evaluating their present procedures and improving their overall quality assurance systems.

FACTORS AFFECTING PERFORMANCE OF HIGHWAYS AND BRIDGES

The performance of a highway or highway bridge is influenced by a number of factors. The major ones that must be considered are:

- Political and economic requirements.
- Traffic.
- Environment.
- Maintenance.
- Materials.
- Design.
- Specifications.
- Contractor performance.
- Inspection procedures.
- Control tests.
- Acceptance procedures.

Political and Economic Requirements

Abdun-Nur (*3*) depicts (Fig. 1) the quality assurance system as being made up of both technical and social factors. The social factors that he includes are:

- Will of the people.
- Political leaders.
- Planners and architects.
- Economic considerations.
- Financing problems.
- Legal problems.
- Human factors.
- Environmental factors.
- Pressures for rush.

Most of these factors are self-explanatory. Decisions concerning most of them are made prior to consideration of the technical factors. However, these factors often prevent the *best* highway facility from being built. Frequently, a greater number of miles of lower quality roads are built in order to provide facilities for a larger number of people. In other situations, the location of a highway

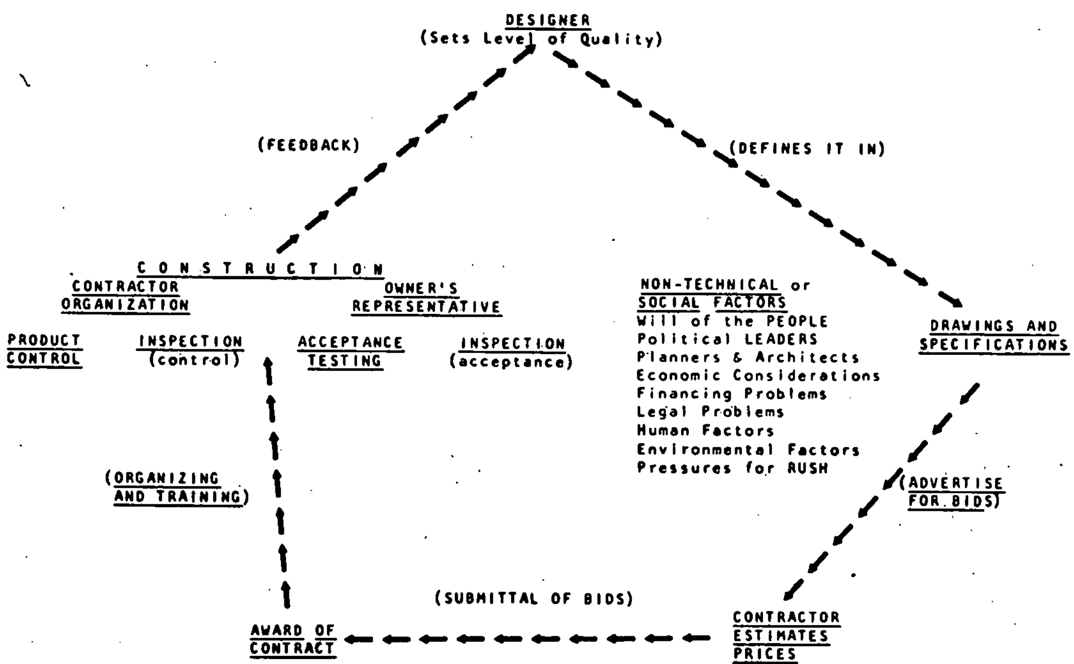

Figure 1. Diagram of a system to promote quality assurance (3).

is controversial and controlled by political rather than technological considerations.

Time constraints often overrule the highway engineer with respect to the rejection of noncomplying materials and construction. The desirability of completing a project by a certain date (e.g., prior to opening an airport or a sports stadium) or the need to complete a project before winter may justify acceptance of noncomplying materials. While earlier maintenance may be required, the total benefits to society may be greater than would accrue from strict adherence to specifications. These uses of noncomplying construction are not always fully documented. This permits the later erroneous assumption that materials and construction were the same on the noncomplying sections as on previously constructed sections.

Traffic

The frequency and weight of traffic are recognized as primary factors affecting performance and are considered in designing a highway or bridge. Because highways or bridges built with equal materials and construction quality can be subjected to different weights and frequencies of traffic, their performance can differ greatly. Grossly overloaded trucks are also a problem in a number of areas, accelerating the damage to highways and bridges. [For those concerned about the controversy concerning allowable sizes and weights of trucks, see references (*4*) and (*5*).]

Environment

The expected severity of the weather—heat, cold, amount of rainfall, etc.—is considered in pavement or bridge design. Such predictions are not always correct, so the relationship of actual performance to design will vary considerably.

Maintenance

The maintenance of a highway or bridge can affect its total performance. A concrete bridge deck on which salt-laden ice and debris are allowed to accumulate is likely to show much more winter damage than bridges of equal quality that are cleaned and drained to minimize salt infiltration. Timely overlay of an asphalt pavement can greatly extend its life. Timely filling of potholes also eliminates far greater damage from the pounding of traffic. Any variation in the adequacy of maintenance measures can introduce variations in the performance of initially equal pavements and bridges.

Materials

Specifications for manufactured materials, such as metallic components of bridges and structures, cement, paint, ets., usually are established so that similar performance can be expected regardless of the manufacturer. However, natural materials, such as soils and aggregates, vary widely from source to source. Specifications for natural materials tend to set the lowest acceptable quality and may be affected by availability. This leads to considerable variability in the materials obtained under the same construction specifications, which may also result in performance variations.

Design

A highway or bridge designer attempts to consider all the traffic, environment, and materials factors affecting the performance of the highway facility and sets the level of quality for the project, which becomes the target for compliance. When environmental factors are more severe than expected or traffic is much greater than predicted, shorter life of the facility may result even though all design specifications were met. This will be discussed in more detail in Chapter Two.

Specifications

Specifications and the problems of assuring compliance to specifications will also be discussed in Chapter Two. At times, inadequate performance can result from inadequate specifications, but performance is often controlled by variation in compliance to the specifications. Thus it is usually impossible to judge whether or not a given specification alone is adequate for assuring good performance.

The variation in construction that can be obtained under the same specification was illustrated by Otte (*6*) at the Transportation Research Board (TRB) 1979 annual meeting. A study of nine South African projects involving cement and lime-treated materials showed day-to-day variations in tested characteristics of the treated material. Statistical analyses indicated that although a day's work using the same materials and equipment could be considered homogeneous, the differences between sections constructed on different days were significant, even when the sections were constructed with the same materials, by the same contractor, and according to the same specification.

Otte also studied 14 pavements that were built by different road authorities (*7*). Although all 14 were constructed to the same specifications, there were significant differences in material properties. The bending strength of beams from field specimens varied between approximately 400 and 4,400 kPa, a factor of 10. The strain at break varied between approximately 113 and $251\mu\epsilon$, a factor of 2.2. And the elastic modulus varied between approximately 3,700 and 38,900 MPa, a factor of 10.5. Otte pointed out that cement-treated materials should not be regarded as having the same structural capacity just because they were built to the same specifications.

It should be noted that these projects involved mixed-in-place construction and probably represent considerably wider variations than would be represented by plant-mixed materials. Nevertheless, the wide variations emphasize the difficulties involved. Otte indicated that about a 30 percent reduction of strength values obtained with laboratory-prepared specimens generally was necessary to estimate field values. However, the actual differences between laboratory and field specimens varied widely.

Contractor Performance

Although it is difficult to document, many highway engineers recognize that different contractors operating under the same specifications, with essentially the same materials and measured degree of compliance, can attain different performance qualities. The reason for this is *people.* No system of specifications and quality assurance procedures can build in quality. That is done by persons operating the equipment, inspecting, and testing. The skill and attitude of the people on the job have a significant effect on construction quality and subsequent performance.

Abdun-Nur (*3*) points out that specifications are often written to infer adversary relationships between the owner's representatives and the contractor and that when the owner's representatives take such an attitude, costs can be increased and the work delayed. "What is needed is contract documents that engender cooperation and teamwork and that are above all equitable to both sides. This cooperation is the only way to reduce costs, expedite the work, and assure attainment of quality."

A review of various states' instructions to their inspectors and highway engineers shows that almost all of them emphasize the need for a cooperative attitude between state and contractor personnel. Fortunately for the highway industry, most contractors intend to do a good job, because this, in fact, is good business. However, the state cannot assume that this is always true and must guard against those few who would take advantage of any weakness in inspection or acceptance procedures.

Inspection Procedures

Inspection procedures will be discussed in more detail in Chapter Two. For now, their importance should be noted. While not necessarily deliberate, there is a tendency to tolerate improper work or poor materials if inspection is not expected and to take more corrective action if inspection is expected. It is human nature to do a better job when someone is looking over your shoulder for mistakes than when no inspection or only token inspection is anticipated.

Control Tests

Control tests measure the compliance of a material to the process or specification tolerances. If the process is properly controlled, compliance with specification requirements is attained. Good performance is also expected under these conditions. However, even 100 percent compliance with a poor or improper specification cannot assure good performance. The significance of and problems associated with control tests will also be discussed in Chapter Two.

Acceptance Procedures

Acceptance procedures are the final step in the quality assurance system. They determine the conformity to the specifications and affect performance to the extent that they adequately detect noncomplying materials and construction and generate necessary remedial measures. They will be discussed in Chapter Two.

CHAPTER TWO

QUALITY ASSURANCE SYSTEMS

DEFINITIONS

To avoid misunderstanding, some of the major terms associated with quality assurance will be discussed and the definitions as used in this report will be given.

Quality Assurance

The term "quality assurance" has been used by different authors in different ways. Willenbrock and Marcin (*8*) define it as follows:

> Quality assurance, broadly interpreted, refers to the total system of activities that is designed to ensure that the quality of the construction material is acceptable with respect to the specifications under which it was produced. It addresses the overall problem of obtaining the quality level of a service, product, or facility in the most efficient, economical, and satisfactory manner possible. The scope of the total quality assurance system (regardless of the type of material specification used) encompasses portions of the activities of planning, design, development of plans and specifications, advertising, awarding of contracts, construction, and maintenance.

Abdun-Nur pictures the total quality assurance system (Fig. 1) as being made up of both technical and nontechnical subsystems. The nontechnical (or social) subsystem was discussed in Chapter One. The technical system begins with the design stage and progresses through drawings and specifications, contractor estimating, awarding of contract, and construction, with feedback from construction and testing. Abdun-Nur sees product control and inspection as responsibilities of the contractor and acceptance testing and inspection as responsibilities of the owner.

Application of the term quality assurance to the total system is also generally reflected by European writers. This is indicated in the various papers published in proceedings of the 1970 Symposium on the Quality Control of Road Works sponsored by the Organization for Economic Cooperation and Development (OECD) (*9*).

At the 1978 Quality in Construction Conference in Texas, LaHue (*10*) defined a modern quality assurance system as:

> . . . the overall process whereby the joint efforts of industry, state, and Federal officials are combined to develop or establish performance related quality criteria, exercise systematic process control, establish attainable specification criteria that recognize product variability and develop unbiased sampling and testing procedures. Or to put this in the most simplistic terms, modern quality assurance for highway construction is a process to assure the development of better highway facilities through effective process control, product acceptance, product sampling and testing, and systematic feedback and evaluation.

This definition outlines in specific terms the objectives of FHWA's program to improve highway quality.

Willenbrock and Marcin employ the term "modern quality assurance procedures" to describe the use of statistical probabilities for quality assurance (*8*). Ledbetter uses the term "quality assurance type" to describe such specifications (*11*). The Associated General Contractors of America (AGC) has defined quality assurance as follows: "The activities of the contracting agency in monitoring the contractor's program when Contractor is responsible for Quality Control" (*12*). The use of the term quality assurance in this restricted sense is not consistent with the general consensus of other literature.

An effort has been made in this report to avoid a single term or acronym to describe specifications making use of statistical probabilities. Rather, such terms as "statistically oriented," "statistical quality assurance techniques," or "specifications using statistical probabilities" have been used interchangeably as appropriate. When such terms are employed, they refer to decision making based on random sampling techniques and the knowledge of how sampling and testing variability are expected to relate to the total population of the item being tested. Estimation of the risk that the decision may be in error is also a part of the total technique.

Quality Control

The term "quality control" (synonymous with "process control") describes the activities that make the quality of a product what it should be. Agencies using statistical probabilities customarily assign the total responsibility for quality control to the contractor. States using the traditional approach generally consider quality control the total effort to produce a product within specification limits, including tests or inspections made to assure that the specifications are met. Consequently, in the latter case there is no distinction between quality control and acceptance sampling and testing.

In this report, quality control refers to those activities (normally assigned to the contractor or producer) carried out to assure that the materials or construction conform with the specifications. This concept of quality control does not include acceptance sampling and testing.

Acceptance Sampling and Testing

Acceptance sampling and testing is the term generally used to define the samples taken and tests made by an agency to assure that satisfactory quality control has been exercised and that the proper degree of compliance to the specifications has been attained. It will be used in that sense in this report.

Recipe or Method Specifications

These two terms are used interchangeably to mean those specifications that not only state what is wanted, but also the manner by which it is to be attained. For example, for an asphalt pavement, the gradation, asphalt content, type of asphalt, etc., would be specified as well as general types of equipment for mixing and mixing temperature. Limitation might also be placed on the hauling and lay down equipment and the types of rollers and patterns of rolling. This type of approach is traditional for many highway operations.

End-Result Specifications

This term means different things to different people, creating considerable misunderstanding. To some, an end-result specification implies that the state or the consumer organization will define the product wanted and will examine only the final product to decide if it is acceptable or not. As yet, no state has adopted a specification under which a total project is to be built by the contractor and the final product in place is to be accepted or rejected by the state. Generally, advocates of end-result specifications for highway construction believe that detailed "how to" instructions should be eliminated and that units of construction should be accepted or rejected on a lot-by-lot basis by measuring significant characteristics of the completed lot. Thus, for asphalt concrete, the job mix formula would be approved and limitations set on gradations, etc., but only the final mixture would be examined for compliance. The contractor would have freedom to choose the type of rollers, rolling pattern, and so forth.

NCHRP Synthesis 38 (*2*) defines end-result specifications as follows:

> Essentially this (adoption of end-result specifications) means that instead of inspecting the process that produces a certain material or item of construction the agency monitors the contractor's control of the process and accepts or rejects the end product.

The synthesis further states that, "An end-result specification places the entire responsibility for quality control on the contractor." It also assumes that random sampling and statistically oriented acceptance plans are requirements of the end-result specification. This definition and the general use in the report imply that all end-result specifications must be statistically oriented. This concept is believed to be the source of much of the concern expressed by the Associated General Contractors (AGC) in their position paper on statistically oriented end-result specifications (*12*), because the term "end result" in highway use does not always mean that statistical acceptance procedures are used.

Performance Specification

This term is also used in different ways by different people. A "performance specification" is sometimes considered synonymous with end-result specification. However, AGC defined performance specification as "that portion of construction specifications that dictates how the work is to be performed, tested, and accepted" (*12*). The AGC includes end-result and recipe (or method) as two different types of performance specifications. This definition is not generally used by highway agencies. More often, a performance specification describes how a product must *perform* its function in the highway or structure. Thus, a traffic marking paint is required to resist certain accelerated tests and have certain drying and reflective characteristics. These are performance requirements—no restrictions are placed on the composition of the paint. Performance specifications are also used with respect to components such as pipe, requiring a particular metal and certain strengths for specific geometric sizes and configurations.

At times, the term performance specification is also associated with the use of statistical concepts for inspection and testing. However, this definition is not universally accepted, as indicated by the replies to the questionnaire discussed in Chapter Five. When that questionnaire was prepared, it was assumed that end-result and performance specifications were synonymous terms. However, some states apparently make a distinction between the two.

In this report, performance specification will be used synonymously with end-result specification to distinguish it as a type other than recipe (or method). However, there can be different types or degrees of performance and end-result specifications.

Standard Terminology

Other special terms referred to in this report are generally well-defined, and there is little disagreement on their meaning. Consequently, such definitions are not included here. However, the reader may wish to refer to *NCHRP Synthesis 38* (*2*) for definitions of terms not discussed.

Efforts are underway to establish more uniform use of terms concerning quality control and acceptance procedures within the highway industry. Several highway organizations have established task forces to accomplish this objective. The American National Standards Institute (ANSI) and the American Society for Quality Control (ASQC) also have recognized the need for better definitions and adopted several joint standards dealing with the problem. They are ANSI/ASQC Standard A1-1978, "Definitions, Symbols, Formulas and Tables for Control Charts"; ANSI/ASQC Standard A2-1978, "Terms, Symbols, and Definitions for Acceptance Sampling"; and ANSI/ASQC Standard A3-1978, "Quality Systems Terminology."

Freund (*13*) reports that ASTM Committee E-11 is reviewing these documents and will probably adopt the standard terminology for use in the "Compilation of ASTM Standard Definitions."

Freund also discusses the confusion that results from each industry adopting special terminology, with the result that a commonly used word or expression may have a special meaning in the context of the standard. In particular, he discusses the difficulties from using a word such as "defect" to mean any departure from a specification. The departure often may be so minor that performance would not be affected, but use of the term implies an inferior product. Freund points out that "the luxury of unique definitions for each specialty is no longer viable." He also states that "loose usage of words like 'defect' may halt the collection of important data or result in unproductive name-changing games."

MAJOR COMPONENTS OF QUALITY ASSURANCE SYSTEMS

It is difficult to categorize all the facets of quality assurance into distinct systems. Various combinations of approaches are used by different agencies. Figure 2 represents the typical steps taken and illustrates the relationships between them. As indicated, the first step for any project is to determine what is needed. This determination is based on society's needs, environmental conditions, expected traffic, etc. The second step, design, represents the first effort to match the physical layout, the appearance, and the functional characteristics to the needs. The plans and specifications then describe the measures to be taken to build the desired facility and spell out the necessary efforts to assure that the constructed facility is what is wanted.

Up to this point, different design techniques may have been used and different decisions as to desired quality level may have been made, but in general all the decisions will have been based on the same principles. However, different approaches are used by different agencies in establishing specifications and determining compliance to those specifications.

A quality assurance system has been pictured as consisting of those efforts needed to answer three questions (*1*, *14*). For completeness, a fourth question needs to be added.

1. What do we want?
2. How do we order it?
3. Did we get what we ordered?
4. What do we do if we don't get what we ordered?

Answers to the first question encompass research, development, engineering technology, and experience. All these combine to define needs with respect to materials, properties, and design characteristics of the highway component.

Answers to the second question depend on the manner in which the details are spelled out in specifications. These include the approach that the specifications take in defining the characteristics that must be controlled, needs with respect to the quality level, and requirements for uniformity of the product from item to item.

Answers to the third question depend on the precision and accuracy of test methods. The time required to perform the tests is also a factor, because it often controls the number of measurements that can be made available for use in decision making. More importantly, the relation of the characteristic or property measured by the test to the performance of the completed component is a major consideration that often is known only empirically, if at all.

The fourth question relates to the controversy over decreased payments when deviations occur that are not sufficient to warrant removal. The question of possible bonus payments for better-than-specified construction also arises.

The following sections explore the prevailing situations with respect to each of these questions.

What Do We Want? (Planning and Design Stage)

Research and the development of technology continually improve design and knowledge of expected behavior. Although they are not often thought of as quality assurance activities, they may be major aspects of the system that establishes acceptable levels of performance. When the proper materials are specified, the design is correct, and good construction practices are followed, gross deficiencies are ruled out from the beginning. Expressed in another way— the *quality of design* may be considerably more important than the system used to assure compliance to that design.

> The quality level is something more than simply the quality of the physical materials that constitute a structure or project. The quality level is judged by how well the finished project or structure serves society—physically, functionally, emotionally, environmentally, and of course economically (*3*).

> *Planning* initiates the Quality Assurance System by surveying society's needs and desires and establishing broad goals to meet those needs. This basically defines the quality needs of a project.
> The next element within the system is design. Herein the quality levels of the transportation facility are set, based on a trade-off analysis of available resources. Quality levels become fixed at this stage in terms of what is required. The end product can have no higher quality than that reflected in the design (*8*).

How Do We Order It? (Plans and Specifications)

In establishing specifications for pavements or highway structures, different approaches have been defined and different terminologies have been used. Willenbrock and Marcin describe three approaches: (a) end result, (b) materials and methods, and (c) statistically based quality assurance (*8*). The system they refer to as materials and methods is defined as recipe type in this report. The system referred to as statistically based quality assurance is that referred to as statistically oriented end-result specification (ERS) in *NCHRP Synthesis 38* (*2*).

Prior to 1950, the recipe system shown in Figure 2 was used to assure the quality of most U.S. highway construction. In more recent years, increasing emphasis has been placed on end-result or performance specifications. Although these two terms are not well-defined, it can be assumed that efforts to move away from recipe specifications are in effect efforts to establish performance or end-result specifications.

Thirty-two of the 43 states replying to the questionnaire said they used both recipe and performance specifications, which may illustrate the evolution now in progress with respect to the manner of writing specifications and determining the degree of compliance. For major items of highway and bridge construction, no state has as yet adopted the performance approach for all its activities, but some have established procedures in which the basic

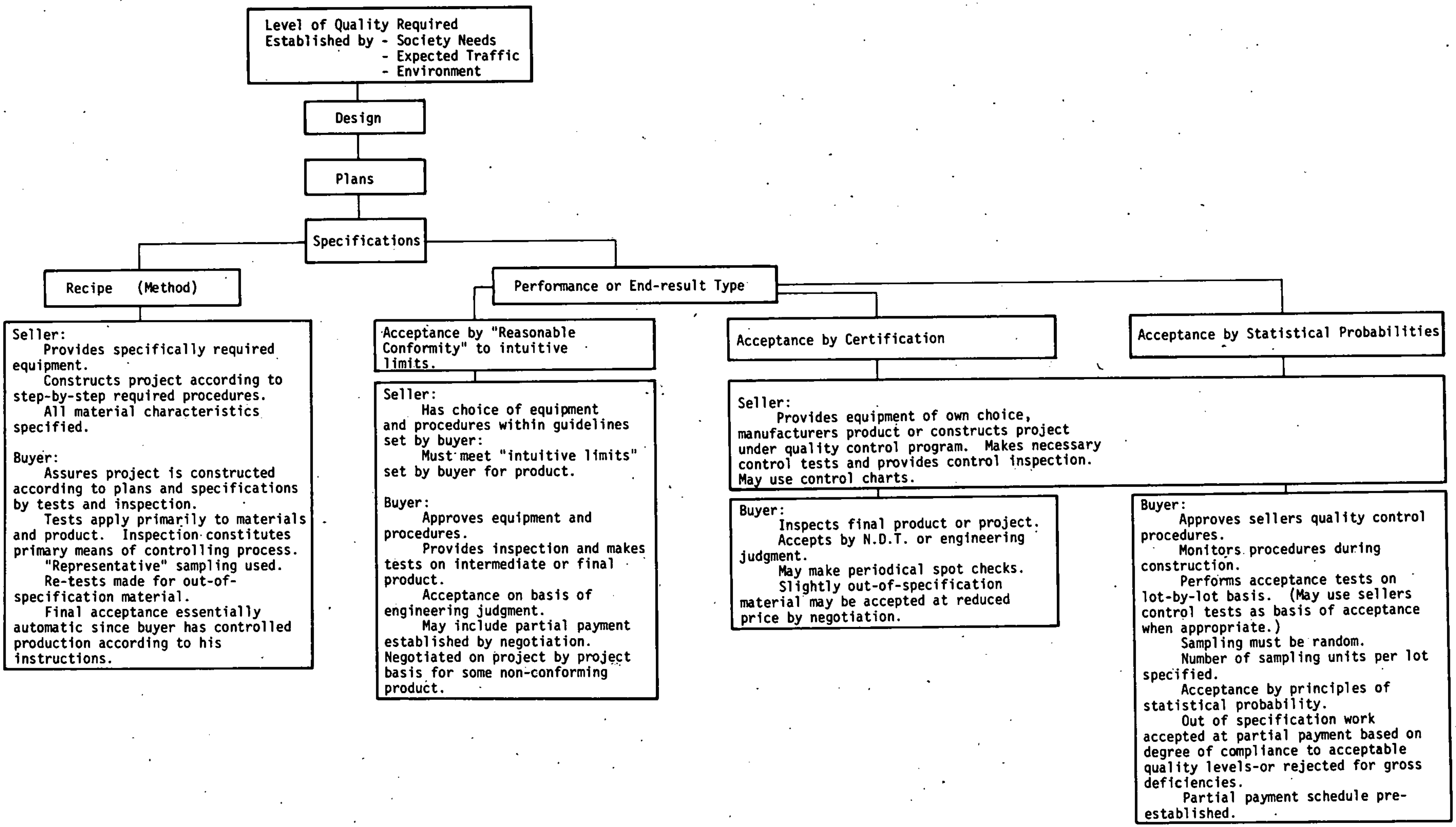

Figure 2. Typical steps in quality assurance systems for highway construction.

principles of separating control from acceptance testing apply and in which estimates of risk can be made. Most states have adopted an end-result approach by establishing the desirable characteristics of intermediate materials or products—for example, requirements for types and weights of roller have been replaced by requirements established on the basis of the density characteristics of the compacted pavement. This type of end result has the support of almost all contractors as well as buyer agencies.

Abdun-Nur (*3*) indicates that the main weakness of most construction specifications is that they are copied from previous work. He points out that many specifications draw a sharp line between passing or failing and do not properly take into account normal variability of materials and construction. Under these circumstances, he says, use of the principles of probability is the best approach to acceptance, but use of the term "statistical specification" has been unfortunate because engineers generally lack familiarity with statistical principles and terminology. This was true at the time the idea was introduced, but as the program to develop specifications using statistical probability has progressed, numerous workshops, symposiums, training schools, etc., have been held to acquaint engineers with the basic concepts and to properly train those involved. Those organizations that have made a determined effort to understand the new approach and to train their personnel have made considerable progress. Unfortunately, there is evidence that those who oppose the use of specifications based on statistical probability have continued to overstress the difficulties and often misconstrue the meaning and significance of such programs.

Did We Get What We Ordered? (Inspection, Testing, and Acceptance Procedures)

To answer this question, reliance is placed both on the skills of the engineer or inspector and on the results of a system of sampling and testing. This is true regardless of the type of specification being used—recipe or statistically oriented end result. There is a difference, however, as to how the samples are taken and how the results are interpreted. The extent to which the inspector or engineer can make subjective decisions also differs somewhat. Under the end-result approach, the contractor's personnel normally control production and make any necessary control tests. The purchasing agency's personnel inspect the finished product and sometimes test (nondestructively, if possible) the representative sections or items. Under the recipe approach, the purchasing agency's inspector observes the procedures and make necessary tests as construction proceeds. Considerable dependence is placed on the ability of the inspector to detect improper procedures or inferior materials. Under this system, representative samples of materials are taken during the course of the construction to document their acceptability. Most agencies have requirements for a minimum number of samples and tests for a quantity of material or amount of construction, but the engineer or inspector may choose when or how such samples are taken. On the other hand, those agencies using statistical quality assurance techniques require that a specific number of samples (sampling units) be taken on a random basis. The inspection and observation of construction are still parts of the total quality assurance process under this system. This is discussed in more detail in Chapter Four.

A number of problems regarding sampling and testing adversely affect the efficacy of *any* quality assurance system in quickly reaching the best decision. Although these problems are often cited as drawbacks to the use of statistical quality assurance techniques, they also apply to the other approaches used to assure quality highway construction. These problems include:

1. The total material used in construction cannot be tested. Consequently, sample test results are only an estimate of the characteristics possessed by the total. How close this estimate is to the "true" value depends on how carefully the sample has been taken.
2. Tests are not precise—sometimes different answers are obtained even when the materials are the same.
3. It often takes too long to get the test results.
4. Often dependence must be placed on indirect or empirical measurements to estimate the characteristic desired.

Solutions to these problems are being sought continuously by organizations such as the American Society for Testing and Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO). These organizations have been actively developing and standardizing test methods for highway materials over the past 50 years. Other activities associated with test development and standardization are the Materials Reference Laboratory sponsored by AASHTO and the Cement and Concrete Reference Laboratory sponsored by ASTM.

Over the past 10 years, ASTM has attempted increasingly to establish the precision (and accuracy, where applicable) of all its standard test methods. Various committees have approached this problem in different ways, and the different approaches have caused some confusion. A series of articles in *Standardization News* (*15, 16*) represents an excellent review of the problems relating to the precision of test methods and how such precision affects specification requirements.

What Do We Do When We Don't Get What We Ordered?

In dealing with a truckload of furniture or other individual small units, the defective items can always be sent back to the manufacturer. However, this is not possible with a section of pavement or a bridge structure. Although it is legally possible to insist that failing material be replaced, replacement delays prolong traffic tie-ups and incur extra work for inspection forces, which increases payrolls. Consequently, the principle of reasonable conformity and partial payments has been established. This principle can be applied under any quality assurance system, and the consequences (with respect to performance) of allowing nonconforming construction to remain in place will be the same in all cases. However, the problem is handled differently by those using recipe specifications and those using statistical quality assurance techniques.

Everyone agrees that at some point gross deviations from specifications justify the replacement of defective material or items of construction. It is also generally agreed that normal variability in materials and construction processes sometimes will result in minor variations from the specifications that will have no appreciable effect on performance and that full payment is justified. In between is the "gray area" where the material or construction can provide good service, although probably not as good as that specified. In such cases, it is advantageous to leave the material or unit of construction in place and reduce the amount paid for it. Ideally, the payment reduction should be based on the loss of effectiveness—including the loss of comfort to the public and extra costs generated by earlier maintenance or reconstruction. Unfortunately, these things are very difficult to determine accurately, and engineering judgment must be applied to resolve the questions.

Under the older system, each nonconforming project was evaluated separately and agreement on payment reached through negotiations between the parties concerned. When using statistical probabilities in this type of situation, a means is provided for systematically applying engineering judgment in a uniform manner. Preset partial payments for different percentages of materials within definite ranges of characteristics are established. The payment to be made becomes a part of the contract, and the question of whether or not deficiencies in compliance with the specification are damaging to the state should not arise. The contractor knows ahead of time what the reduction in payment will be for specific levels of test results and variability. There is, of course, no guarantee that the variability always will be exactly as estimated by statistical probabilities, but if sampling and testing have been properly carried out, a high level of confidence can be assumed. Some of the problems arising from this concept are discussed in Chapter Four.

CHAPTER THREE

CONCEPTUAL DIFFERENCES BETWEEN TRADITIONAL QUALITY ASSURANCE SYSTEMS AND SYSTEMS USING STATISTICAL PROBABILITIES

The purpose of this synthesis is to review the relationship of all quality assurance procedures to the performance of highway facilities. However, the major effort to improve performance through increased quality of construction has centered recently around the use of statistical probability techniques in specification and acceptance procedures. Despite considerable promotion by FHWA and progress within some states, only a few more than half of the states have employed statistical quality assurance techniques, and many of those do so on a limited basis.

A few states have categorically rejected the idea of using statistical probability techniques. Others have experimented and decided not to implement such specifications at this time. Still others have found them highly satisfactory and are continuing to develop the statistical approach. To better understand the reasons for this disparity in acceptance, it is necessary to review the development of statistical quality assurance techniques. The goal of such a review is to dispel misunderstanding and permit a more objective evaluation of the conceptual differences between the traditional approach and the application of statistical quality assurance techniques. Agencies can then better judge the advantages and disadvantages for their specific problems.

In the United States, FHWA was the first to advocate probability concepts as the basis for measuring the compliance of highway construction. The objectives of the program are summarized as follows (*17*):

1. Development of realistic quality criteria.
2. Development of valid quality tests.
3. Development of valid decision-making rules.
4. Quantification of substantial compliance.

Because it was proposed that the principles of statistical probability be used as the basis for "valid" decision-making rules and for quantification of substantial compliance, this program was generally recognized as being aimed at the development of statistical specifications. Many highway engineers and contractors were opposed to such applications, which depended on a calculated result from a formula that they really didn't understand and that even its advocates admitted was not always precise. The opponents believed (and many still do) that it was better to rely on the engineer's judgment, backed by knowledge and experience in making decisions concerning the acceptability of materials and construction.

The U.S. effort to apply statistical probabilities in highway specification and acceptance techniques, although independently initiated, was part of a worldwide recognition of the need to improve quality assurance of highway construction in all areas. This is demonstrated by the proceedings of the 1970 Symposium on the Quality Control of Road Works sponsored by the Organization for Economic Cooperation and Development (OECD) (*9*). Although their approaches differed, almost all of the 14 countries represented at the symposium reported efforts to use probability concepts to develop improved systems. In some cases, these efforts were of long standing (10 years or more). Initial efforts in almost all European countries predated efforts in the United States. Significant sections of the European papers, which reflect the philosophy or approach taken by each country, are given in Appendix A. These papers and the ensuing discussions reveal essentially complete agreement among the various countries as to the overall objective of the quality assurance procedures. The major problems identified were also about the same in each country. However, differences existed in the traditional way these problems had been handled as well as in details of efforts to improve the system.

Appendix B lists some major publications concerning quality assurance that are not otherwise referenced in this report. These publications, along with those specifically referenced here, should provide a general picture of developments in the United States. However, additional references can be attained by inquiry of the Highway Research Information System (HRIS).

The literature reveals several problems with respect to quality assurance, some of which have been partially resolved although others are still subject to considerable controversy. The traditional and statistical approaches also differ somewhat in their concepts and interpretation with regard to sampling, testing, and decision making. The differences are discussed in the following sections.

THE ROLE OF STATISTICS IN QUALITY ASSURANCE

The use of statistics can neither assure quality of performance nor will their application interfere with performance. Statistics and the laws of probability must be recognized for what they are—*tools* for measuring the *quality of compliance* with predetermined levels of characteristics spelled out in specification documents.

One of the problems encountered in using the statistical approach is the difference in meaning of terms in the engineering sense and in the statistical sense. For example, under a statistical approach acceptability is often established by limiting the percentage of defective material. In principle this is a good approach, but a unit of defective material in highway construction is very difficult to define. In statistical terms, a defective unit is one for which the mean of the measured characteristic is outside the range of values established by the specification. The product could be capable of performing its intended function with no loss of usefulness. When dealing with populations of variable materials, it is possible also that a lot will contain some percentage of acceptable material and still be considered statistically defective. On the other hand, an engineer is likely to consider a product defective only when its ability to perform its function has been affected. Thus, a contractor or supplier objects to being penalized for a statistically defective units of material or construction when engineering judgment says that it will provide the performance required.

The difficulties created by use of a term such as "defective" in statistical evaluations have been recognized (*13*). ANSI/ASQC standard A1-1978 makes a distinction between different degrees of departure from conformity. Under this standard, three definitions are given:

Imperfection—A departure of a quality characteristic from its intended level or state without any association with conformance to specification requirements or to the usability of a product or service.

Nonconformity—A departure of a quality characteristic from its intended level or state that occurs with a severity sufficient to cause an associated product or service not to meet a specification requirement.

Defect—A departure of a quality characteristic from its intended level or state that occurs with a severity sufficient to cause an associated product or service not to satisfy intended normal, or reasonably foreseeable, usage requirements.

Using these definitions, what has been termed a "defect" in the preceding discussion would be termed a "nonconformity." It would remain a matter of judgment as to whether the nonconformity was sufficiently severe to be termed a defect. Such subjective judgment does not provide an adequate basis for making consistent decisions concerning product acceptability.

REALISTIC QUALITY ASSURANCE LIMITS

Under the traditional recipe approach to specifications and the system of measuring compliance, certain levels of construction characteristics have been assumed to be present when tests on samples showed conformity to the prescribed limits. However, the AASHTO road test (*18*) and a more recent FHWA report (*19*) both indicate that the amounts of material and construction characteristics outside specified limits are much greater than those assumed to be present.

The FHWA survey concludes that a "considerable gap exists in highway work between the quality of work specified and the quality of work received." (Quality here refers to quality of compliance to specifications limits and not quality of performance.) Further, "in some instances the specification limits are unrealistic and do not allow for normal testing variability and process variability. This accounts for a portion of the seemingly low quality levels registered for the work."

The FHWA verification of findings from the AASHTO Road Test strongly indicates that much of the present variability in highway construction reflects the limitations of the system now employed by most of the industry. The observed variability in many processes probably reflects normal functioning of the equipment in use. There is also a strong indication that when probability concepts are applied, materials and construction providing satisfactory performance exhibit greater variability and a larger percentage of characteristics outside of stated limits than is thought to be present by most highway engineers.

In moving towards a statistical basis for acceptance limits, it was first necessary to obtain data that would show what levels of characteristics and the degree of variability that were exhibited in normally "good" highway construction. Considerable research effort went into this task (*20*). These or similar data have been used to develop acceptance criteria based on statistical probabilities for various types of work. Although it is assumed that the traditional variability and level of characteristics represent generally satisfactory levels of performance, no direct relationships have been developed to show the damaging effects of deviations.

In some instances, statistically-derived limits are used experimentally to duplicate present limits. Use of these limits, coupled with partial payment schedules for materials outside them, means that contractors are paid at a reduced rate for a portion of their work. Under the old system, such material probably would have been judged within reasonable conformity and full payment would have been made. This, of course, generates contractor opposition to such systems. States using statistical quality assurance techniques should be aware of this difference in concept. Unless it is necessary to tighten specifications to improve performance, consideration should be given to designing statistically oriented specifications to provide 100 percent pay for the normally accepted "good" job.

THE ROLE OF ENGINEERING JUDGMENT

There is considerable controversy over the role of engineering judgment in applying statistical probabilities to highway construction (*10, 12*). It is universally recognized that those agencies operating in the traditional manner expect engineering judgment to play a very important role in obtaining good construction. They point out that variations in natural materials, weather conditions, etc., necessitate continued application of good judgment to establish optimum working conditions and keep a project on schedule. In particular, they believe it is necessary to exercise engineering judgment in accepting materials showing reasonable conformity to specifications. Those opposing the use of statistical probabilities often cite the desire to retain this use of engineering judgment as their chief reason for not accepting the statistical concept.

Proponents of the statistical approach point out that engineering judgment is still used to establish proper specifiactions and suitable variability around target values. They also point out that when this is properly done, engineering judgment becomes a known and constant factor. It is applied equally to all projetcs. Under these circumstances, the contractor knows what to expect—the amount to be paid for nonconforming material or the conditions under which removal may be necessary. Although unforeseen circumstances may dictate changes based on engineering judgment, there is no reason why such judgment (or common sense) would not be equally applicable under any system.

LaHue (*10*) points out that statistical quality assurance techniques are not designed to remove engineering judgment from the highway industry:

> Engineering judgment is still very necessary because we use products that have variability. But, this engineering judgment is something that should be applied uniformly and equitably to all contractors. There have been known occasions where local contractors would add a straight percentage to the cost of a project based on their knowledge of who the engineer would be and their further knowledge of how he exercised his particular engineering judgment. Therefore, the best place to utilize good engineering judgment is not in the acceptance of the product, but is instead in the development of specifications that are based on achievable requirements. The use of good engineering judgment at this level and providing the field engineers with a basis for determining acceptability will lead to defensible specifications that can be uniformly applied to any project under the supervision of any engineer. Also the proper application of good engineering judgment in the specification will provide the contractors and material suppliers with the knowledge that they need concerning acceptance procedures and requirements. With this knowledge they will almost immediately know whether or not their product is fully or partially acceptable and they will still have time to make the necessary process adjustments.

SAMPLING

Proper sampling is a necessary step toward determining compliance with the specifications under both the traditional approach and when using statistical probabilities. However, the concept of a sample is different. Under the traditional recipe approach, a sample is a single unit of material that is considered to be representative of the total material involved (lot). Under the statistical approach, the sample will consist of n number of sampling units, which, in order to fulfill the requirements of the theory of statistical probability, must be taken randomly. Each unit is considered representative of the sublot involved, but it does not necessarily represent the total lot. However, the mean of test results on all the sample units estimates the mean of the total lot. The range in values for the sample units gives a measure of the variability of the lot.

Under the traditional concept, sampling and testing are likely to be conducted at regular intervals, with increased testing when the material "fails." Often a failing sample is disregarded when subsequent retests give passing results, or results of several samples will be averaged to represent the reported value. Decisions concerning the acceptability of test results are based on the judgment of the engineer or technician. When the judgment is good, the correct decision concerning the acceptability of the product probably is being made, but trouble could result if the judgment is poor or biased.

Under the statistical approach, the established rules of probability are applied. Here, single test results should not be discarded unless there is *clear evidence* that the sample was improperly taken or the test improperly run. A "feeling" that something may have gone wrong is not sufficient reason for discarding a test result. Acceptability of the lot is based on both the mean of the tests run and the range or variability of individual tests. The number of tests run affects the acceptability ranges, and final decisions concerning the acceptability of the lot can be made only after all applicable tests are completed. Thus, the concept of control testing or process control, as a separate entity from acceptance sampling and testing, is applied.

TESTING

Under the traditional approach, the precision of a test and the number of tests available for making a decision only enter into the subjective evaluation of the confidence that can be placed in that decision. However, when using statistical probabilities, the precision and number of tests available specifically affect the estimated confidence level of the decision and the estimates of the percentages of material within specification. As a general principle, the greater the number of tests available, the lower is the risk that an erroneous decision will be made. Because of the time-consuming nature and costs of most tests made on highway materials, the number of formal tests that are economically feasible is limited. Thus, from a statistical viewpoint, the risk of accepting out-of-specification material may at times appear large.

However, in a broad sense, a test is merely an observation, and a knowledgeable engineer or plant inspector can make a number of tests through observation. For example, the appearance of asphalt mixture as it is discharged from the pugmill will usually indicate to the experienced inspector whether or not the asphalt content is too high or too low or the gradation is normal. None of these eyeball tests, however, become a part of the written record. This is true whether or not statistical techniques are used. Consequently, the lack of written, formal test results does not necessarily indicate a lack of control, provided a knowledgeable engineer or inspector has kept a close watch, assuring that everything was operating normally. For this reason, it is likely that the true risk of accepting nonconforming materials or construction is less than the calculated risks based on recorded test results.

INSPECTION

Good inspection is essential to any quality assurance system being used. Early opponents of statistical quality assurance techniques often misunderstood the role of the inspector with respect to random sampling. Because samples were to be taken on a predetermined, randomized schedule, some thought that an inspector was not needed between sampling periods. They believed that action could not or should not be taken even if something was obviously wrong. This belief is erroneous. The laws of probability operate only when the variations in a process are "normal," that is, when all of the factors affecting results are under control and operating within the range and manner expected. When a valve is clogged or a scale is not properly calibrated, deviations from specifications occur for cause and are not chance variations. Action should be taken immediately when malfunction is detected—and someone, whether an employee of the contractor or a state inspector, should be present at all times to detect possible malfunction.

CONCEPT OF RISK MANAGEMENT

The properly designed, statistically based sampling and acceptance plan allows the state and contractor to establish the risks involved—for the state the risk of accepting materials outside the specification and for the contractor the risk of having acceptable material rejected. This concept is perhaps the least understood element of statistical quality assurance techniques. (For an excellent discussion of risks in specification, control, and acceptance of road materials, see the summary of the article by Mathews and Hardman in Appendix A.) Major objections raised by contractors are the fear of receiving partial payment for work they consider completely satisfactory and the feeling that they have no control over this aspect of the situation. However, through proper control procedures, the contractor often can reduce the risks being taken. With some materials and processes, control levels can be established sufficiently high so that the risk of having any material rejected is very low. In other situations, the risks might be related to the variability of the material or process and would be difficult to reduce. However, the contractor can estimate the risk being taken and adjust the bid accordingly.

States not employing the statistical approach sometimes do not understand the principle of risk. Under recipe specifications and the reasonable conformity concept, the risk of accepting work outside established limits is always present, but it is not estimated or measured in quantitative terms. When determining reasonably close conformity, the state often gives the contractor the benefit of the doubt and makes full payment. Consequently, deviations from specifications under the recipe system are likely to be considerably greater than thought by those using the system. Because the purchasing agency has assumed the responsibility for all testing, it also assumes most of the normal risks for out-of-specification material that would fall to the contractor under statistical quality assurance techniques. Thus, under the recipe system, rejection of material (or partial payment) is likely to occur only when large deviations are present—most likely from assignable causes. These factors do not operate in the contractor's favor when statistical probabilities are employed.

This change in the traditional acceptance pattern is a reason many contractors initially object to the adoption of statistical concepts. However, the overall advantages to the contractors reportedly outweigh the disadvantages, and once the system is understood, they operate successfully under it. In particular, the statistical system favors the contractors with good materials and good control, because they can count on essentially 100 percent payment for all materials. Contractors with poor materials or poor control either have to improve their materials and control or increase their bids to allow for partial payments. This should provide better performance for the purchasing agency and also be an advantage to the better contractors.

RESPONSIBILITY FOR CONTROL TESTS

In general, for any quality assurance system, process control is a responsibility of the contractor (or producer), and acceptance sampling and testing are responsibilities of the purchasing agency. These functions are clearly separated in the manufacture of products such as steel girders, portland cement, and asphalt, but for construction items such as asphalt mixtures or portland cement concrete the functions become interwoven. Traditionally, using recipe specifications, state personnel run the tests and, in effect, control the process. Although a number of states caution their inspectors about giving orders or process changes to plant operating personnel, and the legal responsibility for control is with the contractor, the process, in fact, is controlled by the states' acceptance tests.

Under a complete statistical quality assurance system, the control and acceptance tests are two separate functions—the former being the responsibility of the contractor and the latter being the responsibility of the purchasing agency. Because control tests and acceptance tests are often the same procedure in highway construction, duplication by contractor and state personnel often is considered unnecessary.

This point is emphasized by the AGC (*12*):

> Quality control (sampling and testing) by the contractor is a duplication of effort that will not reduce significantly the number of state personnel required.
> Placing responsibility for quality control on the contractor requires the hiring of technical personnel that cannot be utilized efficiently or the hiring of commercial engineering testing laboratories which charge professional rates.
> Even though the contractor performs the quality control, the state must have similar personnel for its quality assurance (meaning acceptance sampling and testing as used in this report) program.
> Specifying that the contractor be responsible for quality control (sampling and testing) would cause significant increases in the cost of that item to the taxpayer on most projects.

Substantial cost increases predicted by the AGC due to shifting the responsibility of control testing to the contractor have not occurred in those states using statistical probabilities. Most states avoid complete duplication of testing in their acceptance procedures.

In West Virginia's system, the contractor details the methods, including sampling and testing, by which the quality control program will be conducted (*14*). This plan is reviewed by the state prior to the beginning of the project so that any discrepancies from the state's guidelines can be resolved at that time. Although acceptance sampling and testing are the state's responsibilities in these specifications, it may use the contractor's quality control sampling and testing for acceptance.

BONUS PAYMENTS

The concept of a bonus for better-than specified work is unique to statistical quality assurance systems. Normally, the acceptable population of construction characteristics will contain a small amount of material (say 10 percent) with characteristics not as good as desired and 100 percent of the bid price will be paid for such material. When the deviations exceed this acceptable level, partial payment is made if removal is not warranted. Because they are penalized for poorer-than-expected compliance, contractors feel they should be rewarded for better-than-expected compliance. They reason that the product will have increased life and consequently be of more value to the purchasing agency. FHWA has already recognized this incentive payment principle as acceptable for federal aid in experimental projects (*21*), and it is being considered as a general feature (optional to the state) for all federal aid projects in which a state is using statistical quality assurance techniques (*10*).

CHAPTER FOUR

STATE PRACTICES REGARDING SPECIFIC TESTS FOR VARIOUS TYPES OF CONSTRUCTION

SUMMARY OF REPLIES TO QUESTIONNAIRE

To establish general practices with respect to quality assurance, information was requested from materials and testing engineers of each state highway or transportation department. Forty-three states replied regarding their overall quality assurance procedures and the importance of the various tests included in the questionnaire.

How would you classify your specifications for highway construction: As the method or recipe type, as the end-result or performance type, or some of both?

Thirty-two states replied that their specifications were some of both. West Virginia indicated that it used statistically oriented, end-result specifications almost totally. Ten states indicated that they used recipe specifications only.

Do you use statistical concepts in your specifications? If yes, what specific materials or types of construction are accepted by statistically oriented plans?

Twenty-three states replied that they used statistical plans in accepting some materials. Nineteen replied that they did not use statistics. Ten of the 19 indicated that they had both recipe and end-result or performance specifications. Apparently, these states use end-result or performance requirements that do not include statistical plans. Unfortunately, the replies did not clearly define the type of specification that was considered nonstatistical, end-result or performance type.

The replies were generally consistent with the Appendix to *NCHRP Synthesis 38* (*2*). However, 5 states shown to be using or considering use of statistical specifications for some items in *Synthesis 38* now say that they are not using statistical concepts in their standard specifications. Tennessee, shown as not using statistical concepts in *Synthesis 38,* now reports using statistical concepts for density of subgrades, subbases, and bases.

Do you have requirements for the frequency of testing for various items? If you are not using statistically oriented plans, how much material or construction is represented by one sample? If you are using statistically oriented plans, what lot size is used for various items?

All states replied that they had requirements for the frequency of testing various items. In general, where statistics were not used, these requirements were specifically spelled out in terms of the maximum amount of material to be represented by a sample. Lot size varied among the states using statistical acceptance plans. For bituminous concrete or other hot bituminous mixtures, one day's production is often considered the lot, with five random samples selected throughout the day on a sublot basis. In other cases, a lot is defined as a specific number of tons, with some system of randomly selecting one sampling unit from each 20 or 25 percent of the lot. Lot sizes for density or other measurements on the pavement are usually established on the basis of linear or square feet. In an independent survey conducted by Hughes (*22*), the lot size for hot bituminous mixes was reported to be most often 2,000 to 2,500 tons (1 800 to 2 300 Mg), the largest being 4,000 tons (3 600 Mg).

Do you have any studies or information relating the cost or frequency of testing and inspection to the quality of performance?

No state reported specific studies to relate quality of performance to either costs or frequency of testing. California indicated a limited amount of data to show the reduction in testing costs when using a statistically oriented system as compared to the recipe approach.

In Hughes' survey (*22*), 10 of the 22 agencies reporting indicated that the use of statistical quality assurance techniques was beneficial. Six indicated it was not cost-beneficial and six were undecided. Of those replying in the affirmative, the estimated annual dollar savings were $100,000 to $1 million. The source of the savings were stated to be reductions in administration, legal suits and claims, and maintenance costs (through better construction).

Do you use nonstandard, rapid test procedures for process control (or allow contractors to use such)? Are nonstandard, rapid procedures ever used for acceptance testing?

Twenty-three states indicated that some rapid tests were used for control. Fourteen states indicated that such tests were also used for acceptance. An additional four states did not reply separately to this part of the question. Four states reported approval of rapid, nonstandard tests for control purposes but not for acceptance testing. Many of the rapid tests were described as variations of standard procedures, such as eliminating wet sieving, hot plate drying of soils, or elimination of ash corrections in extractions. In other cases, nuclear gauges were used. Nondestructive tests, such as x-rays for welds and magnetic gauges for thickness of paint or other coatings on metals, were also reported in use.

Do you use nuclear gauges or other nondestructive testing equipment for inspection or acceptance procedures? If so, for what purpose?

All organizations reporting, except Puerto Rico, use nuclear gauges in some fashion. Other nondestructive devices used were x-ray and ultrasonic equipment for inspection of welds, magnetic gauges for metal coatings, and holiday detectors for epoxy coatings. Thirty states reported using nuclear gauges for asphalt pavement density, and 35 also reported their use for density control in base courses or embankments, indicating high acceptance of nuclear gauges for these purposes. Nine states reported the use of nuclear gauges for testing the density of plastic portland cement concrete.

How would you rate the importance of the following tests for assuring quality of the final job: (1) very important —failure could affect the durability of pavement; (2) important to the public in terms of comfort but it probably has no effect on durability; (3) important for contractual compliance only—normal deviations are not likely to affect performance; (4) important during the construction phase only—not important to performance; (5) other—state purpose.

This question was designed to establish a consensus on the significance of those tests most often found in specifications for pavement construction. The replies concerning the ratings are given in Table 1. In a number of cases, a state either did not reply to a question concerning a specific test, or it gave no rating. The last column of the table gives the number of states specifically reporting that the test is not used. Those not reporting may or may not use the test, but this could not be determined.

Bituminous Construction

Specification tests for asphalt cement—are all shipments fully tested? If not, what system is used for selecting samples for testing?

Thirty-nine states indicated that not all shipments of asphalt cement were completely tested. It was not clear

TABLE 1

SUMMARY OF RATINGS FOR VARIOUS TESTS

Test	Number of States Giving Rating of: a/					Reported Test Not Made	No Report or Not Rated
	1	2	3	4	5		
Bituminous Construction							
Specifications for Asphalt Cement	36		6				1
Aggregate Gradation	30		10		1		2
Tests on Asphalt Mixture	38		1				4
Stability Test on Plant Mix	24		4		2	11	2
Pavement Density	37		2				4
Pavement Smoothness	2	36	2			1	2
Portland Cement Concrete Construction							
Physical Tests on Cement	31		10	1			1
Chemical Tests on Cement	32		3		2	5	1
Aggregate Gradation for Concrete	22		17	1	1		2
Aggregate Soundness	35		3		1	4	
Air Content-Fresh Concrete	41		1				1
Slump	30		7	3			3
Cylinder-Compressive Strength	25		9		2	2	5
Other Strength Tests							
Flexure	11		6	2	1	21	2
Splitting Tensile			2				41
Thickness Hardened Concrete	22	2	13		1	2	3
Pavement Smoothness	1	31	2			5	4
Earthwork-Soils							
Soil Classification	24		4	6	4	2	3
Maximum Theoretical Density	26		3	4	1	5	3
Moisture Content-Soils	27		8		5	2	1
Field Density	38		4				1
Control Strips-Nuclear Gauge	13					28	2
Aggregate Bases							
Gradation	28		10				5
Los Angeles Wear	16		7				20
Plasticity, Liquid Limit	11		2				30
Density	9		4				30
Soundness	6		4				33

a/ Rating:
1 - Very important - failure could affect durability.
2 - Important to public comfort but probably no effect on durability.
3 - Important for contractual compliance -- "normal" deviations not likely to affect performance.
4 - Important during construction phase only. Not important to performance.
5 - Other (state purpose).

if those states indicating complete testing examined samples at terminals or refineries or checked each shipment to a project. A number of states approved a source on the basis of periodic complete testing, with tests for viscosity or penetration on shipment samples. Others selected a portion of the samples for complete tests. In some cases this was one in every 5 or 10 shipments, and in others a random selection was made. Certification of a source with only spot checking was used by some states.

In general, once a given source of asphalt has been shown to have acceptable properties, most states tested at relatively infrequent intervals. However, measurements of viscosity and/or penetration were made more frequently.

Aggregate gradation—do you use any prequalification procedures? Which ones?

Twenty-nine states considered aggregate gradation very important to the performance of the pavement, assigning a rating of 1. Ten states rated it 3. However, several of these indicated that they considered the reply to apply to small deviations from the specifications.

Thirty-seven states reported that they made prequalification tests. Six states did not use such tests. In some cases, the tests were involved in establishing approved sources of aggregate, and in others, tests were made on aggregates prior to use for a specific project. The tests involved properties such as soundness, abrasion resistance, amount of material passing the No. 200 sieve (75 μm), crushed faces, thin and elongated particles, deleterious materials, and polish resistance. The specific tests made by each state varied somewhat. The choice of tests most likely rests on the overall characteristics of aggregates within a state as well as the purpose for which the aggregate is to be used.

What tests on asphalt mixes are made for design? Are extractions of plant samples made for gradation? Are extractions made for asphalt content?

Twenty-five states used the Marshall method of design for asphalt pavements. Ten used the Hveem method. Six states used the immersion-compression test as a part of their design procedure. Three used the Hubbard-Field method. Several used more than one method or their own variations of the standard procedures for density, voids, optimum asphalt content, etc.

Only six states did not make extractions of plant-mixed samples for gradation control. However, in some instances such tests were made by contractors for quality control purposes. In two cases, tests were run for information only. Most of the states reporting also made extraction tests for asphalt content. Four states base asphalt content on the total amount of asphalt used in a day and the total tonnage of mixture produced.

Pavement density after compaction—rating? Do you use nuclear gauges to measure pavement density after compaction?

Pavement density was considered very important by almost all states. Thirty-seven rated such tests 1, two rated them 3, and four did not report or gave no rating. Thirty-seven states used nuclear gauges, and six reported they did not use them. Nine of the 37 states using nuclear gauges indicated that their use was limited or on an experimental basis. Several states used nuclear gauges on large jobs but used cores for small jobs.

Concrete Construction

Do you make physical tests on cement—rating? Do you make chemical tests on cement—rating? What is the frequency of tests on cement? All samples or selected samples?

Almost all states considered both the physical and chemical tests on cement very important (1 rating), but none completely tested each shipment to a job. In most cases, some type of certification program was in effect, with occasional spot checking. Sometimes the checking was done on a random basis and other times on the basis of time intervals, such as one sample each week of each month. One state reported sampling all shipments and physically testing all samples but did not use chemical analysis.

Aggregate gradations for concrete—rating? Aggregate soundness tests—rating? Do you measure air content of fresh concrete—rating? Do you measure slump of fresh concrete—rating? Do you measure cylinder strengths—rating?

The ratings for all 5 of these tests are shown in Table 1. As can be seen, the large majority of states used the tests and considered all of them of major importance (rating 1). The importance attached to slump apparently reflects the importance given to the water-cement ratio.

Are other strength tests made?

Twenty states used a flexure test. Two used a splitting tensile test, and 13 reported that no other strength tests were made. Four states did not reply.

Do you measure slab thickness—rating?

Only two states did not measure slab thickness. Twenty-two considered it important to durability (1 rating), and 13 considered it important to complying with specifications (3 rating). Eight did not report.

Do you measure the smoothness of the finished pavement?

Most states considered smoothness of portland cement concrete pavements important to the comfort of the public but not to durability. Thirty-one states rated smoothness 2. Five indicated they did not measure the property, and three gave no reply.

Earthwork, Soils

Do you determine soil classification?

Most states determined the soil classification and considered it important to durability and performance, but 10 rated it 4 or 5. Three states did not run soil classification tests.

Do you determine maximum theoretical density? Do you determine moisture content? Do you determine field density? Do you use control strips and nuclear gauges for density? If so, what techniques are used?

This series of questions dealt with the importance of compaction of earthwork and soils. Most states attached considerable importance to such tests. However, six states did not make tests for maximum theoretical density, depending somewhat on control strips as a measure of desired compaction. Moisture content was rated 1 by 27 states and 3 by 8 states. Five rated this test 5. It was expected that moisture content, per se, at time of compaction would have been rated 3 or 4. However, those giving it a 1 rating apparently believed it had an important effect on compaction, which in turn greatly affected durability.

Eleven states reported using the control strip concept along with the nuclear gauge as the control measurement. Several others used the nuclear gauge but not the control strip. The area concept for acceptance of work was used by a number of states.

Aggregate Bases and Shoulders

What tests do you make on the aggregate? How do you rate the tests made?

A number of states reported only that they made "quality tests" on the aggregate and did not designate the procedures used. Thus it was impossible to tabulate all the tests made. The tests shown in Table 1 were those most frequently mentioned, and the ratings indicated those considered to be of major importance. Los Angeles wear or abrasion was considered most important, and plasticity index and liquid limit for the fines was the next most frequently run. From the comments received, it was apparent that the tests made by any particular state were controlled to some extent by the characteristics of the aggregates available to them. Thus, polishing characteristics were important to those states using limestones to a considerable extent. Where gravels were used, crushed faces were considered important.

Other Questions

What products do you accept by certification?

All states accepted some products by certification. Generally these were manufactured materials. Each state maintained a list of products so accepted and had designated procedures for spot checking as required.

What are basic duties of inspectors: at bituminous hot plants, at job sites, at concrete paving sites, at earthwork sites?

A number of states submitted copies of their instructions to inspectors or inspectors manuals in reply to this question. Selected portions of the instructions provided by Washington are included in Appendix C. They are typical of the specific instructions provided by each state.

The replies from states using statistical quality assurance techniques were compared to the replies from states not using this approach. In general, some differences in the number or purpose of tests made at an asphalt plant or a concrete mixing plant were noted, but the overall responsibilities for inspection or plant calibration, condition of equipment, observation of the output, and workmanship were of the same nature regardless of the type of specification being used.

The following quoted excerpts generally reflect the type of instruction given and responsibilities assigned to inspectors.

Idaho—"Samples and tests are essential for the record and to sustain the inspector's judgment but to perform these activities simply as routine chores in order to meet some minimum number of tests contained in a schedule would be missing much of the potential benefit of inspection."

Washington—"It should be remembered that specifications are not arbitrarily arrived at, but have evolved through the years as a result of experience and research."

"Responsibility for obtaining a mixture meeting specification requirements rests initially with the plant inspector."

"The attitude of the inspector and his plant personnel should be one of cooperation—consistent with the requirements of the specifications and his instructions."

Utah—"The inspector should communicate with the batch plant operator, discuss the plant operation, convey his desires, needs and responsibilities to the plant operator and develop a working relationship. Good communication is important in establishing the ability to become a good plant inspector. One of the prime responsibilities of the plant inspector is to see that the mix is proportioned as per the mix design and that the percent of asphalt in the mix is as required."

How do you handle steel inspection and testing?

Most states reported that steel was inspected at the fabrication plant either by state inspectors or inspectors hired by the state under an inspection contract. Certification of composition and strength was frequently used with inspection of the fabricated steel at the job site. Nondestructive tests of welds were also conducted.

How do you handle paint testing and inspection?

Paint inspection and testing varied with the amount of material involved. For some jobs, paints were accepted by certification, with occasional job samples being tested. When large amounts of paints were involved, the raw materials going into the paint were sometimes tested prior to batching, and a state inspector observed the batching, taking samples as needed. In other instances, paints were sampled and tested at the source of manufacture by state inspectors.

How do you handle reports of test results? Do you have a computerized program? If so, does it automatically flag failing tests?

Nine states used a computer program for recording and automatically signaling a failing test. Four other states used computers for recording test results but did not have a program for indicating failing tests. Twenty-eight states did not have a computerized program.

Does your state provide training for contractor personnel?

Twenty-eight states did not provide training for contractor personnel. Nine states had regular training courses or workshops to which contractor personnel were invited; they usually participated in such courses along with state personnel. Six states would provide limited training to contractor personnel when requested but had no regular program for such training. In general, those states providing training to contractor personnel used statistical quality assurance techniques to the greatest degree.

Do you require that the contractor must have a minimum number of trained personnel?

Eight states had some requirements for qualifications of contractor personnel. In some instances this meant only that a qualified person must be either at the plant or readily available. Again, most of the states having these requirements were using statistical quality assurance techniques.

CHAPTER FIVE

CONCLUSIONS, RECOMMENDATIONS, AND NEEDS

In the case of quality assurance systems, the needs for better understanding, training, and implementation outweigh the need for research. This is especially true of establishing improved criteria for sampling, testing, and inspection of materials.

The reports reviewed in Appendix D reveal some of the needs as indicated by the performance of some highway facilities, and these needs will be discussed in this chapter.

First, however, it is useful to review some of the generally held opinions with respect to quality assurance and to assess their validity or the efforts being made to change them.

- Some administrators feel that many tests are not really necessary, thus there is a need to justify the expenses for testing and inspection.
- Although highway engineers feel that performance (or failure) can be related to testing, the data that are available do not clearly show this relationship.
- Expenses for testing may seem to be high in terms of the number of failures that occur. There is a need to relate testing to items such as cost of the material, variability of production, results of failure (costs, criticality, difficulty of repair, etc.).
- Some believe that an inspector, simply on the job and taking interest in what is going on, may be sufficient to insure a good job by contractors.
- Because most inspection is done by technicians, it may be better to have less inspection but with better qualified personnel.
- If a contractor is doing acceptable, uniform quality work, then a lot of acceptance testing is unnecessary. The need is more to monitor the contractor's process.
- There are four types of tests: prequalification testing (not for a specific project), source testing (for a particular project), production control tests, and acceptance tests. The last two are of most concern here.
- The timeliness of testing and acceptance is of major concern. The speed of construction, especially of pavements, has increased greatly, and it is difficult to make standard tests quickly enough or to avoid large quantities of material being out of specification. Thus the need for more rapid tests is recognized as one of the priority problems.
- The significance of some tests with respect to performance should be reexamined. The engineer is forced to use indirect tests, because in some cases the desired property does not even exist when corrective action is possible, for example, the strength of portland cement concrete.

EFFECT OF PROCESS VARIABILITY

The first two opinions represent different views. It is true that in some situations a reduced program of testing would not affect performance, e.g., when either the demands on the material in a project are not critical or when the materials are of such uniform and high quality that normal process variability is relatively small in relation to that permissable before performance is affected. On the other hand, many failures in highway pavements can be related to undetected deficiencies. This would indicate that increased inspection and testing are needed.

More important is a better understanding of process and materials variability and its relation to testing and performance. While a number of discussions in the literature concern variability, the point that the amount of testing does not control variability is often overlooked. It doesn't matter whether one test or a hundred tests are made, the process variability will be the same unless other action is taken to improve the process. Multiple testing better defines what the variability is and allows an assessment of the risks involved with respect to accepting materials outside of limits or rejecting materials within limits, but of itself, it does not improve quality.

The "Highway Condition and Quality of Highway Construction Survey Report" (*19* and Appendix D) indicates that many specifications do not adequately take into account testing and process variability. The results of the AASHTO Road Test (*18*) confirm this opinion. It is also important to remember that quality of compliance to specifications and quality of performance are two different things and are not always directly related to each other.

Even though considerable work has been done to measure variability on a statistical basis in a large number of highway construction processes, little has been done to correlate that variability to performance. In most cases, the degree of variability that can be tolerated before performance is affected is not known nor has the relationship between the loss of performance and the level or variability of a characteristic been determined. Continuing evaluation of the level of measured characteristics and the variability is needed, along with an assessment of performance over the life of the pavement. Whether or not control is by a recipe type approach or a procedure using statistical quality assurance techniques, such evaluations must be carried out in a statistically valid manner.

Along these lines, the finding of Zenewitz and Welborn (*23* and Appendix D) that variability of itself is closely related to performance is significant. In effect, this might be taken as a measure of how close the construction process comes to hitting the targets established by the design criteria. Greater variability means that even though average values may be about the same, larger amounts of materials or larger areas of pavements having less-than-desirable characteristics would be present. This is ultimately reflected in poorer performance. The failure to measure and control variability is a significant shortcoming of the traditional quality control and acceptance procedures. The use of statistical concepts provides for an assessment of such variability.

RELATION OF TESTING TO CRITICALITY OF ITEM TESTED

Further study appears needed to systemize the possible reduction in testing in relation to the criticality of the component. Obviously, it is not cost-effective to spend several hundred dollars making complicated tests on paint for the interior of a control tower or a rest area when the total volume of material to be used and the labor to replace it may cost less than the testing. Purchase and use of off-the-shelf items without testing is satisfactory in such cases because replacement is not difficult. On the other hand, it may be necessary to thoroughly test an item, even if it is limited in use, if its failure would vitally affect performance of an entire system and later repairs would be expensive and difficult. A good example of the latter is elastomeric bridge pads.

A number of states have established systematic criteria to waive testing (usually on the basis of certification) for small amounts of noncritical materials or construction. However, more effort is needed in this respect.

RELATION OF INSPECTION TO TESTING

There is evidence that the role of inspection, as separate from that of testing, has not always been clearly defined. There also seems to be a continuing misunderstanding that inspection can be eliminated when statistical quality assurance techniques are adopted. This impression needs to be corrected.

Statistical quality assurance control and acceptance techniques are based on *normal variability* of a process or material. Inspection is always necessary to assure that everything is operating normally. Under the most desirable use of statistical quality assurance techniques, the responsibility for control is clearly assigned to the contractor—thus, ideally, the contractor should provide control inspection as well as control testing. On the other hand, for some types of operations, the presence of a knowledgeable state inspector favorably affects the contractor's performance. This is basically human nature—so even when using statistical quality assurance techniques, states should provide good inspection. This is especially true in the transitional period when greater responsibility is being shifted to the contractor. Traditionally, contractors have relied on state inspection for guidance, and many now are reluctant to accept full responsibility for control inspection. Most states appear aware of the need for good inspection, and written guidelines often point out the need to observe what's going on rather than merely staying inside the control laboratory running tests.

Although a test is most often thought of as a quantitative measurement of the behavior of a sample or item, in reality, a test is nothing more than an observation and can vary from complicated procedures with multiple recordings of data to a simple notation of appearance. Thus, skilled inspectors make tests by observation because they learn to recognize warning symptoms—e.g., the appearance of a hot mix or the way it behaves during compaction. This seems to be recognized by all states. One of the reasons most often cited for continuing the traditional specification and acceptance procedures is that a skilled inspector or engineer can exercise engineering judgment during the progress of a project and attain better results than could be attained by adhering to a rigid testing schedule. Others adopting statistical quality assurance procedures point out that, although the traditional system works under the proper circumstances, inspectors can be subjected to intimidation—especially when their experience is limited and that of the contractor is more extensive. Thus, a properly designed testing and acceptance procedure provides a uniformly applied, unbiased system for measuring compliance. Users of the statistical approach also point out that their system protects the contractor from improper judgmental decisions by the inspector.

EXPERIENCE AND TRAINING OF INSPECTORS

The FHWA condition and quality of construction survey (*19*) revealed that the technicians and engineers with the least experience were depended on to the greatest extent to provide both inspection and testing. It is likely that this pattern will continue. Broad knowledge and experience may not be essential to good performance by technicians or beginning engineers, and inspection and testing probably provide the most logical starting point for the highway engineer's career. The recommendation by the FHWA report "that comprehensive training programs be developed for technicians so that they may be properly trained to perform a multitude of activities" represents a definite need.

Some efforts are underway to accomplish this objective. One plan is to establish a national program for the qualification of technicians. A technician would be trained and certified as qualified upon completion of courses and satisfactorily passing an examination in a number of highway construction activities. A minimum amount of experience would be required for several levels of qualification.

The report describing this program is summarized in Appendix E (*24*). It has been endorsed by FHWA, AASHTO, and the Institute for Certification of Engineering Technicians of the National Society of Professional Engineers. When completely operative, it will identify a body of trained personnel that is involved in assuring the quality of highway construction whether employed by a governmental agency or a contractor. Training and qualification of such people is greatly needed.

GENERAL TRAINING AND INFORMATIONAL WORKSHOPS

FHWA efforts on behalf of statistical quality assurance techniques are continuing. LaHue reported at the June 1978 Conference on Quality in Construction that two FHWA-sponsored courses were available and a third was in the planning stage (*10*). One course, Statistical Quality Control of Highway Construction, is sponsored by the National Highway Institute, and the other, Highway Quality Assurance-Process Control and Acceptance Plans, was developed through FHWA Demonstration Project 42. LaHue reported that 38 state highway agencies have had one of the courses presented within their states. The third course, Practical Application of Statistical Quality Control in Highway Construction for Engineers and Technicians, should become available for state and contractor personnel in late 1979.

A number of states have conducted regular training courses for several years. For example, the Virginia Department of Highways and Transportation has conducted training in statistical concepts for over 800 persons since 1963.

Despite a sizeable training effort, a number of people do not completely understand the objectives of statistical quality assurance techniques. In particular, it appears that contractor personnel have not generally attended training courses or workshops except in those states adopting statistical quality assurance techniques that require the contractor to provide control plans. There is also considerable evidence that some members of contractor management do not completely understand the purpose of statistical quality assurance techniques, and where a state desires to adopt such techniques, considerable effort must be made to establish such understanding.

TRANSITION PERIOD WHEN ADOPTING STATISTICAL CONCEPTS

In recognition of both the difficulties of understanding statistical quality assurance techniques and the objections raised, primarily by contractors, FHWA has planned to incorporate 3 major recommendations into a modification of its quality assurance directive (*10*):

- First, it would be recommended to the states that a "phasing in" period be allowed for application of partial payment schedules. For a specific time after adoption, the reduced pay provisions would not be applicable, although contractors would be informed of the deviations occurring in their production. This would allow both the state and the contractors to become familiar with the operations of the system and its implications.
- The second change would be recognition of incentive pay provisions that would allow the payment of more than 100 percent of the bid price for materials of higher quality than required by the specifications. In general, this would be based on a greater-than-average percentage of material within the designated limits. It would not be applicable to every item in the contract.
- The third modification is designed to recognize that some contractors are reluctant to establish quality control testing by their personnel. Under the FHWA proposed modification, a state could include a nonbidable item in the contract for the necessary quality control tests. Costs for each required test would be established so that the total costs for quality control testing would not be used in determining the low bidder.

In general, these modifications by FHWA appear designed to assist adoption of statistical quality assurance techniques and reduce contractors' fears concerning such specifications.

OBJECTIONS TO STATISTICAL TECHNIQUES

FHWA's modifications still would not eliminate the objections to statistical quality assurance techniques voiced by a number of states. Some states have considered the statistical approach for limited items of construction but have concluded that it is not advantageous to their situations. The greatest objection appears to be the need to abandon something familiar to all and something that works reasonably well most of the time for something unfamiliar that requires an adjustment in thinking as well as changes in some of the traditional contractor-state relations. In addition, these states view statistical quality assurance techniques as establishing a more rigid set of conditions for acceptance than relying on engineering judgment for substantial compliance. In their opinion, the difficulty of considering all eventualities in any written specification makes it desirable to retain the freedom to adjust to conditions as they arise. Most of these states also believe that the accumulated experience of 40 to 50 years in highway construction and the relatively good overall performance of their highways assure that established limits and levels of characteristics are reasonable and represent a proper balance between the state's interest and the contractor's interest.

In general, the manner of promoting statistical quality assurance techniques has resulted in an attitude that states must either accept or reject a statistical approach to their control and acceptance procedures. More emphasis is needed on the evolutionary nature of adopting statistical quality assurance techniques. To adopt such techniques, some modification of thinking is necessary, but there is no reason why unforeseen circumstances cannot be handled on the basis of engineering judgment or common "horse sense," regardless of the specific procedures being employed for quality assurance.

The greatest need at the present time is to establish the characteristics of the materials and construction that *actually exist* in our highways (not those specified) so that ultimately the levels of these characteristics can be matched to performance.

INFORMATION SYSTEMS

Data processing, storage, and retrieval equipment has permitted the effects of quality control to be more accurately defined. Equipment and procedures now in use could, with only moderate adaptation, store data that is needed if transportation agencies are to measure the benefits of quality control.

Several agencies have developed a computer-based inventory system that will display specific information for any segment of the highway under study. The output may include geometrics (alignment, grade), pavement type, age, traffic (volume, type), surface conditions, etc. However, the construction and materials data that would help to pinpoint the results of quality control have not been accumulated and entered into the system.

Required construction data would include material sources, inspection results, types of tests, project engineer, contractor, weather conditions, personnel assigned, etc. Maintenance and rehabilitation costs, safety data, condition surveys, etc., would help to form the data base that could enable management to decide which quality control procedures are working and which should receive additional attention.

Because of the difficulty of obtaining this information for old projects, the collection effort should concentrate on current projects. After a few years of data accumulation, the effects of specific procedures can be evaluated.

The success of this type of management system hinges upon several different elements. The use of a common reference system is essential. The capability to combine data from several files to produce useful reports is also necessary. However, the critical requirement is the management direction that insures that the information required from each unit is available, complete, and accurate when entered into the system.

MORE RAPID TESTS

The need for more rapid testing is recognized throughout the highway industry, and considerable activity is underway in this area. FHWA has sponsored efforts to develop rapid tests for a number of years, both through its research program and its demonstration projects. It has published a series of rapid tests that have not been standardized by AASHTO or ASTM—indicating that such tests would be acceptable for control and acceptance of materials on federal aid projects. A joint task force of AASHTO, AGC, and the American Road and Transportation Builders Association has also been established (Task Force 14) to review available rapid tests and make recommendations as to their adoption. A summary of the task force's activity was reported at the 1978 Conference on Quality in Construction (*25*). A synthesis report on rapid test procedures is also being prepared by TRB as a part of Project 20-5. Because of these reports, detailed discussion of the possible tests will not be included in this report. However, the need for tests that can indicate the acceptability of materials within a time that will permit corrective action is an important part of the overall problem of improving quality control during construction and reducing quality control costs.

MORE MEANINGFUL TESTS

In addition to more rapid tests, tests that measure characteristics directly affecting performance are also needed. To obtain some idea of the relative importance assigned to various tests, the states were asked to rate them. Most states assigned a rating of 1 (important to durability of the pavement) to almost all tests except smoothness. However, some of the tests are only secondary indications of satisfactory properties or composition. For example, the slump test for concrete is an indication of the proper water-cement ratio and has a bearing on workability, but slump, per se, has no meaning in the finished pavement.

FHWA-sponsored studies relating the performance of specific pavements to the measured characteristics of the pavement system as a whole indicated that even with the most sophisticated tests and equipment it is not always possible to predict a pavement's performance. One report (*26* and Appendix D) stated that additional damage models should be developed to supplement and advance present layer system analysis techniques. In the search for zero-maintenance pavements (*27* and Appendix D), major causes of distress were often related to inadequate design for the traffic loadings encountered.

These performance studies were not concerned with the normal quality control or acceptance tests, and the degree of compliance to such tests was not measured. However, the findings strongly imply that more meaningful tests related to design factors and expected traffic and environmental conditions are needed to assure better performance.

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APPENDIX A

EXCERPTS FROM THE PROCEEDINGS OF THE SYMPOSIUM ON THE QUALITY CONTROL OF ROAD WORKS

The following excerpts from various papers and discussions published in the proceedings (*9*) of the international symposium of the Organization for Economic Cooperation and Development at Aix-en-Provence, France, in November 1970 are believed significant and establish the international dimension of the problems relating to quality assurance of highway construction recognized in the United States.

BONITZER, J., Laboratoire Central des Ponts et Chaussées, France, "Specific Problems of Pavement Quality Control in France."

The Ponts et Chaussees have been investigating ways and means of improving highway construction control for some fifteen years.

Considering that other industries had long since developed efficient quality control techniques, the first and very natural idea was to apply similar techniques to highway construction, such control to be characterized by:

—separation of production control, including the phase of the operation control of construction equipment which is a responsibility of the supplier (in this case the contractor), and acceptance control, mainly of the end product, which is the responsibility of the resident engineer representing the Highway Authority;

—application of statistical methods with statistical sampling and decisions based on statistical tests.

It soon appeared, however, that application of such control methods to road construction would be less readily achieved and that their general application would not materialize as soon as expected.

The difficulties too frequently encountered at the present time in attempting to improve control of highway construction quality are due to uncertainty as to the exact relationship between that which is being controlled and the actual quality of the work itself. . . .

MATHEWS, D. H., and HARDMAN, R., Road Research Laboratory, United Kingdom, "Risk in Specification, Control, and Acceptance of Road Materials."

Most of the materials used in road construction are variable, sometimes highly variable, in quality and also, therefore, in performance. The conditions of service are also variable and thus there is usually a distribution of quality, a distribution of service conditions and a distribution of performance, all of which must be considered when formulating a design or a specification. The specification writer has the difficult task of calling for a quality of material which will suffice under the conditions of use; at the same time he should not make unnecessarily severe demands. To assess this quality, it is necessary to take into account the variables of the materials themselves as well as those of the conditions of use and of practical performance. . . . The producer should try to make a quality which will meet the specification and, therefore, he should attempt to control his process to produce the quality which will suffice and thus limit his costs. The consumer has no right to expect a quality which is appreciably better than that specified and it is not usually in the economic interest of the producer to offer a quality beyond that which he expects to be accepted. The consumer's real concern should be with whether the offered material meets his specified quality requirements and how he can reach decisions on compliance with specifications at a reasonable cost.

For the design of a decision criterion, it is necessary first to define, as acceptable, a quality of material expressed in terms of the population of sample measurements that will satisfy the technical requirements and is reasonably attainable. With variable materials and variable methods of measurement, this means that the acceptable material will inevitably include some small proportion defective to the limit or limits chosen to define acceptable quality. Second, it is desirable in theory that the quality defined as unacceptable should be completely and utterly unacceptable on technical grounds (for example, catastrophic failure is likely). Such a quality will normally be considerably worse than that defined as acceptable (or desirable) and will not merely be the complement of acceptable quality. . . . In many cases with road materials it is not possible to give such an absolute technical definition of unacceptable quality and the 'grey' area, which represents the gradual deterioration of performance as quality deteriorates, may cover a larger range of quality of materials not classed as desirable. The third requirement is to consider more than one sample measurement of quality in the criterion of decision. When the decision is based on more than one measurement at a time it is possible to vary the balance of the risks of mistaken decision in relation to the quality of material.

It is unusual to be able to specify a highway material in true end-product terms, that is, in terms of actual performance or of actual properties determining that performance. This is largely because current knowledge of the materials is incomplete. At the same time there are obvious economic advantages in placing as few restrictions as possible on the method of working. The result is that almost all specifications contain a mixture of end-product requirements and restrictions on the method of working.

The balance of "end-product" and "method" requirements varies widely with different materials and even for the same type of material between one country and another.

The use of a "method"-based specification does not eliminate risk although it may be used to limit risk, usually at some cost. The specification of "method" implies that the use of the method will guarantee satisfactory performance under all likely conditions of processing and use. Since the prime assumption cannot be tested over all likely conditions, but only a sample of these conditions, there is inevitably some risk that satisfactory performance will not be obtained under some particular set of circumstances. This risk is usually unquantifiable and therefore it is impossible to derive and balance the two cost functions expressing the consequences of risk and performance.

Risk in Control

The aims of the Producer are to maximize his compliance with the requirements of the specification and to minimize his production costs. Control is one of the tools he has available to achieve these aims. . . . Control is very dependent on measurements and observations on the raw materials, on the processes and, usually, on the final materials. Because the materials and processes must be judged through sampling techniques, there is an important element of risk in all decisions on control. It is important to be able to attach a probability to such decisions so that they are made consistently rather than randomly.

. . . The Producer needs to be able to detect both the average current level of the process and its current variability. He needs to be able to make changes quickly when these are justified but at the same time he should avoid reacting to chance variability.

The amount of control required in any practical case depends mainly on the size of the "grey area" between desirable and undesirable quality. Where the limits demarcating undesirable quality are not much wider than those indicating process capability, it may well be almost impossible to control the process, and hence the risks, effectively. On the other hand, when the margin is large, it is possible to base the amount of control mainly on economic considerations.

Risks in Acceptance

A specification defines acceptable quality and it should also define the method by which quality will be judged. There is an economic limit to the amount of testing which is justifiable. . . .

No amount of testing can ever give the consumer an absolute assurance that the specified quality has been obtained. Even a reasonably high degree of assurance is likely to be very expensive. It is for this reason that . . . Quality is assumed to be satisfactory unless and until it is proved with an adequate degree of assurance to be unsatisfactory. . . . It follows that if the Consumer wishes to maintain the balance of risks, it is essential that he take action to penalise the Producer whenever a quality indicated as unacceptable is detected.

NAGEL, J., Technical University, Aachen, Germany, "Assessment and Accounting of Building Operations in the Field of Road Construction Using Statistically Guaranteed Characteristic Values."

The rules for assessing completed road works and the accounting procedures as applied at present in Germany can be considered unsatisfactory from a scientific point of view.

The assessment of building operations . . . is entirely based on single test values which are usually related to a fixed area or production volume and which have direct consequences, e.g., price reduction based on area. Finally the arithmetic mean of all the ascertained single values is used in working out the total account.

Although this method may appear satisfactory in practice, its validity is doubtful since single values seldom provide objective evidence. . . .

The characteristic values obtained when evaluating building materials, building operations, etc., should therefore only be measured by methods allowing for objective interpretation. . . . It is only possible to achieve this by using statistical methods. . . .

In order to establish a practical scheme, it is first of all necessary to exclude all traditional methods and to rethink the whole basic process with particular reference to road-building.

Any such consideration must proceed from the basic principle that there can be:

"no production without dispersion" (variability)

The causes for dispersion are manifold and can be roughly summarized by the so-called four M's:

"men, material, machine, method-of-measurement". . .

However, statistical treatment of characteristic values is only possible when a statistically random sample is made.

In our opinion, this is the method of the future, as it correctly assesses all test data and thus the building operation as a whole. All other methods are, intentionally or unintentionally, speculative and subjective. . . .

SCHUHBAUER, A., Alfred Kunz & Co., Germany, "Statistical Quality Control in Bituminous Road Construction."

According to the control system used in the Federal Republic, control tests are executed by official test laboratories; a completely independent and more intensive control of the production of the plant is carried out by the contractor. This is a duplication of effort which provides no advantages.

If the laboratories of the firms on the sites were controlled by the client, tests in the so-called officially approved laboratories would no longer be necessary. . . . It is difficult to understand why a double control of bituminous building material is necessary. . . .

The advantages of statistical quality control are so obvious that it should be applied immediately in bituminous road construction. There are no arguments against statistical quality control of bituminous road construction.

VAN DE FLIERT, C., and BROUWERS, J. A. C., State Road Laboratory; SPAN, H. J. J. H., Royal Company for Road Construction; and WESTER, K., Study Centre for Road Research; Netherlands, "Quality Control of Road Pavements in the Netherlands."

The four authors represent both the government and the contractors of the Netherlands. This itself illustrates the present situation in the Netherlands in the field of quality control. The Dutch quality control system has been developed and completed by the government after deliberation with the contractors' organisation and with their cooperation. The specifications are fully accepted by the Dutch contractors and also considered by them as quality improving and reasonable.

From 1960 to 1965, some methods of quality control, which had been laid down in the contracts of a number of works were tried out. In mid-1968 an accepted method was generally inserted in the contracts for the construction of state highways. The method was revised in September 1969.

These methods were introduced because of the lack of skilled supervisory staff and also because of the urgent need for rapid control methods due to increasing mechanisation and automation of roadworks and their increasing magnitude.

The "Dutch" System

The system is based on a consistent separation between, on the one hand, a daily production control under the full responsibility of the contractor, and on the other hand, an acceptance control carried out by the Authorities after completion of the work, and combined with a system of reduced payment.

The interests of the Authority are covered to a large extent by the penalty clauses, as they force the contractors to work with greater accuracy and to carefully control the production and execution. . . .

One of the most important consequences of the system is the fact that guarantee clauses are now omitted in these contracts, since in our opinion guarantee conditions are contrary to a quality control method, connected with a penalty system.

Further development of the relation between these more or less theoretical and fundamental methods of defining performance of pavement, and the actual properties of the construction, will lead to a more accurate and more balanced fixation of the level of reduced payments.

Finally, it should be determined whether a completely mathematical-statistical judgment, based on mean values and standard deviations should not be preferable to the system of a more indirect statistical method which is at present still employed in the Netherlands.

It may be expected that such a more direct mathematical-statistical method will be introduced in a short time.

HONDERMARCQ, H., and DOYEN, A., Ministry of Public Works, Belgium, "Control of Road Construction Work in Belgium."

Objectives in highway construction . . . can be reduced to two points: satisfactory service to road users and economic efficiency.

Four factors have to be considered: pavement design, adoption of quality criteria, achievement according to plan, and value of such achievement.

. . . The criteria adopted in terms of these two objectives will be covered by contract clauses governing the relationship between the two parties. Control operations by the resident engineer are merely a means of checking compliance with the provisions of the contract.

. . . Application of contract provisions should be constantly adapted to changing circumstances.

Such provisions should cover the various factors that are likely to have any influence on the final quality of the finished product. This mostly concerns the type of contract, the size and duration of construction, the equipment and other means available, and the criteria adopted.

With speed of execution as a major requirement, the notion of preliminary inspection and approval of materials no longer applies in most cases.

The only logical procedure is to make the contractor responsible for the quality of the materials and so avoid the necessity of preliminary tests. Quite recently, the Highway Administration made a ruling that all material for flexible pavements should be delivered with a certificate of origin and of compliance with specifications. A similar measure is envisaged with regard to base course and cement concrete pavement materials. Before operations begin, the Highway Authority will make random tests to check the veracity of the certificates.

Criteria

The criteria should refer to . . . properties either specifically or by inference and their value will depend on the objectivity of such reference. The criteria may be put into two categories:

—direct criteria related to a quality of the project itself such as permeability, evenness, coefficient of friction;

—indirect criteria for the purpose of checking whether a desired result will be obtained where one or more conditions are satisfied (in the case of raw materials). Such criteria will not however, suffice to assess the final result and they will have to be associated with others for reliable deduction.

Control

. . . Opinions are nowhere more varied than in the field of control. . . .

1. *Preliminary tests and control of work in progress*

This item has been simplified by introducing certificates of origin. . . . Control of work in progress is mostly concerned with mixing and laying.

2. *A posteriori control.*

Such control is applied to different stages of road structure while work is in progress or after partial completion.

Some objections have been raised in regard to a posteriori checks, the main one being that the data obtained after a project is completed cannot be used for corrective action while the work is in progress. It should, however, be recalled that manufacturing and laying provisions are merely indirect criteria which, even under favourable conditions, will not in themselves ensure the required overall quality unless other, implied, conditions are satisfied. If specifications had to lay down all the criteria, rules and practice to be satisfied and/or followed to achieve overall quality of a finished project and provide for effective control of each item, the contractor would no longer have any real function and it would show a saving if the resident engineer himself were to take over with the contractor's equipment and personnel.

Statistical control is applied on projects exceeding 5,000 m^2 in one holding. . . .

The statistical control principle is based on a statistical threshold to be respected by 95% of the run of samples. . . . This notion of statistical threshold will be extended in the near future, at the request of the contractors, to percentages of voids and bitumen content of flexible pavements. . . . The coefficients of value based on statistics have been applied in Belgium for about ten years. . . .

. . . The contractors wish to have them extended to fields other than those at present envisaged. . . .

SUMMARY OF DISCUSSIONS [1]

Control, as applied to public works, has a twofold aspect, as emphasized by Mr. Bonitzer:

—a legal aspect for transfer of responsibility from the contractor to the highway authority;

—a technical and economic aspect to achieve a high level of quality.

The Resident Engineer and the Contractor

The legal aspect of control brings into play the respective roles of the resident engineer and the contractor and the question of premiums and penalties. It could be held that the resident engineer should go no further than acceptance control and take no part in production control. It is also possible to imagine collaboration between contractors and engineers with division of responsibility.

Mr. Abdun-Nur, in this connection, emphasized the need for both parties to unreservedly accept production control. Mr. Sleep concurred and observed that contractors should be made to realize that control was in their interest. Mr. Fichtl felt that when contractors knew they would be controlled, they would not make "cut-rate" tenders and this would safeguard the good contractors. Mr. Bonitzer also agreed that the respective roles of the engineer and the contractor could not be separated. Specifications should not, of course, limit the contractor's freedom of technical innovation; they could, on the contrary, be stimulating by requiring, for instance, measurement on the job of certain parameters which had not previously been measured.

Mr. Durrieu found another reason for not completely separating the roles of engineer and contractor: owing to the present lack of knowledge regarding important parameters, tests and sampling procedures, control of finished work needed to be very much improved to be of any great use. Mr. Van de Fliert also believed that a good control system could not but be based on co-operation between the resident engineer and the contractor.

Mr. Lee was concerned about the waste caused by the two separate control operations by the engineer and the contractor. He observed that, in the event of disagreement, the results accepted were generally those of the resident engineer's laboratory (although it might not have any better knowledge of the variability or its degree). He therefore wondered whether it might not be possible to suppress acceptance control by closer collaboration between the resident engineer's laboratory and the contractor, especially considering that the tests for production control greatly outnumbered those made for acceptance control.

Premiums, Penalties, and Guarantees

The question of premiums and penalties could not be separated from guarantees. Mr. Abdun-Nur disapproved of the penalty system because it could only encourage contractors to include provision for penalties in their tender rates so that in the end the penalties would be paid by the highway authority. He felt that statistical control was encouraging, more beneficial, and more agreeable than sanctions.

Mr. Mathews was of the opinion that a system of penalties should logically be based on a forecast of performance or in other terms on the maintenance costs of the finished project. Mr. Lee agreed and considered that penalties should be calculated in terms of the consequences of deviation. . . At the present stage, no one is capable of exactly assessing such consequences and the only real standard of reference must come from experience regarding the behaviour and durability of similar projects.

Mr. Van de Fliert agreed with Mr. Lee that there was no strict mathematical relationship between the measured shortcomings of works and their length of life, but with sound experimental experience of dispersions obtained, it should be possible to establish an approximate relationship as the basis of a system of penalties acceptable to the contractor as well as to the highway authority. He emphasized, nevertheless, that such a system depended on willing co-operation between the administration and the contractors.

Referring to guarantees, Mr. Ceintrey observed that they should not be considered by the highway authority as a means to make the contractor carry the risks taken on a project to effect a saving or owing to inadequate knowledge of quality criteria as related to pavement performance. In this connection, Mr. Mathews said that specifications should be realistic and take our lack of knowledge into account.

Mr. Durrieu observed that the shorter periods of guarantee claimed by French contractors might find some justification in the considerable part taken by the highway administration in planning the projects, providing raw bases and in carrying out control tests. Even if some countries continued to impose long guarantee periods, these periods were still much shorter than the actual pavement life.

[1] Summary of Session I, reprinted in entirety from proceedings.

Significance and Purpose of Control and Specifications

Control might be considered from another point of view. As observed by Mr. Bonitzer, production control directly contributed to achieving quality in the finished product. It was at this control level that there should be cooperation between authority and contractor. Indeed, statistical control was no safeguard against mistaken decisions, but it could be used to calculate the risk in taking a given decision.

Mr. Sleep emphasized that specifications should also serve as a means of communication open to all at every level of a project with the resident engineer's office as well as the contractors.

Mr. Remillon said that control could . . . facilitate subsequent maintenance and operation and be used as data for improving control specifications for later works. Such improvement being considered to a large extent in the light of possible savings on the cost of works, with particular reference to developing countries.

Mr. Fichtl remarked that control results could, at least to some extent, determine the cause of failure to achieve the specified quality. In this connection, Mr. Durrieu emphasized the need for good liaison between the design of a project and, later, control operations on the job. It was essential at the design stage to foresee the conditions in which control of work in progress could be carried out. It was also essential to closely follow the work in progress. Such investigation was distinct from control in that it merely sought to increase knowledge and was devoid of any legal aspect.

Statistical Methods

Whatever might be thought of them, statistical methods were increasingly used for such control. Certain specific characteristics of public works projects constituted a source of technical and practical difficulty in application of statistical methods. Such difficulties were outlined by Mr. Fauveau by comparing the conventional application of statistical control in industry with its counterpart as applied to highway construction. Industrial statistical control was based on notions of manufacturing and compliance control and a definition of suppliers' and customers' risks. Such control was based on a certain assumption that hardly applied to road construction. In the first place, a rejection of a poor job was extremely difficult because the cost of refusal was prohibitive. On the other hand, there was unawareness of certain considerable difficulties:

—statistical variation due to sampling or to test variance was often of the same order as the variance of the product itself;
—certain specifications of an apparently statistical nature were more concerned in actual fact with leaving the resident engineer with every possible means of not rejecting a product, as in the case where recuperation tests are allowed;
—sequences of successive assumptions should not be readily adopted because although they might seem very trustworthy at each stage, they might lead to an unreliable final conclusion;
—on the basis of the central limit theorem, statistical tests assumed in many cases that the applicable laws were normal, but the main condition under which this theorem was applied was that the weakness of each of the causes working to produce a phenomenon did not always appear. This had little importance with respect to tests bearing on the mean value, but it had a great deal with respect to those bearing on variance. In an attempt to overcome this difficulty, it might be of some interest to make greater use of non-parametrical tests which did not require any assumption of a law governing the parameter considered.

Mr. Arquie listed a certain number of difficulties encountered in applying statistical methods to highway construction:

—owing to the continuous nature of the products manufactured, it was difficult to define individual products to control because it should be borne in mind that the size of such individual products had a bearing on the dispersion;
—such continuous nature also led to difficulty in defining a random sampling of which the size and mode of extraction might influence the variance. This causes great difficulty, especially in comparisons as between different projects;
—highway construction products were not interchangeable and the highway authority was therefore left with only limited freedom of acceptance and/or rejection.

Such difficulties did not seem insuperable to some participants and Mr. Hardman maintained that comparisons as between different projects were possible and Mr. Halstead found that statistical methods could be applied to highway construction as long as they did not prevent the engineers from using their common sense and experience.

Among other practical difficulties that might be encountered, it should be recalled, as pointed out by Mr. Van de Fliert, that statistical methods only applied where the resident engineer and the contractor used the same methods of control. This difficulty could only be overcome by recognizing, as suggested by Dr. McMahon, the principle of complete separation between the contractor's method of control and the one used by the resident engineer for acceptance. All these difficulties offered some explanation of the divergencies of the methods as applied in different countries: the principle put forward by Mr. Kierkegaard-Hansen, for instance, was based on a constant risk to be carried by the client and a variable one to be carried by the contractor, so that the contractor would be encouraged to make a large number of tests whereas Mr. Hardman's principle was the opposite.

Other Problems

Mr. Mathews and Mr. Wester emphasized the need for control tests giving ready information.

Finally, Mr. Durrieu expressed concern for the control problem on small and medium projects. . . .

APPENDIX B

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APPENDIX C

TYPICAL DUTIES OF INSPECTORS FOR ASPHALT AND PORTLAND CEMENT CONCRETE PAVING

5-4 ASPHALT CONCRETE PAVEMENT [1]

5-4.1 Responsibilities and Duties of the Plant Inspector

5-4.1A General

Good work and a successfully completed job depends on good equipment, skillful operation of the equipment, and competent supervision and inspection.

Intelligent and adequate inspection throughout the period of preparing and laying asphalt concrete is of the utmost importance. Inspectors should be well trained for their particular duties and thoroughly familiar with all details of the specifications. They should be instructed by the Project Engineer as to their responsibilities and the limit of their authority. They should exercise tact and good judgment in securing maximum cooperation on the part of the contractor.

In the construction of asphalt concrete pavement, it is extremely important that the plant-mixed material meets all requirements of the specifications. It should be remembered that specifications are not arbitrarily arrived at, but have evolved through the years as a result of experience and research.

Experience has shown that pavements which do not meet all specifications will not perform satisfactorily, resulting in high maintenance costs. The responsibility for obtaining a mixture meeting the specification requirements rests initially with the plant inspector. The importance of his work cannot be overemphasized, since the best possible construction at the lowest cost to the State cannot be obtained unless the mixture produced at the plant is of uniformly good quality.

The method of obtaining the best possible asphalt mixture can be stated very simply—**careful inspection and control of the component materials and of the mixing process, in accordance with the specifications and instructions.** Various testing procedures are available to the inspector to insure that the component materials and the completed mixture meet the requirements of the specifications. However, since only relatively small samples of each day's production can be tested, the inspector's duties and responsibilities involve a great deal more than merely performing the required tests. He must be familiar with the workings of the asphalt plant, particularly the various controls which are under his general supervision. He is responsible for the uniform application of these controls, so that the end product is of uniform quality. Only in this manner can samples be considered representative of the material produced.

All contracts specifying more than 5000 Tons of Asphalt Concrete Pavement require the use of Automatic Controls for production and placing.

There is one key word to describe quality production of asphalt mixtures. It is **UNIFORMITY.** The aggregate in the stockpiles must be of UNIFORM quality and gradation; they must be fed into the plant in a UNIFORM, controlled manner; the heating and drying of the aggregate must be UNIFORM; the separation of the aggregate in the bins must be UNIFORMLY controlled, and the aggregates and asphalt must be combined and mixed in a UNIFORM, consistent manner.

In order to achieve this uniformity of quality, it is necessary that the entire operation be conducted so that each phase of the production operation is in balance with all other phases. The production of the pugmill cannot exceed that of the dryer or screens, for instance. The productive capacity of the plant is, of necessity, limited to the capacity of the least productive unit in the production cycle, whether it be dryer, screens, pugmill or any other unit. For these reasons, it is imperative that the inspector be thoroughly familiar with all phases of the mixing operation.

Attitude of the Inspector

The attitude of the inspector toward the Contractor and his plant personnel should be one of cooperation, consistent with the requirements of the specifications and his instructions. He must remember that the Contractor has his rights under the contract as well as the State, and these rights must be respected. The inspector should assume the attitude that the Contractor is honestly trying to fulfill his part of the contract and that errors and difficulties which may arise are the result of a lack of information, or as a result of misunderstandings, rather than a desire on the part of the Contractor to do dishonest or poor work. Generally, if the inspector shows that he intends to cooperate in every way he can to facilitate the operation, he will find that the Contractor will meet him halfway. When troubles occur, the inspector shall make every effort to locate the cause of the trouble and make the necessary corrections. If violations or misunderstandings of the specifications arise that cannot be promptly settled, he must notify the Project Engineer immediately.

The plant inspector must be in close communication with the street inspector. A few minutes spent at the paving site will indicate whether or not the mixture has the workability and other characteristics desired. Close

[1] Construction Manual of the Washington Department of Highways.

cooperation between the plant and the street inspectors will aid greatly in achieving a satisfactory job.

Instructions shall be issued to the Contractor or to the foremen, rather than to the workmen, whenever possible. A diary must be kept, showing all instructions received from the Project Engineer and all instructions issued to the Contractor.

It is highly desirable that before construction begins, the Engineer and his inspectors confer with the contractor's superintendents and foremen and carefully plan the entire operation.

5-4.1J Plant Inspector's Check List

Some of the most important details of inspection on asphalt plants are listed below:

1. See that testing tools and equipment are on hand and in good condition. Make sure you understand all tests.
2. Inspect all components of mixing plant; make sure all deficiencies are corrected **before** mixing is begun.
3. Check all scales for performance daily.
4. Make weekly test of scales and inspection of plant.
5. See that stockpiled aggregates are kept separate; see that no intermingling occurs at cold feeders.
6. See that cold aggregate feeder gates are set correctly and that cold aggregates are feeding continuously.
7. Make frequent checks of temperature of heated aggregate.
8. Watch for evidence (Dark smoke from plant exhaust and oily coating of aggregate) of incomplete combustion of burner fuel.
9. Are the aggregates properly dried?
10. Check frequently the temperature of the asphalt.
11. Establish scale settings for batch weights; observe plant operator frequently to see that correct weights are obtained.
12. See that each batch is mixed the required length of time.
13. Make frequent visual inspections of mix leaving plant for evidence of non-uniformity or incomplete mixing.
14. Check temperature of mix frequently.
15. Inspect truck beds before loading; see that bed is free of congealed chunks of mix and excess diesel oil.
16. Check occasionally with street inspector concerning workability and uniformity of mix at the paving machine and air flow tests.
17. Take samples of mix for field extraction and submission to laboratory.
18. Make accurate, complete record of all test results, number of batches mixed, asphalt used, and other pertinent data.

5-4.2 Responsibilities and Duties of the Street Inspector

5-4.2A General

In the construction of asphalt pavements, it is the responsibility of the street inspector to see that construction methods and equipment used, as well as the finished pavement, meet the requirements of the specifications. In order that he may properly discharge this responsibility, it is necessary that he thoroughly understand the Standard Specifications, the special provisions of the contract, and the instructions set forth herein. He must also have a good working knowledge of methods and equipment involved in the construction.

The street inspector should adopt an attitude of cooperation with the Contractor. He must so conduct his inspection duties that no unnecessary delays to the paving operation result. A smoothly organized, continuous paving operation will generally produce the best results, both in quality and economy.

The remarks contained in Chapter 5-4.1A of these instructions concerning the attitude of the inspector toward the Contractor apply to the street inspector as well as the plant inspector.

A means of communication between the street inspector and the plant inspector must be established and the street inspector shall cooperate with the plant inspector by keeping him informed of any difficulties encountered in the laying of the mixture or of any faulty mixture received at the paving site.

5-4.2H Street Inspector's Check List

Some of the most important details of inspection on asphalt paving are listed below:

1. Check condition and adjustment of paving machines and rollers.
2. Has width of spread in successive layers been determined?
3. See that traffic control is organized and functioning properly; make sure required signs are in place.
4. Check application of tack coat; do not allow tacking of more base than will be paved each day.
5. Examine pavement base, see that required patching and/or pre-leveling is done. Don't be afraid to get the front of your shirt dirty; do a lot of "belly-grading". Make check of surfacing depths before paving begins; (See Chapter 4-1.3).
6. See that paver guidelines are set.
7. Check transverse joint for smoothness and appearance.
8. Watch trucks dumping into paver hopper for adverse effect on paver operation.
9. Check temperature of mix occasionally.
10. Maintain constant inspection of mat behind paver for signs of roughness or non-uniformity of mixture.
11. See that longitudinal joint is raked and compacted properly.
12. Make frequent checks of yield and depth.
13. Watch rolling operation; see that the rolling pattern established by test is used; watch for variation in speed of rollers and correct. See that optimum air flow readings are maintained.
14. Keep record of truckloads used each day; check with plant inspector concerning weights.
15. Make sure the job is in good shape before you leave at the end of the day; see that lights, barricades,

etc., are placed properly; see that all signs not required during non-working hours are removed or covered.

5-5 CEMENT CONCRETE PAVEMENT

5-5.1 General Instructions

Modern concrete paving is a highly complex, mechanized operation involving construction of tens of thousands of dollars worth of pavement in a single day's production. Proper organization and planning of the work are essential on the part of both Contractors and Engineers. Cement concrete pavement has a relatively high initial cost and the State expects many years of satisfactory service from this type of pavement. It is imperative that the Project Engineer and his inspectors are thoroughly familiar with the specifications and techniques applying to the work, if this objective is to be attained.

Before construction begins, the Project Engineer should review all phases of the work, and see that all members of his crew are familiar with the duties to which they are to be assigned. Advance planning and organization of the engineering and inspection teams will do much to eliminate the confusion and improper construction sometimes found during the first day's work. All inspection equipment and testing tools should be on hand in advance of beginning of paving, and demonstrations should be made to acquaint inspectors with their proper use.

The size of the inspection crew will be dependent to some extent upon the circumstances peculiar to each project. The following listing of inspectors and their responsibilities is intended as a guide:

1. The batch plant inspector is charged with the duty of checking all operations at the proportioning site, seeing that the proper amounts of aggregate and cement are batched for transportation to the mixer.
2. The mixer inspector is responsible for inspection of mixing operations, and must see that the proper control of consistency, air content and mixing time is maintained. He is usually assigned an assistant to aid in conducting air content tests, making of test beams, etc.
3. The finishing inspector is assigned to check on all finishing and curing operations, seeing that equipment and methods meet all requirements of the Specifications.

Other inspectors and checkers may be assigned to subgrade and form inspection, inspection of joint construction, straightedging, etc., as required.

The Project Engineer should make certain that all inspectors are instructed in the proper methods of keeping notes, records and diaries. Accurate records of construction progress and test results are absolutely essential in evaluating pavement performance through the years.

5-5.10 Inspector's Check List

For the convenience of the inspector, some of the most important inspection duties on concrete paving work are listed below:

1. See that all testing tools and equipment are on hand and in good condition.
2. Inspect Contractor's paving equipment; see that all deficiencies are corrected before paving is begun.
3. Calibrate water meter and air-entraining agent dispenser on mixer.
4. Check capacity and condition of batch trucks.
5. Check preparation of subgrade; watch for soft spots.
6. See that forms are in good condition and are set securely, true to line and grade. If slip form paver is used, check position of wire.
7. Make sure subgrade is wetted thoroughly in advance of paving.
8. Observe batch trucks dumping into skip; see that no intermingling or spillage of materials occurs.
9. Check mixing time frequently.
10. Make slump tests as required under Chapter 9. Watch for variations in consistency of mixed batches.
11. Make tests of air content of mix in accordance with Chapter 9.
12. Check quantity of air-entraining agent used against number of batches mixed.
13. Make cement factor test in accordance with Chapter 9. On projects using slip form pavers, density tests shall be made in accordance with Chapter 9.
14. Make test beams as required by Chapter 9; see that they are cured properly.
15. MAKE COMPLETE, ACCURATE RECORD OF TEST RESULTS AND COMPUTATIONS.
16. See that tie bars and dowel bars are installed properly.
17. Watch for excessive movement of forms under weight of paving equipment.
18. Check frequently to see that vibrators are operating properly.
19. Check pavement surface with straightedge; require necessary corrections to be made.
20. Watch finishing operations to make sure excessive amount of water is not added to surface; allow fine spray only to be used.
21. Check burlap drag (or brooming operation) to see that proper, uniformly textured surface is obtained.
22. See that curing compound is placed uniformly, at the required rate and at the proper time.
23. See that concrete is consolidated properly at night headers; use straightedge to make sure smooth joint will be obtained.
24. Inspect joint sawing operation to see that required depth is cut, and that the best possible saw cuts are obtained.
25. Watch removal of forms; see that damage to pavement does not occur; require curing compound to be applied on edge of slab immediately following form removal.
26. See that additional curing compound is applied over areas scuffed by foot traffic.
27. Make sure pavement is protected from traffic with necessary barricades, lights, etc.
28. See that sawed contraction joints are sealed properly.
29. Check surface smoothness each day in accordance with Section 5-05.3(12) of the Standard Specifications.

APPENDIX D

OBSERVATION FROM PERFORMANCE SURVEYS

Although the states report little direct information to relate quality assurance testing and inspection to performance, a number of performance surveys provide indirect evidence of the causes of poor performance. A limited number of these reports were reviewed to provide some insight into possible shortcomings of the quality assurance system used. These are summarized in the following sections.

HIGHWAY CONDITION AND QUALITY OF HIGHWAY CONSTRUCTION SURVEY REPORT

An FHWA report (*19*) is the most recent and comprehensive available that reflects the relationship of quality assurance to performance. The survey was conducted to provide information on the condition of recently completed highways and to identify problem areas in the quality of highway construction. The survey consisted of (a) condition surveys of recently completed pavements and bridge decks (0 to 7 years of service life), (b) surveys of construction quality of ongoing projects, and (c) surveys of the staffing of ongoing projects.

The information was analyzed on the basis of five fundamental questions:

1. Are these elements performing in accordance with specifications and service life expectations, and if not, is there an association with construction quality?
2. What are the current quality levels of ongoing construction?
3. What are the critical quality parameters that assure good performance?
4. What are the trends in staffing of construction projects?
5. Does project staffing affect the quality of work?

Condtion Surveys

The condition surveys noted that the present serviceability ratings of both rigid and flexible pavements are extremely variable, ranging from 2.5 to 5.0. Approximately 50 percent of the projects surveyed have present serviceability ratings below 4.0. It was noted also that axle loads were being applied to recently completed projects at a faster rate than design procedures anticipated. Friction (skid) numbers of rigid pavements ranged from a low of 24 to a high of 88. Forty-two percent of the projects surveyed had friction numbers that indicate possible loss of some original skid-resistant surface texture.

The principal types of distress for flexible pavements were longitudinal cracking (60 percent of projects), rutting (58 percent), and transverse cracking (52 percent). Alligator cracking (16 percent), edge cracking (16 percent), block cracking (12 percent), and patching (11 percent) were other recorded defects.

The largely visual condition rating of bridge decks 0 to 7 years old showed that 90 percent were in good condition. Ninety percent were also given a riding quality rating of good. On a subjective basis, 38 percent were rated fair to poor on skid resistance. The principal types of distress observed for bridge decks were shrinkage and stress cracking expansion joint damage and aggregate polishing.

Construction Quality Surveys

Data from the construction quality surveys were analyzed on the assumption that a 90 percent quality level was the dividing line between good work and levels where improvement was needed. The quality level is a statistical estimate of the percentage of material within the limits of the specification. Consequently, it is influenced greatly by the specification and does not necessarily relate to the performance of the unit of construction.

A relatively large number of projects indicated low quality levels for moisture control, density control, and control of the amount of material passing the No. 200 (75 μm) sieve. For subgrade and subbase, the numbers of projects with less than 90 percent quality levels were 42 and 34, respectively. Thirty-eight percent of the subgrade projects had quality levels less than 90 percent for density control. Thirty percent of the subbase projects and 24 percent of the untreated base projects had quality levels less than 90 percent.

The percentages of projects falling below the 90 percent level for various quality control factors are given in the report as follows:

Mix laydown temperature	18 percent
Density	40 percent
Bitumen content	30 percent
No. 200 sieve	20 percent
Control sieve	28 percent
Surface smoothness	0 percent

Of the eight factors considered essential to good rigid pavement construction, four appeared to be lacking in good quality control. These four are slump, air content of the concrete, thickness of the pavement, and density of the pavement. The percentages of projects that have less than 90 percent quality levels are 40 for slump, 24 for air content, and 28 for thickness. The control of strength was judged satisfactory; only 6 percent of the projects surveyed appeared to have quality control problems with this factor.

For bridge deck construction, problems were evident with respect to slump—52 percent of the projects had quality levels less than 90 percent. For air content, 28 percent had quality levels less than 90 percent. For reinforcing steel placement (depth of cover over steel), 70 percent of the projects had quality levels less than 90 percent. For deck thickness, 62 percent of the projects had quality levels less than 90 percent.

Staffing Survey

The construction staffing survey collected data on staffing involved in inspection and testing activities for subbase and base construction, flexible and rigid pavement construction, and bridge deck construction. Eighty-one percent of the inspection and testing man hours for the activities studied were reported by the entry- and second-level technician and entry-level engineer classifications. Of the total manhours involved, about 35 percent were in testing and 65 percent in inspection. For both the engineering and technician classifications, the relative percentage of time spent on inspection as compared to testing increased as the grade level of the employee increased. For example, on the average, a level I technician spent 58 percent of the time in inspection and 42 percent of the time in testing, while a level V technician spent 89 percent in inspection and 11 percent in testing.

Conclusions and Recommendations

For the conditions surveys, the major conclusions and recommendations were:

• In general, both rigid and flexible pavements (0 to 7 years of service life) are performing in accordance with design life expectations even though axle loads are being applied at a more rapid rate than design procedures anticipated.

• The levels of serviceability in terms of present ratings are quite variable and, on the average, are somewhat low for both types of pavements. There appears to be room for improvement in this regard.

Serviceability ratings are principally related to the riding quality of the pavement, and the report recommends that performance specifications for riding quality be developed and used for both rigid and flexible pavements.

• The emphasis on skid resistance has apparently paid dividends for flexible pavements. Seventy-eight percent of skid number measurements were above 40 (at 40 mph). For rigid pavements, most of the newer construction was receiving a tine finish with good results. However, because the bulk of rigid pavements completed in the last seven years did not have this type of finish, it is anticipated that corrective action may be required to improve skid resistance.

• The problem of bridge deck performance quality is well-recognized. However, this survey indicated that severe distress occurs sometime after seven years of service. Emphasis on improving both the durability and skid resistance is needed. A tine or similar finish was recommended for all decks. Only 22 percent of the decks surveyed had such a finish.

For the construction quality survey, the chief conclusion was that quality control problems existed in all three major items of work—flexible pavement construction, rigid pavement construction, and bridge deck construction. Review of the various specification requirements indicated that there were two problems. In some instances the specification limits were unrealistic and did not allow for normal testing and process variability. This accounted for a portion of the seemingly low quality levels registered for the work (quality used in this context refers to quality of conformance to the specification and not quality of performance). Second, conventional practice, where acceptance of the work was made on the basis of one test and resampling and testing was commonly employed, increased the risk of accepting low quality work.

A general recommendation to solve these problems was that specifications using statistical quality assurance procedures be adopted. These should be performance-related and take into account normal testing and process variability. Much development has already been accomplished in this regard. Implementation and use need to be spurred.

Specific suggestions were made concerning needs in each of the major construction areas:

• Foundation Elements (Subgrade, Subbase, and Untreated Bases)—The specification limits appeared reasonable for these elements. Increased emphasis on moisture control was apparently needed to attain specified densities for all three of these elements.

• Flexible Pavement Construction—Improved quality control of density, bitumen content, and gradation was recommended. In some cases, specification limits should be adjusted to accommodate normal testing and process variability. Performance specifications were recommended for improving the riding quality of flexible pavements. Control or specifications on a thickness basis for flexible pavements should directly reflect design criteria.

• Rigid Pavement Construction—Improved quality control of water-cement ratio, slump, air content, thickness, and density of the concrete was suggested. The low quality levels registered for slump appeared to be related to unrealistic specifications. To include normal testing variability, specification limits need to be set at ± 2 in. (50 mm) of the target value for 100 percent conformity on an individual test basis. Air content specification limits, likewise, would need to be set at ± 2 percent of the target value for 100 percent conformity on an individual test basis. Thickness specification limits appeared reasonable; thus, improved control is apparently needed.

• Bridge Deck Construction—Improved quality control of the slump and air content of the concrete, the placing of reinforcing steel, and the deck thickness was needed. The suggestions made regarding slump, air content, and density for the concrete used in rigid pavement construction applies here as well. In addition, it was strongly recommended that rapid test procedures be developed and used to measure cement content, water content, and water-cement ratio of the concrete used in bridge decks. The latter factors are critical to good bridge deck performance and long service life.

The low quality levels registered for reinforcing steel placement and deck thickness were partially explained by very tight specification limits. Recognizing the current process capability (± ⅜ in.) of workers to place reinforcing steel in its proper location, the only tenable solution is to require a slight over-design in the concrete cover over reinforcing steel. The design should allow 2.5 in. of cover to assure that 95 percent of the reinforcing steel is covered with a minimum of 2 in. of concrete.

The major findings with respect to the staffing survey have already been discussed. The report recommended better and more extensive training for the technicians who do most of the quality control testing and inspection. Because inspection activities are highly manpower-intensive, the report also recommended development and use of random acceptance sampling plans to reduce construction and engineering costs.

Analyses of work productivity rates revealed extreme variability from project to project and from state to state. For instance, in bridge deck construction, productivity varied from a low of 0.4 cu yds per man-hour to a high of 14.1. A program to normalize productivity rates so that manpower needs could be more effectively and efficiently established was recommended.

The report suggested strategies for improving the quality of highway construction. These included introduction of pavement management system concepts, with adequate training and workshops to implement the ideas.

A REVIEW OF PAVEMENT PERFORMANCE OF VIRGINIA'S INTERSTATE SYSTEM

A total of 195 projects were surveyed and rated in a study by McGhee (*28*). Of these, 119 (66.2 percent) were flexible pavements, 57 (21.2 percent) were jointed portland cement concrete pavements (JPCCP), and 19 (12.6 percent) were continuously reinforced portland cement concrete pavements (CRCP). Analyses of the ratings given each pavement type indicated that 84 percent of the flexible pavements, 56 percent of the JPCCP, and 89 percent of the CRCP were expected to exceed their design life (10 years for flexible, 25 for JPCCP, and 35 for CRCP).

A wide variety of materials and variations in design were used for the JPCCP. Some designs performed poorly and some well. Maintenance costs were $603 per mile per year for flexible pavements, $1,228 per mile per year for JPCCP, and $334 per mile per year for CRCP.

The $608 average maintenance cost for flexible pavements included overlays on 44 percent of the projects. The average pavement age at the time of the overlay was 8 yrs, 2 months. (Eight years was considered the design life with overlay.) Flexible pavements that had not been overlayed had average maintenance costs of $190 per lane mile.

The study concluded that the principal problems with jointed portland cement concrete pavement were associated with poorly draining subbases and metal joint inserts. In the case of flexible pavements, settlements and stripping-prone aggregates have caused the most severe damage. The most serious problems with CRCPs have been the results of poor concrete consolidation. With the exception of fill settlements (still under study), most of the problems have been corrected through modification in design standards or construction specifications.

It was noted that many Interstate pavements are subject to significantly higher-than-design traffic loadings. Interstate ramps have performed much more poorly than main line pavements. The study also noted that most efforts to seal the joints between PCC pavements and asphalt concrete shoulders have been unsuccessful due to excessive strains in the joint sealing material. In six cases where valid comparison could be made, flexible pavements gave better service, and in three cases, the portland cement pavement performed better. A need was noted for increased diligence on the part of the inspection personnel because of numerous instances in which asphalt concrete construction has given inferior performance due to segregation, low asphalt content, high asphalt content, or excessive tack coat.

DURABILITY OF CONCRETE

An American Concrete Institute publication (*29*) covers a wide range of factors affecting the performance of concrete, especially the effects of aggressive environments—freezing and thawing, chloride and sulfate attack, and moisture. Of particular interest to quality assurance is the report included in it, "Factors Affecting the Durability of Concrete Bridge Decks" (*30*). The latter report gives the results of a survey of 249 four-year-old bridge decks in Pennsylvania. The chief purposes of the survey were to determine the extent and severity of the decks' deterioration and to provide insight into the relative importance of those factors that cause deterioration. Several of the conclusions and recommendations are of interest from the standpoint of quality assurance.

Conclusions

1. Perhaps the most important conclusion from this work is that both excellent and poor quality bridge decks can be constructed using present practices and specifications. Many sound and badly deteriorated four-year-old decks bear out this conclusion. It appears that specific practices and specific materials cause deterioration or at least allow it to occur.
2. As suggested in past studies and aptly pointed out in this study, different contractors produce decks of widely different qualities. This suggests that some construction practices are better than others in reducing or eliminating the principal forms of deterioration (fracture planes and spalls, cracks, and surface mortar deterioration). The prime example of this is the recurrent relationship observed between fracture planes and spalls and shallow reinforcing steel.

Recommendations

1. The thickness of concrete cover over the upper reinforcing steel in bridge decks should be made to conform to the specification or final drawing. Provision of this cover should be made a basis of payment. . . . The results of this study tend to support the 2 inch minimum cover currently advocated by most agencies.
2. More uniform inspection practices are recommended. Depth of reinforcing steel and concrete finishing demand especially vigorous control.
3. More detailed and critical standards should be considered for aggregate to be used in bridge decks.

4. A rigorous specification concerning hot weather concreting should be considered. Reduction of evaporation rates on the fresh concrete surface and tighter control on the initiation of curing should be provided.
5. In view of the much better performance of higher strength decks, it is recommended that current concrete strength requirements be increased for bridge decks.

COMPARISON OF PROPERTIES OF FRESH AND HARDENED CONCRETE IN BRIDGE DECKS

A report by Newlon (*31*) is one of the few available in which it is recognized that the characteristics of hardened concrete in bridge decks are not always as would be indicated by the specifications under which the concrete is placed. The report also attempts to relate performance to measured characteristics of the hardened concrete.

The study was made on 17 bridge decks constructed in 1963 under regular construction procedures. These structures are considered representative of the last ones built under Virginia's old specifications and are not representative of the state's current practice. The report includes data concerning such characteristics of fresh concretes as slump, water-cement ratio, air contents, stiffening rate and mixture temperature, yield, and variation of components. A summary of construction operations such as mixing, placement, screening, application of final texture, and curing is also included.

Conclusions

The results of this study furnish some quantitative data in an area where considerable speculation has existed. While the results are undoubtedly influenced by local conditions, the author is of the opinion that similar studies in other geographical areas would yield equivalent results.

The results are, in general compatible with and substantiate the findings of other studies in which valid tests of the fresh concrete were usually not available. The principal conclusions are:

1. When viewed against the perfection desired by the engineer, the performance of these decks has been disappointing or borderline. When viewed against the performance that would be expected from concrete with the properties observed, the performance has been better than might be expected.
2. The performance of the 17 structures in this study closely parallels the performance of a large sample of bridges included as part of a nationwide study of bridge deck performance.
3. The primary cause of variable or borderline performance of concrete in bridge decks is variable or borderline fresh concrete. Many of the deficiencies have been overcome by changes in specifications and procedures instituted since the construction of the bridges included in this study.
4. Even with the use of elaborate mechanical equipment, diligent attention must be given to the details of accepted practices of good concreting such as maintenance of low water-cement ratios, adequate air contents, and prompt and thorough curing.
5. The agreement of properties such as unit weight and air content measured in both the freshly mixed and hardened concrete is acceptable for engineering purposes.
6. No influence of the screeding method on the properties of the concrete in place was found. However, several indirect relationships may exist. These include:
   (a) The average slump of concrete placed on jobs using mechanical screeding equipment was 2.8 while that for jobs utilizing hand methods was 3.8. To the extent that slump reflects water content, the use of mechanical screeds should result in a better quality concrete.
   (b) Of the four bridges screeded with the longitudinal screed, three have shown relatively serious deficiencies. Two have been resurfaced primarily because of deficient cover over the uppermost reinforcement. The third span has surface spalling, which also appears to be related to insufficient cover over the reinforcement. Hopefully research nearing completion at the Research Council will shed light on this problem and suggest means for eliminating it.
7. Traffic volumes and design features seem to have had little influence on the adverse performance of the seventeen bridges in this study.
8. The only three bridges that are free from scaling were the only three bridges that contained an adequate entrained air voids system.
9. For the class of mixtures used in these decks, a minimum air content of 5 percent was found to be necessary in order to provide a void spacing factor of 0.0055 in., while air contents of 4 percent provided spacing factors below 0.0075 in.
10. The importance of the early application of curing was reflected in the scaling of several decks of apparently satisfactory concrete to which curing was applied very late.
11. Uncertainty exists as to the exact proportions of the components, especially water, in the concrete in these bridge decks. Procedures established since this project should improve this situation.
12. The influences of water-reducing admixtures on retarding the setting and reducing the water requirement were apparent in the samples from this project, as was the accelerating effect of high mixture temperature.
13. The data from three spans suggest that the cracking common to them might be explainable from high sand equivalents of the fine aggregates used. [Note: Correspondence with the author indicates that this statement should read, . . . "low sand equivalents. . ."]
14. Popouts were confined to structures using aggregates previously known to be susceptible to this type of defect.

PREDICTING ASPHALT PERFORMANCE

A report by Zenewitz and Welborn (*23*) is the final one of a series involving a study of the performance of asphalt pavements. The primary objective of the survey was to measure changes in the fundamental properties of asphalts during service in pavements and, if possible, to relate those changes to performance. This was to be done by computer analysis of variance and other statistical procedures to determine if relations existed that were not readily apparent from observation of the data. In this study, surviving pavements were defined as those still in service without an overlay after 12 years. Nonsurviving pavements were those overlaid prior to 12 years. The projects were distributed in 19 states and contained asphalts from 29 sources. In 1967, when the samples were taken, 34 pavements were in service as originally constructed and 19 pavements had been overlaid.

Findings

The study findings were:

1. Pavements should be sampled at several random sites to obtain meaningful estimates of the existing levels of mixture properties.

2. Because significantly lower sampling plus testing variability of the bulk specific gravity measurement is obtained in 8-inch (203 mm) core samples than for 6-inch (152 mm) or 4-inch (102 mm) core samples, the 8-inch (203 mm) core should be used whenever possible.
3. Lower variabilities of some mixture properties were significantly characteristic of 'surviving' pavement projects and higher variabilities of some mixture were significantly associated with 'non-surviving' or poorly performing pavement projects.
4. Lower project variability of bituminous mixture properties such as percentages of asphalt, air voids, mineral voids, mineral voids filled, bulk specific gravity, and aggregate passing the ⅜ inch (9.5 mm), Nos. 4, 8, 16, 30, 100, and 200 sieves were significantly characteristic of higher rated surviving pavements.
5. Long-term hardening of asphalt binder in a pavement is essentially dependent on the asphalt content and air voids in the pavement mixture.
6. Regression equations are reported for predicting consistencies of binders in aged 'surviving' pavements from the consistencies of the original asphalts or their laboratory aged residues, the percentages of asphalt and air voids in the pavement mixtures, and the percentages of certain chemical fractions in the original binder.

The most significant of these findings from the standpoint of relating quality assurance to performance are numbers 3 and 4.

Assuming that a satisfactory mix design was used in constructing these pavements, "the durability and performance are affected by the level of variability associated with pertinent mixture properties." (These levels are given in Tables D-1 and D-2.)

Recommendation

On the basis of these findings, it is recommended that specifications for assuring uniformity of construction be used in future construction. These would be based on project variabilities of mixture properties. The starting point could be the variabilities of a significant nature presented in this report with revisions where indicated by trial. The random samples for this determination can be taken at the outset of the construction or after a certain level of traffic consolidation of the pavement.

A SURVEY TO DETERMINE THE IMPACT OF CHANGES IN SPECIFICATIONS AND CONSTRUCTION PRACTICES

A study by Newlon (*32*) was made in 1972 on 129 bridge decks constructed after 1966 when all improvements in specifications shown by earlier research to be needed had been made. Performance of the newer bridge decks was compared to the performance of a similar sample that had been surveyed in 1961. The conclusions were as follows:

1. The frequency of early bridge deck scaling has been dramatically reduced by the upgrading of specification requirements and construction practices. Several specific changes such as increased air contents, use of linseed oil treatments as well as increased awareness of the problem all contribute to this improvement. Because concrete susceptible to scaling usually exhibits the defect at an early age this is an encouraging result. The elimination of premature scaling was a major target of the specification upgrading effort. The success of this effort is evident.
2. Transverse and random cracking are indicated to be more frequent than before the upgrading. The reason for the increase in transverse cracking is not apparent and there is other evidence that the indicated increase in random cracking is related to closer observation and differences in classifications rather than to real causes. The severity of cracking does not seem to be serious enough to warrant attention. Real differences, if any, will become more apparent with time.
3. The frequency of all other observed defects is very low. Based upon previous studies this will undoubtedly increase with age, traffic, etc., but experience suggests that serious problems are indicated at comparatively early ages.
4. The measured average cover over reinforcement is fortunately significantly greater than that specified. For the two levels of cover specified, 8 and 16 percent of the

TABLE D-1

SIGNIFICANT LEVELS OF STANDARD DEVIATIONS OF MIXTURE PROPERTIES OF IN-SERVICE AND OUT-OF-SERVICE PROJECTS (*23*)

	Survivors	Nonsurvivors	Probability of a Chance Occurrence
Mixture Property			
Asphalt Content, percent	0.1 or less	0.3 or more	less than .01
Air Void Content, percent	-	1.5 or more	between .02 and .05
Mineral Void Content, percent	0.6 or less	0.7 or more	less than .01
Mineral Voids Filled, percent	none	none	
Bulk Specific Gravity	.017 or less	.034 or more	approximately .05
Maximum Specific Gravity	.007 or less	.013 or more	between .01 and .02
Effective Specific Gravity of Aggregate	.010 or less	.011 or more	approximately .05
Percent Aggregate Passing			
3/8" (9.525 mm) sieve	2.0 or less	2.1 or more	between .001 and .01
No. 4 sieve	1.6 or less	-	between .02 and .05
No. 8 sieve	1.0 or less	-	between .01 and .02
No. 16 sieve	1.2 or less	1.3 or more	approximately .05
No. 30 sieve	none	none	
No. 50 sieve	none	none	
No. 100 sieve	none	none	
No. 200 sieve	none	none	

TABLE D-2

SIGNIFICANT LEVELS OF STANDARD DEVIATIONS OF MIXTURE PROPERTIES OF RATED IN-SERVICE PAVEMENT PROJECTS (*23*)

	"Superior" (Higher Ratings)	"Average" (Lower Ratings)	Probability of Chance Occurrence
Mixture Property			
Asphalt Content, percent	0.1 or less	0.2 or more	between .05 and .10
Air Void Content, percent	1.0 or less	1.1 or more	between .05 and .10
Mineral Void Content, percent	0.6 or less	0.7 or more	between .025 and .05
Mineral Voids Filled, percent	2.5 or less	2.6 or more	less than .025
Bulk Specific Gravity	0.020 or less	0.021 or more	between .05 and .10
Maximum Specific Gravity	none	none	
Effective Specific Gravity	none	none	
Percent Aggregate Passing			
3/8" (9.525 mm) sieve	1.1 or less	1.3 or more	between .025 and .05
No. 4 sieve	1.6 or less	1.7 or more	approximately .025
No. 8 sieve	1.0 or less	2.0 or more	less than .005
No. 16 sieve	1.5 or less	1.6 or more	approximately .025
No. 30 sieve	1.3 or less	1.4 or more	between .025 and .05
No. 50 sieve	1.0 or less	1.1 or more	approximately .10
No. 100 sieve	0.8 or less	0.9 or more	between .10 and .25
No. 200 sieve	0.8 or less	0.9 or more	between .05 and .10

measurements are less than required. This is believed to reflect an acceptable level of control.

5. Ninety-five percent of the spans have average corrosion potentials below 0.20 volt, which indicates no active corrosion. On one percent of the spans the average values are above 0.40 volt, which suggests the presence of active corrosion. The potential for corrosion will increase with age and exposure to deicing chemicals.

6. The techniques developed for the BPR-PCA survey in 1961 and used in previous studies by the Research Council provide reproducible and useful evaluations of performance based upon visual observations. The procedures reflect general trends and levels as opposed to detailed causes and effects.

7. When the bridges to be surveyed are similar in age and condition and when the sample is sufficiently large, observations on a single randomly selected span provide the same results as observations of all spans on the bridge. Stated in other terms, the observation of spans rather than bridges appears to be a valid approach.

CASE STUDIES OF PAVEMENT PERFORMANCE, PHASE I, KENTUCKY

A study (*33*) was conducted by the U.S. Army Engineer Waterways Experiment Station for the Federal Highway Administration to identify the causes and mechanisms associated with cracking and rutting of flexible highway pavements. Comparative tests and theoretical analyses were made on two areas of the same pavements—one in a distressed area containing cracks and the other in a nondistressed area. Even though extensive tests were made on the pavement, base, and subgrade, there were no apparent differences in test results to explain why the pavement would be cracked in one test location but not in the other. Differences in rut depth were attributed to greater permanent deformation of the subgrade in the higher rutted area.

CASE STUDIES OF PAVEMENT PERFORMANCE, PHASE II, TEXAS

Phase 2 of the FHWA study (*26*) to identify the causes and mechanisms associated with cracking and rutting of flexible highway pavements was approached through in situ field investigations, laboratory testing, and theoretical analysis. As in the Kentucky (phase I) study, comparisons were made between distressed and nondistressed pavements.

Resilience and creep characteristics of materials were developed and used to evaluate the existing prediction techniques. Values of measured deflections and those obtained from layer system analyses were generally in agreement. However, present analysis techniques are not sufficiently advanced to account for all the pavement behavior mechanisms contributing to cracking and rutting. This suggests that additional damage models should be developed to supplement present layer system analysis techniques.

ZERO-MAINTENANCE PAVEMENTS: RESULTS OF FIELD STUDIES ON THE PERFORMANCE REQUIREMENTS AND CAPABILITIES OF CONVENTIONAL PAVEMENT SYSTEMS

Darter and Barenberg (*27*) reported on studies of requirements to provide zero-maintenance performance of heavily travelled conventional pavements. Five types of pavements were included in the study: plain jointed concrete (JCP); reinforced jointed concrete (JRCP); continuously reinforced concrete (CRCP); flexible pavements (FLEX); and composite pavements (COMP). Results are given in four areas: (a) an evaluation of the adequacy of commonly used design procedures to provide maintenance-free performance; (b) identification of major distress types, their causes, and maintenance performed; (c) limiting design criteria for zero-maintenance design; and (d) determination of the maximum maintenance-free lives of each pavement subjected to different environments. Recommendaitons are made as to the most promising pavement types for consideration in zero-maintenance design.

The major types of distress and their causes for each type of pavement as given in the report follow.

Jointed Concrete Pavement

The major distress types in JCP are faulting at the joints (where no load transfer dowells are used) and transverse cracking. Causes are any of the following: lack of adequate load transfer combined with heavy traffic loadings, inadequate slab thickness, inadequate drainage and pumping. The major maintenance activities associated with these pavements are crack sealing, patching, and leveling of faulted joints by grinding or slab jacking.

Jointed Reinforced Concrete Pavements

The major distress types in JRCP are joint deterioration (spalling and blow-ups) and transverse cracking, with spalling and faulting of the crack if reinforcement ruptures. The causes may be any one of the following: heavy traffic loadings, inadequate drainage, improper joint design, and corrosion of load transfer dowels, probably augmented by heavy use of deicing salt. Major maintenance procedures are crack sealing, slab patching, joint repair, and slab jacking.

Continuously Reinforced Concrete Pavements

Major distress types in CRCP are localized failure, surface depression, crack spalling, yielding of the reinforcing steel (with subsequent spalling and faulting of the crack), and construction joint deterioration. Causes include the following: heavy traffic loadings, inadequate steel lap, poor joint construction, inadequate drainage, pumping of subbase, inadequate slab thickness for the specific subgrade support conditions, and corrosion of steel, especially in areas of heavy deicing salt applications. The major maintenance activities associated with CRCP are slab patching and repair of edge distress.

Flexible Pavements

Major types of distress in flexible pavements include fatigue or alligator cracking, transverse cracking, longitudinal cracking, and rutting. Causes include the following: heavy traffic loadings and inadequate pavement structure, low temperature shrinkage, poor lane joint construction, aging of asphalt cement, and disintegration of cement treated base from deicing salts and freeze/thaw cycles.

Major maintenance activities are crack sealing, pavement patching, and application of thin overlays.

Composite Pavements

The major distress in composite pavements is transverse cracking, with subsequent crack spalling and deterioration. Causes are primarily reflective cracking from the PCC base with concomitant spalling associated with heavy traffic loadings. Major maintenance activities are crack sealing and patching.

The major design procedures were evaluated and found generally inadequate for designing pavements that are maintenance-free for 20 to 40 years.

APPENDIX E

CERTIFICATION OF TRANSPORTATION ENGINEERING TECHNICIANS

A study on the certification of transportation engineering technicians (*24*) was conducted by the Institute for the Certification of Engineering Technicians (ICET) of the National Society of Professional Engineers (NSPE) in cooperation with an American Association of State Highway and Transportation Officials (AASHTO) Task Force. The report presents a program concept for certifying transportation engineering technicians. The program provides for four levels of certification in six transportation disciplines. Under this program, technicians will be certified by ICET upon verification of relevant experience and performance capabilities by professional engineers and qualified technicians and upon satisfactory completion of tests administered by ICET.

The program has the endorsement of FHWA, AASHTO, and NSPE. The endorsement, in part, states:

> The certification program compliments the management improvement efforts now underway in many state and local transportation agencies. It focuses on preparing transportation technicians to perform their jobs better. We believe that this program and the education and training initiatives that the program will generate have high potential for enriching the skills of transportation technicians for decades. These skills translate into better transportation programs.

The report consists of four parts: procedures and standards for certification of transportation engineering technicians, detailed description of work elements for transportation engineering technicians, available training resources relating to specific work elements, and bibliography of training materials related to certification of transportation engineering technicians.

The six work elements covered by the present program are: construction, design, materials, traffic operations, surveys, and maintenance.

The purpose of the program and its goals are set forth in the following basic policy statement:

> The purpose of this program is to provide a system to insure uniform standards of ability and performance for engineering technicians in transportation through a nationwide system for defining types and standards of work to be performed and by providing a means for enrolling, testing, and certifying transportation engineering technicians.

The objectives of this program include:

- Promotion of versatility and improved performance among technicians.
- Recognition of status through meaningful national certification.
- Increased effectiveness of manpower management through expanded utilization of all members of the engineer/technician team.
- Availability of a personnel classification model that may be adopted by agencies or firms and used in union agreements if appropriate.
- Support of the plan through an AASHTO-approved guide for a national training program.

Guidelines used in formulation of the program include:

- Directly related to work required of transportation engineering technicians.
- Based upon merit and individually demonstrated performance with no requirements for knowledge not related to work requirements.
- Contains minimal artificial barriers to progression within the career field.
- Encourages advancement for permanent and seasonal employees.
- Provides a continuing career pattern, even for technicians who do not remain employees of a single agency or firm.
- Provides economy and uniformity by utilizing national standards, training, and testing.
- Provides, at Level IV (Senior Engineering Technician), for recognition of effective performance of supervisory or management duties based upon sound technical skills and knowledge.

Four levels of competence are established for each of the six technical areas, and specific work elements within each level are identified. The procedures and requirements for obtaining certification are spelled out in detail, and guidelines for training materials are included.

THE TRANSPORTATION RESEARCH BOARD is an agency of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. The Board's purpose is to stimulate research concerning the nature and performance of transportation systems, to disseminate information that the research produces, and to encourage the application of appropriate research findings. The Board's program is carried out by more than 150 committees and task forces composed of more than 1,800 administrators, engineers, social scientists, and educators who serve without compensation. The program is supported by state transportation and highway departments, the U.S. Department of Transportation, and other organizations interested in the development of transportation.

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The National Academy of Sciences was established by a congressional act of incorporation signed by President Abraham Lincoln on March 3, 1863, to further science and its use for the general welfare by bringing together the most qualified individuals to deal with scientific and technological problems of broad significance. It is a private, honorary organization of more than 1,000 scientists elected on the basis of outstanding contributions to knowledge and is supported by private and public funds. Under the terms of its congressional charter, the Academy is called upon to act as an official—yet independent—advisor to the federal government in any matter of science and technology, although it is not a government agency and its activities are not limited to those on behalf of the government.

To share in the tasks of furthering science and engineering and of advising the federal government, the National Academy of Engineering was established on December 5, 1964, under the authority of the act of incorporation of the National Academy of Sciences. Its advisory activities are closely coordinated with those of the National Academy of Sciences, but it is independent and autonomous in its organization and election of members.

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