National Cooperative Highway Research Program

NCHRP Synthesis 212

Performance-Related Specifications for Highway Construction and Rehabilitation

A Synthesis of Highway Practice

Transportation Research Board
National Research Council

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Synthesis of Highway Practice 212

Performance-Related Specifications for Highway Construction and Rehabilitation

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

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PREFACE

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

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

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of interest to administrators, including contract and specifications administrators; research, construction, materials, specification, and design engineers; agency project managers and staff; and highway construction contractors. This synthesis describes the state of the practice with respect to the development and present status of performance-related specifications (PRS) for highway materials and construction.

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

Highway construction specifications have changed significantly since the end of World War II. This report of the Transportation Research Board summarizes the historical events that have prompted U.S. interest in PRS development and describes the underlying concepts. In addition, this synthesis describes current practice with regard to PRS implementation and refers to the principal PRS literature with emphasis on performance and cost models. This synthesis emphasizes the utility of PRS in providing objective/rational measures that can be used for special contract conditions, such as incentive or disincentive adjustments.

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

Scott A. Sabol, Senior Program Officer, National Cooperative Highway Research Program, Transporation Research Board, assisted the NCHRP 20-5 staff and the Topic Panel.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance were most helpful.

PERFORMANCE-RELATED SPECIFICATIONS FOR HIGHWAY CONSTRUCTION AND REHABILITATION

SUMMARY

Performance-related specifications (PRS) in the highway industry are specifications for key materials and construction quality characteristics (M&C factors) that have been demonstrated to correlate significantly with long-term performance of the finished work. These specifications are based on quantified relationships (models) between such characteristics measured at the time of construction and subsequent performance. They include sampling and testing procedures, quality levels and tolerances, and acceptance (or rejection) criteria. Typically, PRS also include payment schedules with positive and/or negative adjustments that are directly related through the performance models to changes anticipated in worth of the finished work as a result of departure from the quality level defined as acceptable.

PRS are a logical outgrowth of changes that have been occurring in the form of highway construction specifications since the end of World War II. They address some specific concerns of construction managers that are not resolved by contemporary statistical end-result specifications alone, such as the inability to identify or measure the essential M&C factors that determine performance, uncertainty as to the value to be gained from the cost of implementing statistically based specifications, and reservations as to the essential fairness of in-use or proposed price adjustment systems.

Performance models are the essential elements of PRS. Conceptually, designs are developed on the bases of these models to achieve predetermined service lives for specific conditions of load and environment. These models are also the means through which enhanced or diminished life is estimated from results of acceptance tests and, when combined with appropriate economic principles, how rational payment factors are determined. Correctly applied, PRS could enable the identification of the level of quality that provides the best balance between cost and performance and assure the attainment of that level in the constructed work.

The objectives of this synthesis are to identify current use of PRS by highway agencies and to describe the development and present status of PRS for highway materials and construction.

With the exception of the New Jersey Department of Transportation's specifications for portland cement concrete (PCC) strength and its experimental specifications for PCC pavement, no examples of operational PRS that conform to the definition adopted for this study were identified among highway agencies. Further, it was concluded from questionnaire responses that while the concepts of PRS are well understood within the research community, they have not been communicated effectively to the highway construction community at large.

While many of the elements supporting PRS development have evolved independently over a number of years, it has only been since the early 1980s that development has

proceeded in a coordinated fashion through a small but well-funded group of projects focusing on the surface layer of asphalt concrete (AC) and PCC pavements. A sound conceptual framework for PRS has been developed from these studies; also, useable primary and secondary relationships (models) have been identified from the literature, new secondary relationships have been developed from short-term laboratory experiments, and other short- and long-term experiments have been planned to develop the remaining relationships. In addition, the process of PRS development has been demonstrated through the production of prototype specifications that include various economic approaches to designing adjustable payment plans based on sound legal principles. The role of sensitivity analysis in developing practical expressions of the performance models and the role of computer simulation in generating operating characteristic and expected payment curves for the specification have been demonstrated as well.

Continuation of PRS development at the national level is recommended, as well as parallel efforts at local levels, to increase awareness of PRS concepts among state highway personnel and encourage the development of experimental specifications. Immediate preparation of educational and instructional materials on current and planned adjustable payment acceptance plans and their operating characteristics is also recommended as a means of addressing the issue of their fairness to both owners and contractors.

CHAPTER ONE

INTRODUCTION

DEFINITION

Performance-related specifications (PRS) in the highway industry are specifications for key materials and construction quality characteristics (M&C factors) that have been demonstrated to correlate significantly with long-term performance of the finished work. These specifications are based on quantified relationships (models) between such characteristics measured at the time of construction and subsequent performance. They include sampling and testing procedures, quality levels and tolerances, and acceptance (or rejection) criteria. Typically, PRS also include payment schedules with positive and/or negative adjustments that are directly related through the performance models to changes anticipated in worth of the finished work as a result of departure from the acceptable quality level.

In terms of their intent, construction specifications have always been performance-related. That is, they have always been vehicles through which an owner attempted to convey standards to a contractor in an effort to assure that the contractor's product performed in the manner that the owner desired. However, while the intent of construction specifications has remained unchanged, their form and substance have become increasingly more sophisticated as engineers have developed better predictors of performance and methods of measuring them in a timely manner, and as construction managers have developed better measures of compliance. These advances have been driven by an awareness that traditional specifications and acceptance procedures have not provided the assurance of quality once thought, and by the public's demand for greater accountability that has accompanied the burgeoning capital expenditures for highway infrastructure since the end of World War II (Figure 1).

In this context, the term "performance-related" has come to have a specific meaning, more restrictive than the understanding traditionally associated with it. In contemporary usage, PRS embody the following elements:

- *End-result*—Specifications based on measurable attributes or properties of the finished product, rather than on the processes used to produce the product.
- *Statistically based*—Sampling plans and decision criteria that consider the variability inherent in the finished product, as well as in the processes of sampling and testing.
- *Performance-modeled*—Specifications based on attributes that are related to performance of the finished product through quantitative relationships, or models, that have been validated for the specific materials and climatic conditions anticipated.
- *Cost/performance optimized*—Quality levels with sampling and testing procedures and frequencies, the combined costs of which are consistent with the criticality of the performance benefit sought.
- *Adjustable payment*—Positive and/or negative pay adjustments, sometimes referred to as incentives and disincentives, which reflect changes in the worth of the product resulting from departures in the level of acceptable quality.

Because of the evolutionary nature of construction specifications over the last three decades, the meaning intended by joining the terms "performance" and "specification" has been inconsistent. To avoid confusion, the following distinctions are used in this synthesis:

- *Performance specification*—One that describes how the finished product should perform over time. For highways, performance is typically described in terms of changes in physical condition of the surface or its response to load, or in terms of the cumulative traffic required to bring the pavement to a condition defined as "failure." Such specifications are not applicable to highway pavement components (e.g., soils, subgrades, subbases, bases, riding surfaces) because the technology is not sufficiently advanced, but may be applicable to some manufactured highway products (e.g., portland cement, light standards).
- *Performance-based specification*—One that describes desired levels of fundamental engineering properties (e.g., resilient modulus, creep properties, fatigue properties) that are predictors of performance and appear in primary performance prediction relationships (i.e., models that can be used to predict pavement stress, distress or performance from combinations of factors representing traffic, environment, roadbed, and structural conditions). For the most part, these properties are not amenable to timely acceptance testing.
- *Performance-related specification*—One that describes desired level of M&C factors that have been found to correlate with fundamental engineering properties that predict performance. These factors are amenable to acceptance testing at the time of construction.

To correct another frequent misunderstanding, the goal of PRS is not to improve the quality of construction, per se. Viewed simply, quality can be improved merely by changing the level of the quality characteristics that are specified. Rather, the goal of PRS is to identify the level of quality providing the best balance between cost and performance and to assure this level is attained in the constructed work. Stated differently, the goal of PRS is to improve specifications to reflect the best understanding of what determines quality and to create a contractual framework that maximizes cost effectiveness. Accordingly, much of the current research on PRS seeks to quantify the relationship between test results and subsequent performance.

OBJECTIVE

This contemporary definition of PRS requires a thorough understanding of materials and construction (M&C) quality and how

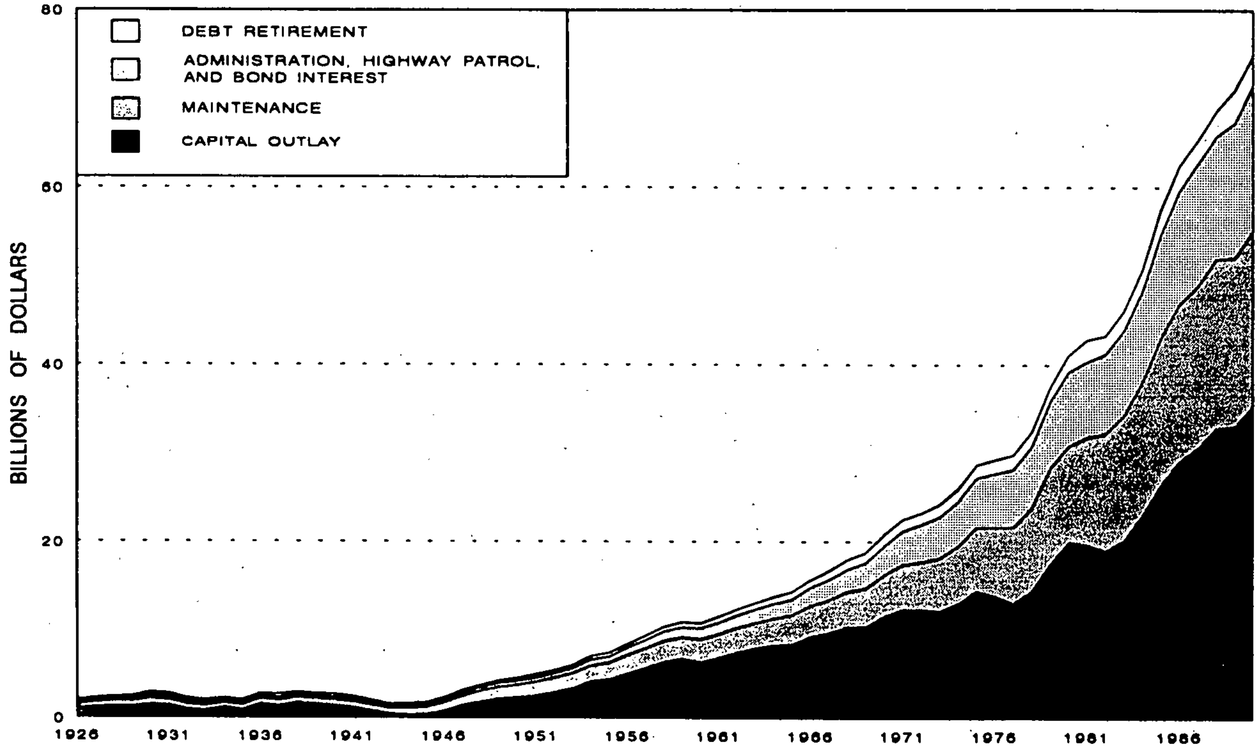


FIGURE 1 Total disbursements for highways, by function: 1926–1990 (*1*).

quality affects both performance and cost. As an ideal, this definition challenges construction managers, in both the public and private sectors, to levels of refinement in their procurement practices not heretofore required. Because it recognizes and values quality, this definition encourages and rewards innovation and good construction practices. The importance accorded by the highway industry to the development of PRS is reflected in the results of a 1990 study of research and development needs in the management of highway construction engineering (*2*). Of the 16 highest priority needs identified in the study, development of PRS for highway construction was ranked first and a funding level of $27 million, equivalent to 60 percent of the total funding in this topic area, was proposed.

A number of important developmental studies focusing on PRS are either in progress or recently completed(*3-13*) and, in recent years, most highway agencies have incorporated one or more PRS elements in their specifications, particularly statistically based sampling plans and adjustable payment schedules (*4,14*). However, there is a need for knowledge of the extent to which true PRS are currently being used by highway agencies and a description of the defining elements of those specifications; specifically, the M&C factors being used to control quality and determine acceptance, and the relationship between those factors and the performance and cost of the finished products. Thus, the initial objectives of this synthesis were to 1) conduct a tightly focused search for and enumeration of PRS in current use by highway agencies, including case studies, and 2) describe the development and present status of PRS for highway materials and construction.

Because very few highway agencies have implemented or even developed true PRS, and the concepts of PRS are not widely understood outside of the research community, the focus of this synthesis was changed to place more emphasis on describing the development and current status of PRS.

This synthesis provides useful information to highway agencies that may be interested in PRS. It includes a summary of historical events that have prompted U.S. interest in PRS development and a description of the underlying concepts. In addition, this synthesis includes a digest of current practice with regard to PRS implementation and references to the principal PRS literature with emphasis on performance and cost models. Other elements of PRS are treated largely by reference to other reports and studies. Finally, because the literature on PRS, when taken as a whole, is inconsistent in its use of technical terms, care has been taken to conform to the definitions proposed by Irick (*9*, pp.4–8).

PROCEDURES

The synthesis was prepared from a survey of the literature, results of a questionnaire mailed to highway agencies in the United States and Canada, and direct inquiries to a variety of persons experienced in the field, both domestic and foreign. Literature was accessed through the Transportation Research Board's Transportation Research Information Service (TRIS) and through published and unpublished research reports sponsored by the Federal Highway Administration (FHWA), the National Cooperative Highway Research Program (NCHRP), and the Strategic Highway Research Program (SHRP), as well as through various bibliographies and references cited in those documents.

The questionnaire (Appendix A), designed to identify PRS in current use, was mailed to the highway agencies of the 50 states, Puerto Rico, the District of Columbia, 10 Canadian provinces and territories, and 15 transportation authorities selected from among members of the International Bridge, Tunnel and Turnpike Association (IBTTA). Follow-up contacts (limited to the 50 states, Puerto Rico and Washington D.C.) with agencies that failed to respond to the initial mailing, were made by a second mailing and by telephone.

Examples of PRS outside of the United States and Canada were sought through a TRIS search and through contacts provided by members of the advisory committee.

CHAPTER TWO

HISTORY OF HIGHWAY CONSTRUCTION SPECIFICATIONS

OVERVIEW

Performance-related specifications (PRS) are one element of the construction management activity referred to today as quality assurance (QA). The term "quality assurance" has been defined in a number of ways (*15*, p.7). The American Association of State Highway and Transportation Officials (AASHTO) currently defines it as, "The activities that have to do with making sure that the quality of a product is what it should be" (*16*).

During the past 40 years, the highway construction industry has been evolving toward the QA model that is illustrated schematically in Figure 2. In this model, the owner describes the product desired through design drawings and specifications that include quality characteristics, quality levels and tolerances, acceptance sampling and testing schemes, and acceptance criteria. The contractor creates the product by establishing a process for manufacturing or constructing the product and by exercising control over the quality of the output. The contractual agreement is then structured in a way that assures an equitable distribution of risk between the contractor's expectation of fair compensation and the owner's expectation of reasonable quality. The model is generally applicable to both manufactured materials (i.e., portland cements, asphalts, and steel) and project-produced materials (i.e., compacted soils, granular subbases/bases, and paving mixtures).

Though the owner's QA prerogative may be exercised by specifying the manufacturing process and even performing the contractor's quality control (traditionally called recipe or method-type specifications), the trend in highway construction management has been toward recognizing and separating the responsibilities of the contractor (for controlling quality) and the owner (for judging acceptance) to the extent possible.

Implementing this model in the highway industry is an evolving process as engineers and contractors have become familiar with a variety of statistical QA and quality control (QC) techniques, as research has produced more efficient predictors of quality, and as the attendant educational, economic, and legal implications have been addressed. The process has also been aided by the advent of the personal computer and the development of QC/QA-specific software packages, permitting timely manipulation of data and allowing statistical quality management to move from centralized offices to job sites. Also, economic considerations have resulted in wider use of techniques such as manufacturers' certification of specification compliance (acceptance by certification) and sampling and testing to verify reliability of the contractor's process control (verification testing) (*18,19*). Acting on the belief that other countries have been more innovative in their contracting practices, U.S. highway engineers have begun to examine the experience of some western European countries (*20,21*).

The literature on QA of highway materials and construction, and its various elements, is extensive. A number of good reviews and tutorials exist, or are in progress, including ones on materials variability and tolerances (*22,23*), statistically oriented QC and acceptance procedures (*8,14,24-29*), cost-effective sampling and testing programs (*6*), rapid testing methods (*30*), PRS (*3-10,31*), adjustable payment strategies (*8,14,32-34*), and general QA (*28,31*).

Specifications for highway construction materials and elements have taken different forms through the years as highway engineers have developed better predictors of performance and construction managers have adopted better methods of measuring compliance, both in response to changes in the size and complexity of the highway construction industry. These forms have typically been labeled as method, prescription, restricted performance, performance, end-result, statistically oriented, and performance-related.

In practice, most specifications include elements of more than one of the forms. Notwithstanding, the labels are helpful in describing the conceptual basis and intent of the specification and are widely used. Collectively, they represent a progression from practices that were more intuitive in their design, more directive in their instruction, and more subjective in their application to labels that are more science based, that account for variability, that recognize the contractor more fully as an equal partner, that distribute risk more equitably, and that provide a better basis for accountability.

TRADITIONAL SPECIFICATIONS

The evolution of written specifications as an element of construction contracts has not been described, as such, but it is certainly linked to the emergence of contracting as a business enterprise from pools of laborers and craftsman that individually brokered their services to owner-builders. The tradition of contracting for construction of public roads in the United States dates from at least the mid 19th century when William M. Gillespie, a Union College professor and early author of road-building manuals, advised his readers that:

> The actual construction of a road, after its location has been completed, may be carried on . . . under the superintendence of the agents of the company, or town, by which it has been undertaken; but it will be more economically executed by contract (*35*, p.147).

Though nearly a century and a half old, Gillespie's account of the contracting process (e.g., drawings, specifications, advertisement, sealed bids, performance bonds, performance time and penalties, payment schedules, retainages), is strikingly familiar, and his description of the specification as ". . . containing an exact and minute description of the manner of executing the work in all its details" (*35*, p.147) concisely and unequivocally states what has come to be known as a methods specification or, alternatively, a prescription or materials and methods specification. Clearly, its intent was to convey to the contractor that which was necessary for him to do the work, in much the same manner that one would

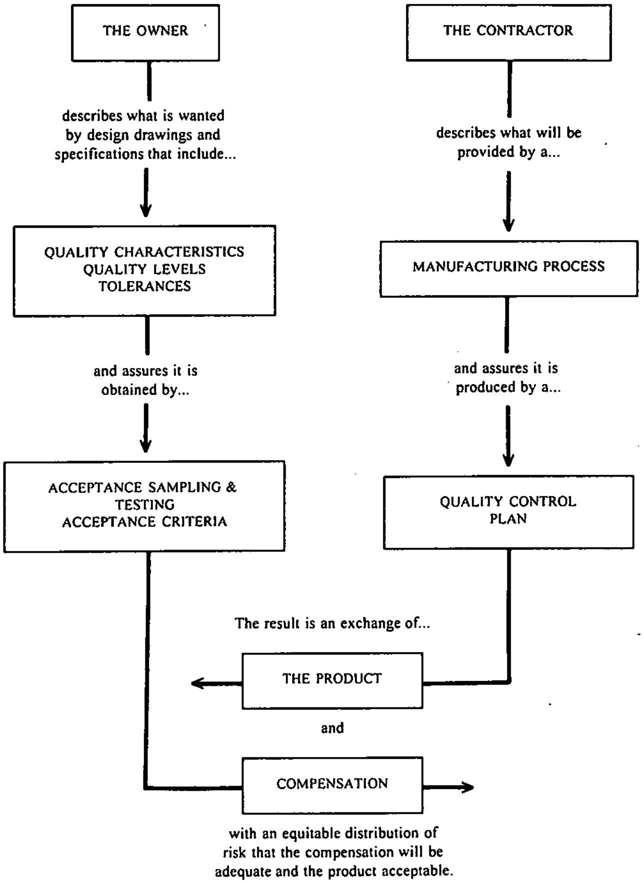


FIGURE 2 Elements of an ideal quality assurance system (after *17*).

convey the same information to one's own employees. Such specifications have been characterized in QA and PRS literature as traditional. A contemporary description of such a traditional specification (for pavement construction) follows:

> . . . the highway agency specifies the exact materials and procedures for the contractor to follow. These . . . specifications typically include material proportioning and mixing limits, and the proper procedures to follow for a job to be acceptable. Variability in material properties and construction techniques is generally ignored. As long as the contractor adheres to the prescribed methods, full pay can be expected (*11*, p.1).

This approach to construction specification development is predicated on the assumptions that the owner, or the owner's agent, fully understands the relationships between the construction process and the quality of the product, and is the primary repository of the technical knowledge needed to link the two. These assumptions prevailed through much of the first half of the 20th century during which they provided the basis for the specifications for most highway construction items. Methods- or prescription-type specifications are, in fact, the only alternative where the essential characteristics of the completed work are not known or are not measurable, or where no practical or timely acceptance test is available.

The effectiveness of this type of specification depends on the assumption that instructions required to perform the work satisfactorily can be reduced to written or graphic form. Because this is rarely the case, traditional specifications rely heavily on the skill and integrity of the contractor and on the knowledge and judgment of the inspectors and engineers overseeing the work. A major weakness of methods specifications is that, even when properly followed, the specifications may not always produce the desired end result. This is because they are based on past experience obtained under conditions that may not be replicated in the new situation (*25*). Thus, the cause of deficiencies in the finished work can be unclear and the responsibility, therefore, is often disputed.

Another weakness of methods specifications became apparent with the increase in highway construction after World War II, and particularly with the beginning of the Federal-Aid Interstate System in the 1950s. As large companies specializing in highway construction began doing more work, the knowledge required to build modern roads became more equally distributed between highway agencies and their contractors, and innovations in construction methods were more commonly initiated by the contractor, when the owner's cooperation could be obtained. However, methods specifications, typically codified in written documents and often supported by attitudes not easily changed, frequently lagged and sometimes even retarded advances in construction technology. This situation could sometimes be addressed by the practice of value engineering (*36*) in which an enterprising contractor who could conceive a quicker or less costly way of doing a job was invited to share monetarily in the savings to be realized.

GROWTH OF U.S. HIGHWAY TECHNOLOGY

The evolution of traditional specifications into forms more appropriate to the complexity of contemporary construction has been a gradual and continuing process. More than anything else, it has depended on the development of a U.S. highway technology in which the quality of the completed work is understood in terms of specific measurable attributes, and can be determined by controlling selected materials and construction (M&C) variables through the processes of design, inspection, and testing at the time of construction.

Highway technology in the United States had been based largely on English and European practices through most of the 19th century with the construction and improvement of roads and streets carried out through an uncontrolled variety of techniques administered by a plethora of local jurisdictions. However, three unrelated events in the last two decades of that century—improvements in the bicycle, inauguration of rural mail delivery, and introduction of the automobile—created a demand for better roads precipitating actions that by 1920 involved the federal government, with the states and eventually the universities and industry, in the development of a domestic highway technology that in time would not only support, but would demand alternatives to the traditional methods of specifying materials and construction. Discussion of these events and their impact on highway technology are found in a number of publications (*37–40*), as well as in reviews of the development of asphalt pavement specifications (*4,41*) and of concrete pavement specifications (*42,43*). Seele has provided an interesting analysis of the development of pavement design theory through the years of World War II (*44*).

Ironically, the factors that gave rise to the development of highway technology in the first half of the 20th century also resulted in standardization of M&C specifications and, in so doing, probably inhibited their evolution into forms more appropriate to the increased volume and complexity of construction that occurred in the second half of the century. The Federal-Aid Road Act of 1916 and its 1921 amendment established the concept of a cooperative federal-state program and set forth the roles of each in administering it, including preparation and public advertisement by the states of plans and specifications against which prospective contractors were required to bid (*40*). The American Association of State Highway Officials (AASHO), organized in 1914 as a forum for the state highway departments to discuss common problems resulting from the motorization of highway traffic, adopted standards of practice to guide member states in technical matters. In so doing, AASHO and its successor, the American Association of State Highway and Transportation Officials (AASHTO), became the principal vehicle through which states negotiated highway standards with their funding partner, the federal government (*39*).

While M&C specifications varied from state to state in their technical details, a tradition of strong commonality based on AASHO recommendations developed during the 1920s and 1930s, and was generally supported by the consensus standards of the American Society for Testing and Materials (ASTM). Although there was, during this period and afterwards, a gradual adoption of requirements for M&C attributes that could be called end-result (e.g., concrete strength, soil density), highway specifications continued to be based largely on the prescription of methods.

THE PROBLEM OF VARIABILITY AND MEASURING COMPLIANCE

Two events in the early 1960s focused the highway community's attention on the need to rethink the manner in which it was specifying highway materials and construction. The first was the unprecedented documentation of construction associated with the AASHO Road Test (1956–1962). The test was an experiment designed principally to determine the effect of variations in traffic loadings on different pavement cross sections (*45*). An unexpected result of this work was that nearly all of the M&C variables, even though tightly controlled, had unexpectedly high variations (*46*). Most deviations from the specified tolerances exceeded those considered normal by most highway engineers (*14,15*). Data from the AASHO Road Test were not the first to record variations in highway M&C variables (*47,48*), nor did the road test result in the first attempt to influence specifications to reflect such variations (*49,50*). However, it was by far the most comprehensive and visible demonstration, and its impact on the design of highway specifications would be lasting. Engineers associated with the project concluded that:

> Sampling plans now being used are not adequate for estimating the true characteristics of materials or construction items for which the specifications are written, and certainly cannot guarantee 100 percent compliance to the specification limits (*51*).

The second event was the occurrence of several highway failures that attracted the attention of Congress and led to establishment of the House Committee on Oversights and Investigations. The 1962 report of the Committee cited many instances of accepted highway construction in which the prevailing acceptance practices had resulted in less than 100 percent compliance with M&C specifications. As a result, Congress threatened to pass laws making it a federal offense to "knowingly incorporate" any noncomplying materials in highway work (*14,15*).

These events called into question the practice of engineering judgment that had been so much a part of traditional acceptance procedures. The reason for this was not so much that failure to comply fully with established limits had been shown to result in serious performance deficiencies, but that the unprecedented funding for highway construction after World War II simply demanded a higher level of accountability. The problem was compounded by a construction pace greatly enhanced by a virtual revolution in paving technology and equipment and an increasingly sophisticated highway contracting industry. It became increasingly difficult to staff construction projects with experienced inspectors and engineers who could apply the detailed oversight necessary to make informed engineering judgments that had sufficed during a simpler period.

STATISTICAL END-RESULT SPECIFICATIONS

One reaction to these events was to seek an alternate method of measuring the characteristics of M&C items and their compliance with specification limits. In effect, this meant recognizing and measuring the inherent variability of M&C variables, adjusting construction tolerances to reflect that variability, and acknowledging the impracticality and cost of expecting 100 percent compliance with specification limits. A concept of reasonably close conformity, or substantial compliance, gained popularity and methods of industrial QC and acceptance sampling based on statistical concepts were promoted. Collectively, these methods are now included under the more general term statistical quality assurance (QA). However, although these new tools permitted more accurate measure of the degree of compliance, the definition of what degree constituted reasonably close or substantial remained a matter for engineering judgment to quantify.

Inherent in this new technology, much of which was adopted from procurement procedures developed by the U.S. Department of Defense during World War II, was a clear distinction between the respective responsibilities of the vendor (for QC) and the purchasing agency (for specifications and for acceptance sampling and testing). Thus, a second reaction to the events of the early 1960s was the initiation of a dialogue within the highway construction community regarding the desirability and feasibility of 1) contractors assuming more responsibility for QC, and 2) highway agencies relinquishing many of their traditional prerogatives in this area in favor of judging acceptance on the basis of end results. End results, in this context, were understood to mean those characteristics of the end product that had traditionally been measured during or immediately after construction. The prospect of highway agencies having to rely more heavily, and possibly exclusively, on end-result testing became a primary motivator in the search for new and more rapid testing methods (*30*).

While statistically based sampling procedures and end-result acceptance criteria can, theoretically, be adopted independent of one another, they have been wedded in the literature and practice of highway construction management since the 1960s and have come to be referred to collectively as statistical end-result specifications (ERS). Thus, ERS are ones in which the contractor and the contractor's suppliers are responsible for QC; the purchasing agency is responsible for describing the level of quality desired in the end product and the procedures that will be used to judge quality and acceptance, and for determining acceptability through a program of sampling, testing, and decisions based on statistical principles. While not a defining component of such specifications, negative payment adjustments became a popular mechanism through which work that was deficient in terms of specification compliance, but not without some value, could be accepted at a reduced unit price, as an alternative to its removal. Most, if not all, of these early disincentive provisions were arbitrary in that the amount of reduction in payment was not related to the loss of performance. Because of the current level of interest in these adjustable payment plans, their development is reviewed later in this chapter. A number of reports provide detailed discussions of ERS (*14,15,22,52*).

The application of statistical methods provided a basis for dealing with the problem of M&C variability as well as a defensible technique for assessing specification compliance in a manner that optimized the risk to both the agency and the contractor. Both were clear improvements over traditional methods and addressed the concerns expressed in the early 1960s by the highway community and by Congress. However, full implementation of statistical ERS has proceeded slowly even though the applicable statistical sampling and decision theory had been fully developed for highway construction by the early 1970s. Even now, implementation status is more that of an ideal toward which to strive than an accomplished fact. Most highway agencies have been cautious in their application of ERS, opting typically to apply them to selected M&C items, or to specific characteristics of single items; their widest application, however, has been to paving materials.

A number of reasons for this caution have been cited, some of which are technical, some economic, and some educational (*14,53*). However, three of the technical reasons speak directly to the principal weaknesses of ERS and are particularly relevant to the continued evolution of specifications for highway materials and construction: 1) the inability to identify or measure the essential performance-related characteristics of the end product, 2) the inability to quantify substantial compliance and to determine price adjustment factors that relate to reduced or enhanced value, and 3) the uncertainty as to value to be gained from the cost of implementing statistically based ERS.

Thus, while ERS may guarantee improved compliance and improved evidence of compliance, in themselves they do not guarantee improved performance, which depends on a better understanding of the relationship between the factors controlled during construction and the performance and worth of the finished product. For example, the essential performance-related characteristics can only be identified if one knows the relative impact on performance of all of the characteristics thought to be performance-related. Similarly, the boundaries of substantial compliance and the magnitude of price adjustment factors can only be set rationally if the relationship between departures from acceptable quality levels and changes in worth of the finished product are understood. Thus, it is only when these relationships are known that the value to be gained from statistically based ERS can be judged through anything but intuition, even as informed as that intuition may be. Because of these reasons, there has been a growing interest in recent years in what are now called performance-related specifications (PRS), as distinguished from statistical end-result specifications (ERS).

PERFORMANCE-RELATED SPECIFICATIONS

While the development of relationships between construction quality measures and performance has always been a major component of highway research, it has only been since the early 1980s that there has been a coordinated effort to integrate the results of that research into a format for M&C specifications that meets the definition of performance-related. That effort has included the contract research programs of FHWA, NCHRP, and SHRP, plus the efforts of a small number of states that have taken an interest in PRS. The effort has also been influenced by the *1986 AASHTO Guide for Design of Pavement Structures* (*54*).

In 1980, FHWA initiated a new research program category, Performance-Related Specifications for Highway Construction and Rehabilitation, with the following objective:

> To identify those existing specifications for construction of flexible and rigid pavement structures that relate directly to performance and to develop additional specifications, as needed, to provide complete systems of performance-related specifications for such construction (*55*).

An additional objective was to provide a more rational basis for payment reduction plans, which had been based primarily on experience. An attempt was made to develop PRS along two parallel lines, one for portland cement concrete (PCC) pavements and one for asphalt concrete (AC) surface courses and overlays. Both systems were expected to include requirements that would assure rideability, skid resistance, structural capacity, and durability (*55*).

The first two FHWA administrative contracts to be reported under this program, both in 1984, included extensive literature searches and syntheses of background information for the development of PRS, for both AC pavements (*4*) and PCC pavements (*5*). Both studies identified major pavement distress modes and the factors thought to have the most influence on each; and both found existing models for predicting performance from M&C variables to be lacking. In 1985, investigators working under AASHTO-sponsored NCHRP Project 10-26, "Data Bases for Performance-Related Specifications for Highway Construction" (January 1985, unpublished) also concluded that existing data bases were inadequate for deriving these performance models.

The NCHRP 10-26 investigators concluded from their studies that further research on PRS should be within a general framework that clearly distinguished among the different classes of variables and that would provide for a multi-stage derivation of the required PRS relationships. In effect, this conclusion recognized that while there are a number of *primary relationships* between one or more *performance indicators* (such as load applications to failure) and known *performance predictors* (such as layer thickness or layer modulus), most of these relationships include variables that are not amenable to control during construction. Therefore, *secondary relationships* would be required to show the nature and extent of associations between the performance predictors and other M&C factors that are amenable to control (such as asphalt content or mix proportions) (*3,9*). A primary impact of this conclusion was to acknowledge that the rational development of PRS is a more complicated task than first thought, and that much of the subsequent developmental work on PRS would have to consist not only of identifying existing primary and secondary relationships and evaluating their usefulness, but also of identifying current research that could be expected to supplement or improve those relationships, designing new long-term field experiments to derive new or refine existing primary relationships, and designing and conducting new short-term laboratory and field studies to develop new or refine existing secondary relationships. This basic conceptual framework for PRS is discussed in more detail in Chapter 3.

First published in 1988 (*3*), these ideas were instrumental in refining the direction that PRS development would take in subsequent years. Also in 1988, a Transportation Research Board (TRB) steering committee on research and development needs in highway construction engineering management identified development of PRS as the highest priority need in this topic area (*2*). FHWA further increased the visibility of PRS development by declaring it a High Priority National Program Area with the objective to, "Develop and implement specifications based on effective predictors of pavement performance with appropriate incentive/disincentive clauses based on those predictors" (*56*).

Development of PRS for pavement construction continued along two parallel courses within this new framework, one for AC pavement and one for PCC pavement. NCHRP Project 10-26A, "Performance-Related Specifications for Hot-Mix Asphalt Concrete," was initiated in 1986 to refine the framework and to demonstrate its reliability and implementability for hot-mix asphalt concrete. Research results from this project were published as *NCHRP Report 332: Framework for Development of Performance-Related Specifications for Hot-Mix Asphaltic Concrete* (*10*). An important feature of this refined framework was a payment adjustment scheme based on comparing as-constructed, life-cycle costs (LCCs) to target or design LCCs. It was concluded that:

> . . . development of performance-related specifications for hot-mix asphalt concrete is a realistic and implementable goal . . . [but that] before such a specification can be used as a replacement for current end-result specifications, additional or refined pavement performance prediction models must be developed (*10*).

A particularly useful feature of this study was to identify the anticipated outputs of ongoing research that could help to meet these development needs. Included were SHRP projects intended to identify performance-related asphalt binder properties, develop test methods to measure these properties, and conduct experiments to validate the resulting design/performance models, as well as the long-term pavement program (LTPP). Also included were NCHRP projects to develop laboratory test procedures for measuring resilient modulus of pavement component materials and to identify and develop testing procedures for performance-related properties of asphalt-aggregate mixtures. PRS development for AC pavements was continued under FHWA sponsorship in the form of additional laboratory studies to refine the primary and secondary relationship, and through the design of an accelerated field study to be conducted at a test track facility and to include both conforming and nonconforming sections (*13,58*).

To parallel *NCHRP Report 332*, FHWA initiated a new project in 1987 to develop PRS for PCC pavement construction, building on the generalized methodology developed under the NCHRP project (*9*). New laboratory experiments were designed and executed to improve the secondary relationships and a demonstration performance-related specification was developed based on the three primary M&C factors in the AASHTO rigid pavement performance prediction equation: slab thickness, initial serviceability, and PCC flexural strength (*54*). Two approaches for assessing contractor penalties and rewards, in addition to the one presented in *NCHRP Report 332*, were identified. The first was a method that had been developed earlier by the New Jersey Department of Transportation based on a concept of liquidated damages (*58*). The other was based on the LCC analysis model presented in the 1986 AASHTO Guide (*54*).

A follow-up study, begun in 1990, recommended additional laboratory experiments to refine the existing materials-related secondary relationships and field studies to develop construction-related secondary relationships for such factors as dowel and tiebar misalignment, poor consolidation, high steel mesh, and untimely joint sawing (*11*). New relationships were developed through laboratory testing between concrete material quality characteristics and transverse cracking caused by repeated loading and thermal curling, and between concrete material quality characteristics and joint spalling caused by an inadequate air void system. Also, plans were developed for field studies to evaluate the effect of various construction variables on various forms of cracking, spalling, and scaling (*12*).

As part of the follow-up study, a prototype performance-related specification was developed for PCC pavements drawing on the earlier research and on PRS development by the New Jersey DOT (*8*). The new specification requires measurement of thickness, concrete strength, air content, and roughness of the in-situ pavement. The specification uses estimated LCC of the as-constructed pavement as the overall measure of quality, and compares that value to the LCC of the as-designed pavement to develop pay adjustments (*12*).

Development of PRS for both AC and PCC pavements is continuing under FHWA sponsorship with conduct of the recommended laboratory and field studies for PCC construction variables and an accelerated test track study of conforming and nonconforming AC sections. FHWA has also declared its intent to use the best information currently available in conjunction with the opinions of a panel of experts to develop an interim set of PRS for use by highway agencies until research in this area is completed (*57*).

ADJUSTABLE PAYMENT PLANS

As with current statistical ERS, the purpose of PRS is to ensure that the pavement is built in accordance with the design levels and tolerances of the M&C specifications. Unlike current ERS, payments to the contractor under PRS are in accordance with the expected performance of the completed work defined by a performance model, that is, they are adjusted to conform to the level of quality estimated to be received (*10*). This does not mean that adjustable payment plans have no place in ERS. To the contrary, most of their current use is in connection with ERS and such use has been encouraged by FHWA (*59–61*). However, adjustable payment plans are an integral part of PRS, by definition; for that reason, a brief discussion of their historical development is included next. The conceptual basis for adjustable payment plans now being developed for PRS is addressed in Chapter 3, and specific plans that have been proposed or used are included in Chapter 4.

The major problem in developing adjustable payment plans for PRS is how to set payment levels that accurately reflect diminished or enhanced value of the completed work. This was not a problem with traditional specifications, which were generally written on a pass-fail basis with little consideration given to variability. Deficient work was either removed or, at the discretion of the engineer, accepted either at full price or at a reduced price. When price reductions were applied, they were typically negotiated on a case-by-case basis after the fact. They were always arbitrary and frequently inconsistent from case to case. However, the advent of statistical ERS, which permitted variability and specification compliance to be measured accurately, encouraged the incorporation of adjustable payment schedules into construction specifications as an additional means of enforcing the contract agreement. Various approaches have been used or proposed for constructing adjusted payment schedules, and they fall into two broad categories: plans based on judgment and plans based on a rational relationship between quality and performance.

Judgment Plans

The earliest adjustable payment plans were developed around quality characteristics already being controlled. Because their primary objective was to enforce the contractual agreement by exacting a monetary penalty from the contractor when the work was deficient, the plans included penalty provisions only. In fact, federal law for many years actually prohibited payments to the contractor that exceeded the contract price. Payment schedules were based initially on judgment, and then modified as the result of experience under actual contract conditions (*33*). Graduated price reductions under judgment plans were typically keyed to the average value of the quality characteristic being measured, to the frequency of deficiencies, or to the percent of work within tolerance (such percentage calculated from the mean and standard deviation of test results) (*14*). In those instances where acceptance was based on more than one quality characteristic for the same item (i.e., pavement density and thickness), payment was based on the item with the lowest pay factor, on the average of the individual pay factors, or on their product (*14*).

Judgment plans are not considered to be rational because they are not supported by a relationship that quantitatively links the payment schedule to the anticipated performance of the finished work. However, rationality is not an essential element of an adjusted price plan if the plan's objective is merely to enforce the contractual agreement (*28*). All that is required is that the plan not impose an undue hardship on either party to the agreement. Operating characteristic (OC) curves can be used to evaluate the reasonableness of judgment plans by relating the quality of an acceptance lot to the probability of its being accepted at different payment levels (*8,33,62,63*). For plans using specification limits (tolerances) for a single quality characteristic, OC curves can often be derived mathematically; for plans containing specification limits for more than one quality characteristic, OC curves are best obtained through computer simulation.

OC curves can also be employed directly in the design of new price adjustment schedules for judgment plans, either alone or in conjunction with development of the entire acceptance plan (*8,32,34*). This approach permits both the owner and the contractor to anticipate the consequences of different payment schedules without having to incorporate them into the specifications of an actual contract, and to negotiate a schedule that is mutually acceptable. If the tentative plan appears to be unreasonable, it can be altered by changing the sample size, the acceptance level or tolerances, the number and amount of the payment levels, or any combination of these (*32,34*). While OC curves are discussed here in connection with judgment plans, it should be clear that they can be used to examine the reasonableness of both judgment and rational plans.

Judgment plans have been widely used and many continue to be used today. In a 1975 survey of state highway agencies (*14*), 28 states indicated some experience with specification provisions for adjusting the price of at least one construction item, including asphalt content, aggregate gradation, density, compressive strength, pavement thickness, and smoothness. All of these schemes were for price reductions only and were judged to be arbitrary to some extent. By 1983, users still described most of their adjustment payment plans as arbitrary and still including only penalty provisions (*64*). Unfortunately, but not surprisingly, the arbitrary nature of many judgment plans has caused them to be controversial within the construction industry (*53*), a concern that persists (personal communication, D.R. Lukens, Executive Director, Marketing Services, Associated General Contractors, Washington, D.C., 1993).

Rational Plans

A more rational approach to selecting payment factors than one based on judgment alone is required if, in addition to enforcing the contractual agreement, it is intended to compensate the contractor in proportion to the level of quality estimated to be achieved. Rather than being a simple system of rewards and punishments, a rational plan must reflect the actual diminished or enhanced worth of the completed work, or some identifiable cost associated with its construction. A number of approaches to the development of rational payment plans have been suggested.

Willenbröck and Kopac (*32,34*) investigated approaches based on the assumption that it costs less to produce materials or work that is deficient in one or more quality characteristic than it does to comply with the quality level specified. For instance, it would be argued from this approach that thinner-than-specified pavements or under-asphalted mixes cost the contractor less to produce by amounts that are related to the level of the deficiency. Thus, these reduced costs could be reflected in a payment schedule that would motivate the contractor to comply with the specified levels. Similarly, an adjustable payment system could be based on the reduced cost of QC presumed to be associated with inferior materials and products or on the cost to remove and replace the deficient work. Adjustable payment systems based on production costs, QC costs, or replacement costs have never been very popular, because of the difficulty in identifying the specific cost data. A national survey of state highway agencies in 1979 identified only one agency that had based pay factors for AC mixes on production costs, one that had based them on QC costs, and four that had based them on replacement costs (*33*).

A more logical approach to establishing payment reduction is based on a quality characteristic with a known and mathematically quantifiable relationship to the level of performance or serviceability anticipated (*32,34*). In such a plan, the adjusted unit price is related directly to the expected percentage loss or enhancement in performance or serviceability. For example, if a correlation between the thickness of a new AC pavement and its service life has been established, price adjustments would be applied that are in proportion to the reduction or enhancement in service life anticipated by the difference between the as-built thickness and the design thickness. Such plans typically include a quality level below which the work is unacceptable, with the payment schedule being applied to quality levels between that value and the design value, or greater. Payment schedules based on a variety of performance and serviceability relationships have been proposed (*14,58,65-69*), and some are now in use.

Since the early 1980s, the development of adjustable payment plans has focused on approaches that are based on some measure of the anticipated cost associated with diminished or enhanced performance, rather than on incremental differences in the performance itself. To do this, the M&C variables related to performance, and over which the contractor has control, must be identified and separated from the materials, construction, design, and environmental variables over which the contractor has no control. As many of the selected M&C variables as possible must then be related to pavement performance by some mathematical algorithm(s), ideally, the same algorithm(s) used for the specification and for designing the pavement.

With the performance algorithm(s) defined, the anticipated performance of the as-constructed pavement may be predicted from results of acceptance tests and compared to that for the design pavement. LCC, or some other appropriate economic factor, may then be used to judge the relative costs of the as-constructed and design pavements. The difference between these costs determines the payment schedule and the price adjustments to be assigned to the contractor (*9,10,31*). These are typically multicharacteristic plans, based on measurement of more than one M&C factor, and including both positive and negative price adjustments. The underlying concepts of such plans are discussed in Chapters 4 and 5.

CHAPTER THREE

CONCEPTUAL FRAMEWORK FOR PERFORMANCE-RELATED SPECIFICATIONS

A comprehensive and systematic conceptual basis for the development of performance-related specifications (PRS) for materials and construction, as defined for this synthesis, has been proposed in a paper by Irick (*3*). Prepared as a working document for the advisory panel of *NCHRP Report 332* (*10*), the paper set forth principles that are generally applicable to the development of PRS in any area of materials and construction and that have subsequently been adapted to provide the conceptual framework for advances in the development of PRS for both asphalt concrete (AC) and portland cement concrete (PCC) pavement construction (*9,10*).

An important element of the paper is a description of the relationship among variables that characterize the design, construction, and service phases of pavements in a way that permits one to better visualize the relationships that must be developed to craft specifications that are truly performance-related; that is, specifications in which variations in the materials and construction (M&C) factors controlled during construction have a known and quantifiable relationship to variations in performance and worth of the finished work.

The paper is targeted at the community of research engineers and statisticians who routinely deal with pavement design and quality assurance (QA) theory, and the nature of its subject dictates a certain level of symbolic language. Digested versions of the conceptual framework for PRS can be found in several reports (*9,10,13*). If PRS are to be used in operating highway agencies, their fundamental concepts must become well understood. These concepts are most easily conveyed by describing 1) the design/construction/performance process variables, and 2) the steps that one must go through to develop performance-related M&C specifications.

The following two sections constitute an overview of these two subjects using, for ease of discussion, PRS for pavement construction. Several reports, including the paper by Irick, provide a more thorough treatment of the above (*3,9,10,13*).

DESIGN/CONSTRUCTION/PERFORMANCE VARIABLES

Irick has classified all of the major variables relevant to the pavement design/construction/performance process and to the development of PRS for M&C characteristics as either:

1) Primary dependent variables,
2) Primary stress or distress prediction factors,
3) Secondary stress or distress prediction factors,
4) Design criteria, or
5) Uncontrolled independent variables (see Table 1).

PRS are predicated on the development of links, in the form of quantitative models (or algorithms), among these five classes of process variables. Class 1 represents the output (dependent) variables to these models and Classes 2–5 represent the different categories of input (independent) variables. The interrelationship among the variables and the models that link them in the development of PRS is shown in Figure 3, in which the boxes represent variables and the ovals represent models. The abbreviations (M, E, or A) indicate the classes of models that may be used to establish the relationships (i.e., mechanistic, empirical, or algebraic, respectively). The specific variations of this construct that have been adopted for the development of PRS for AC and PCC pavement materials and construction are based on and are consistent with this conceptual framework (*9,10*).

Primary Dependent Variables

The primary dependent variables (Class 1) are either stress indicators, distress indicators, performance indicators, or cost indicators.

Stress indicators (Class 1.1), represented by Box B in Figure 3, are generally strains and deflections, or functions thereof, because they are induced by some combination of load and environmental conditions. They are often called pavement response variables because they indicate the response of the pavement to a single stress condition or load application.

Distress indicators (Class 1.2), represented by Box C in Figure 3, reflect undesirable changes in the physical condition of the pavement over time, resulting from some combination of repeated environmental stress, repeated load applications, or age-related deterioration. Distress indicators have been developed for each singular distress mode such as fatigue cracking, thermal cracking, rutting, faulting, joint deterioration, scaling, and raveling. Such singular distress indicators (Class 1.2.a) provide an essential basis for the diagnosis and repair of structural conditions.

Composite distress indicators (Class 1.2.b), such as longitudinal roughness or present serviceability index (PSI) loss, are essential to evaluating the functional condition of the pavement. These indicators measure the degree to which the pavement has begun to fail to provide a smooth and safe ride for its users. In principle, a composite distress indicator is a weighted index of all singular distress indicators that bear on the functional condition of the pavement.

Performance indicators (Class 1.3), represented by Box F in Figure 3, embody the assumption that pavement performance is defined by the amount of service to users that the pavement provides while in an acceptable functional condition. Amount of service, in turn, is a function of the traffic carried; being in acceptable functional condition implies that a criterion distress indicator has

TABLE 1
CLASSIFICATION OF PAVEMENT DESIGN, CONSTRUCTION, AND PERFORMANCE PROCESS VARIABLES (*3*)

Variable Classes and Subclasses
1. **Primary Dependent Variables**
1.1 Stress Indicators (B)
1.2 Distress Indicators (C):
a. Singular distress (cracking, rutting, etc.)
b. Composite distress (roughness, PSI loss, etc.)
1.3 Performance Indicators (F):
a. Fixed stress applications to terminal conditions
b. Mixed stress applications to terminal conditions
c. Performance period to terminal conditions
1.4 Cost Indicators (H):
a. Cost component for M&C
b. Life cycle costs for analysis period
2. **Primary Stress-Distress Prediction Factors**
2.1 Traffic Factors (A3):
a. Load frequencies, distributions, growth rate, etc.
b. Load equivalence factors and ESAL accumulations
2.2 Environmental Factors (A2):
a. Climate
b. Roadbed and roadside
2.3 Structural Factors (A1):
a. Material and layer properties
b. Construction and maintenance procedures
3. **Secondary Stress-Distress Prediction Factors (G1-3)**
3.1 M&C surrogate factors for primary prediction factors
3.2 M&C control factors
4. **Design Criteria**
4.1 Distress-performance criteria (E1):
a. Distress indicators and prediction functions
b. Terminal distress levels and performance indicators
4.2 Reliability criteria (E2):
a. Reliability level
b. Process standard deviation
c. Reliability factor
4.3 Time and applications criteria (E3):
a. Design period
b. Design applications
c. Design period traffic
5. **Uncontrolled Independent Variables**
5.1 Uncontrolled deviations from specified levels
a. Stress-distress prediction factor deviations
b. Design criteria deviations
5.2 All remaining uncontrolled independent variables

Note: Letters that appear in parentheses pertain to Figure 3 codes.

not reached an unacceptable terminal level in the eyes of users. A specific performance indicator would be the number of equivalent single axle load (ESAL) applications that the pavement has carried until its PSI loss has diminished to a terminal level. A distinction is made between accumulated load applications that occur at a fixed stress level (Class 1.3.a), and those that occur under mixed stress and load conditions (Class 1.3.b), as in normal highway operations. If the rate of load applications is known, then either of these can be converted to total years of acceptable service. Thus, the performance period (Class 1.3.c) is also a primary dependent variable.

Cost indicators (Class 1.4), represented by Box H in Figure 3, are considered in two categories, individual components and life-cycle costs (LCCs). Cost indicators for cost components (Class 1.4.a) are associated with the acquisition and processing of pavement materials, pavement construction (including quality control and acceptance testing), routine maintenance applied over the performance period, and rehabilitation needed before the M&C process is iterated for the next phase of the pavement's life. Aggregate costs for each phase lead to LCC indicators (Class 1.4.b). Combined with the stress/distress/performance indicators, the cost indicators provide a basis for assessing benefits relative to costs for particular sets of pavement design specifications. Alternatively, they can provide a basis for assessing diminished or enhanced worth resulting from different levels of specification compliance.

Primary and Secondary Independent Variables

Prediction factors for pavement stress, distress, and performance are classified as primary or secondary. The primary factors (Class 2) appear explicitly in the prediction functions for stress and distress that are recognized by the pavement design community and represented by relationships R1, R2, R4, and R6 in Figure 3. The secondary factors (Class 3) for the design and performance process include accepted surrogates for the primary factors plus those control factors that have demonstrable relationships with the primary factors. The primary factors are performance-related by definition; but the secondary factors are only indirectly related to distress or performance. M&C specifications, represented by Box G in Figure 3, are typically based on combinations of primary and secondary factors.

The primary factors, represented by Box A in Figure 3, have three subclasses: traffic, environmental, and pavement structural factors. Traffic factors (Class 2.1) describe individual loadings (Class 2.1.a) that produce pavement stress and accumulated loadings (Class 2.1.b) associated with pavement distress. Examples of individual loading characteristics include individual axle loads, rates of loading, load placement, average daily traffic, traffic growth rate, and years of traffic. Cumulative load applications derived from the individual traffic factors include the number of axle loadings at different distress levels and the number of ESAL applications that have accumulated at any particular time.

Environmental factors (Class 2.2) include various indicators of climatic moisture and temperature; roadbed strength, moisture, temperature, swell propensity, and frost-heave potential; and roadside conditions such as drainage and shoulder support.

Pavement structural factors (Class 2.3) include physical properties of construction materials; layer properties such as thickness, strength, and load transfer capabilities; construction procedures such as compaction; and routine maintenance procedures.

The secondary factors (Class 3), represented by Boxes G1 and G2 of Figure 3, include factors that do not appear in the prediction functions for stress, distress, and performance but that may be substituted for them by means of known relationships. For

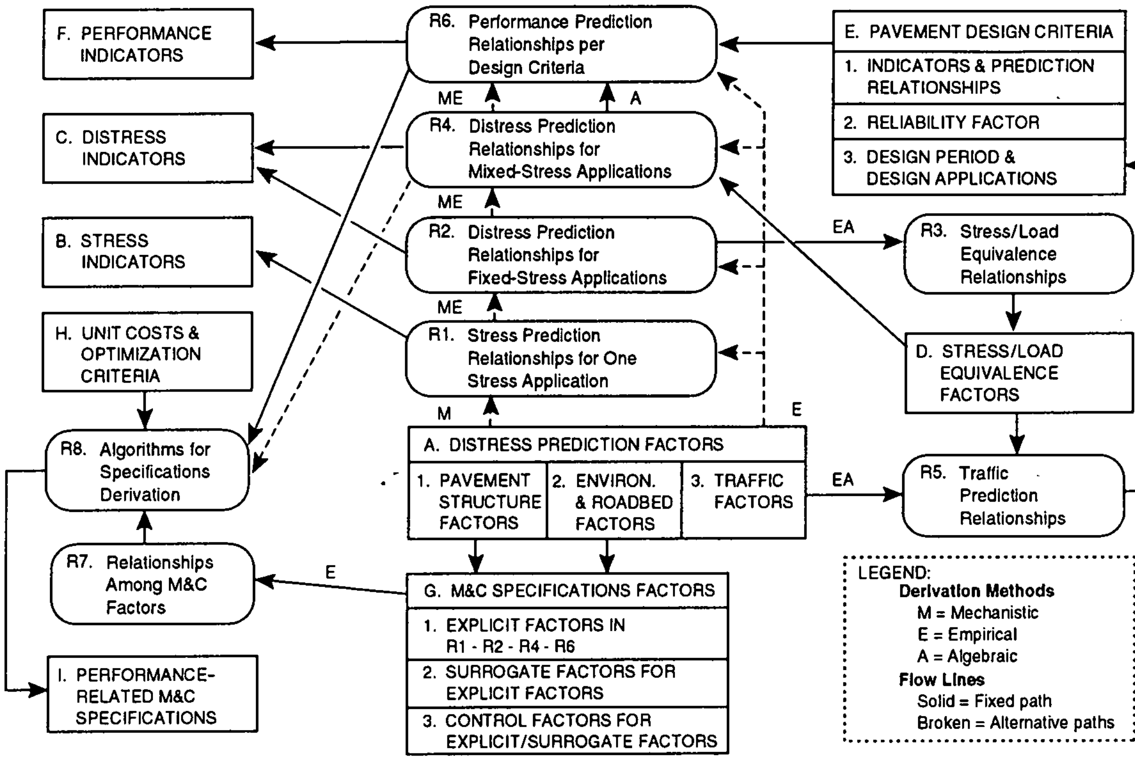


FIGURE 3 Elements of performance-related M&C specifications (*3*).

example, if one of the primary factors is subgrade resilient modulus and if a particular California bearing ratio (CBR) indicator is predictably related to that modulus, then CBR values can be used to determine the modulus values within a known degree of precision. Therefore, if CBR is more easily controlled during construction than subgrade modulus, it may be used as a surrogate (Class 3.1) for modulus if the sacrifice in performance prediction is acceptable. The effectiveness of substituting secondary factors for primary ones depends on the particular form of the relationships and particularly on the associated prediction errors.

Secondary prediction factors may also include control factors (Class 3.2) that are neither primary factors nor their surrogates but have predictable effects on one or both of them. An example would be the water-cement ratio of PCC because it influences the flexural strength of PCC (a primary prediction factor) and compressive strength (its surrogate), but is not a primary or surrogate factor in itself.

Design Criteria

Design criteria (Class 4), represented by Box E in Figure 3, are those performance-related variables for which values are assumed or specified by the designer. They include distress/performance, reliability, and design period criteria. No variable in this class is an M&C factor, but all have indirect effects on M&C specifications.

Distress/performance criteria (Class 4.1) imply selection of one or more singular or composite distress indicators, selection of the relationship between the indicator(s) and prediction factors, and specification of a terminal distress level for each indicator. Specification of reliability criteria (Class 4.2) involves selection of a reliability level, assumption of a process standard deviation, and calculation of a reliability factor. Design period criteria (Class 4.3) include the length of the design period (often dictated by a pavement management system as some multiple of 5 years), the predicted design period traffic, and the predicted design applications (a product of the design period traffic and the reliability factor).

Uncontrolled Independent Variables

Uncontrolled independent variables (Class 5) operate during the course of the design/construction/performance process. In statistically designed experiments, the collective effect of these variables is known as experimental error. In pavement design applications, uncontrolled independent variables contribute to prediction errors. These variables include error variances that arise because the prediction factors have uncontrolled deviations from specific design levels (Class 5.1), plus all of the remaining uncontrolled variables (Class 5.2). The magnitude of uncontrolled variation is an important element in the development of acceptance levels and tolerance limits for M&C factors and may be partially controlled through the application of tolerances. However, the balance must be accepted as a normal aspect of the overall prediction process. The collective effect of the variables can be estimated through statistically designed experiments.

STEPS IN M&C SPECIFICATION DEVELOPMENT

The steps to develop logical performance-related M&C specifications (*3*) are described next, and are also shown as a flow chart in Figure 4.

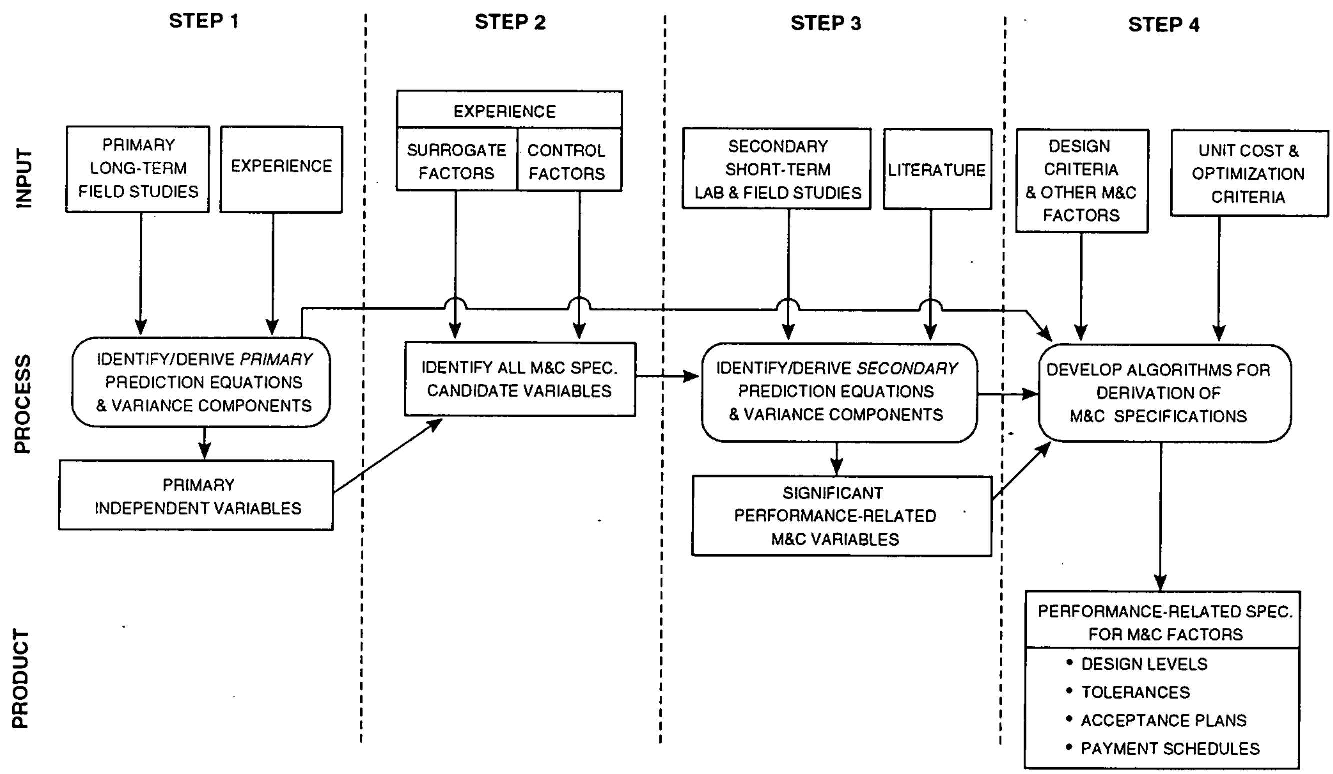


FIGURE 4 Flow chart for development of performance-related M&C specifications.

1) *Primary relationships*—Identify and/or derive all of the primary prediction equations, including the primary independent variables, and their variance components. The primary independent variables (or primary factors) appear in one or more of the primary relationships (R1, R2, R4, or R6 of Figure 3) as predictors of stress, distress, or performance. Once identified, they become candidates for M&C specifications. Many of the primary prediction equations are already known from experience and are reported in the literature. Others have to be derived or refined from primary long-term field studies.
2) *M&C candidate variables*—Identify all independent variables that are candidates for M&C specifications, that is, that are amenable to control prior to or during construction. These variables include the primary independent variables from Step 1 that are amenable to construction control (such as layer thickness), as well as secondary factors that are either surrogates for the primary variables or that exercise a controlling influence on a primary variable, or its surrogate, in instances where either is too difficult or too costly to measure. Examples of surrogate factors include CBR for roadbed modulus and compressive strength for PCC flexural strength. Examples of control factors include slump as a partial control for PCC strength, asphalt content for enhancement of AC stiffness, and roadbed density for indirect control of subgrade strength.
3) *Secondary relationships*—Identify and/or derive all of the secondary prediction equations and their variance components. Some of these relationships, which are known from experience and reported in the literature, can be used directly or can be modified to fit the particular situation. Others may have to be developed anew from short-term laboratory and field studies. Also, determine which of the secondary factors are truly performance-related and to what degree. More specifically, determine the degree to which each candidate surrogate factor is related to one or more of the primary independent variables, and the degree to which each candidate control factor is related to one or more of the primary independent variables or surrogate factors. The significance of each of these candidate M&C factors will be determined by its variance component or through sensitivity analyses. All of the secondary performance relationships are shown collectively as R7 in Figure 3.
4) *The M&C specification*—Develop the algorithms for and produce the M&C specifications (including design levels and tolerances, acceptance plans and payment schedules) using as inputs the primary and secondary prediction equations, the significant M&C variables, the project design criteria (including various non-M&C factors, such as prequalification tests for aggregate), and appropriate costs and cost optimization criteria.

ADJUSTABLE PAYMENT PLANS

As noted earlier, in the ideal PRS the algorithm(s) used to relate the M&C variables to performance and to derive the M&C specifications are the same ones used to design the pavement in the first instance, or derivatives therefrom. They are also the algorithms from which the effect on performance of deviations from specified quality levels can be measured and, thereby, the economic impact of such deviations assessed. This is the single feature of PRS that most distinguishes it from other forms of specifications, and the development of these quality-performance relationships is the subject of much ongoing PRS research.

Recent advances in PRS development have led to a consensus that adjustments to the contractor's bid price in response to work that deviates from the quality level anticipated should correspond to the present worth of the cost differential resulting from such deviations (*8–13*). According to this approach, the pay schedule is designed to withhold sufficient payment at the time of construction to cover such costs. It is also designed to award a positive price adjustment in consideration of enhanced performance or service life when the work exceeds the design quality. This approach involves incorporating estimates of the percentage loss or enhancement in performance or service life with certain basic concepts of engineering economics (*70*). At present, there are three methods for doing this depending on how the quality differential is measured and on which costs are included in the computations:

1) An approach used by New Jersey DOT (see below) and others that uses the difference in estimated pavement life to measure the quality differential. Costs include neither maintenance nor user operating costs (*8*).
2) An approach developed through research sponsored by FHWA (see below) that uses the difference in estimated LCCs, and includes maintenance costs but not user operating costs in the computations (*9*).
3) An approach presented in *NCHRP Report 332* (see below), uses estimated economic life, defined as the age at which minimum annual cost occurs. Both user maintenance and user operating costs are included in the computations (*10*).

The general concept is illustrated by the following example using the quality differential measure and the cost elements employed in the New Jersey approach. A complete development of the New Jersey approach is found in two recent publications (*8,58*) and has been abridged in a third (*31*), from which this example is taken.

In the case of highway pavement, layer thicknesses and materials characteristics are chosen to carry the estimated loading for the desired service life, at the end of which the pavement will commence receiving a series of overlays. If the pavement is incapable of carrying the estimated loading for its design life, because of construction deficiencies, it will fail prematurely and the overlays will be moved forward in time, resulting in an added expense to the transportation agency. Similarly, if the pavement is able to carry the estimated loading beyond its design life because of construction quality that exceeded the design, the overlays will be delayed in time, resulting in a savings to the transportation agency. Using standard compound interest and present worth formulas, the following equation can be used to calculate the appropriate pay factors for various levels of expected life (*8*).

$$PF = 100\ [1+C_o(R^{Ld}-R^{Le})/C_p(1-R^{Lo})] \qquad (1)$$

in which:

PF = pay factor (percent of C_p),
C_p = present unit cost of pavement,
C_o = present unit cost of overlay,
Ld = design life of pavement,
Le = expected life of pavement,
Lo = expected life of overlay,
$R = (1 + R_{inf}/100)/(1+R_{int}/100)$,
R_{inf} = annual inflation rate (percent), and
R_{int} = annual interest rate (percent).

The C_p term in Equation 1 is the unit bid price for the work, C_o is the total in-place cost of the overlay estimated from representative historical data, Ld and Le are calculated from the pavement performance (design) algorithm using respectively the design and as-constructed levels of the M&C variables, Lo is estimated from experience or calculated from an overlay design algorithm, and R_{inf} and R_{int} are projected from historical data.

In practice, a simplified version of Equation 1 that includes the measured level of each of the quality characteristics ($X_1, X_2, \ldots X_n$), with appropriately weighted coefficients ($a_1, a_2, \ldots a_n$) is more convenient to use, such as:

$$\text{Pay Factor} = \text{Constant} + a_1X_1 + a_2X_2 + \ldots a_nX_n. \qquad (2)$$

Weed (*71*) has suggested the following four-step process for developing such a payment function:

1) Select the maximum (bonus) pay factor that is felt to be justified by truly superior quality. This is the intercept (constant term) of the pay equation.
2) Select the coefficients of the individual terms so that the equation pays 100 percent when all quality measures are at their respective acceptable quality level (AQL) values, the magnitude of each coefficient reflects the relative importance of the corresponding quality measure, and the amount of pay adjustment (bonus or reduction) is consistent with available performance models.
3) Select appropriate rejectable quality level (RQL) values and the minimum pay factor to be assigned when the option to require removal and replacement is not exercised. This provision often has considerable influence on how the average pay factor declines as quality decreases.
4) Check the operating characteristic (OC) curves for the complete acceptance procedure to be sure it will perform as intended.

The OC curves for an acceptance sampling plan with an adjustable pay schedule are similar to the OC curve for a conventional accept/reject acceptance plan (Figure 5) except that a set of OC curves is needed to reflect the various payment options (Figure 6).

Another useful tool for evaluating the acceptance procedure, a variation of the generic OC curve, is the expected payment curve, which relates the actual quality of a lot submitted for acceptance to its mathematically expected payment value. In the example shown in Figure 7, work completed at the AQL (10 percent defective) can expect to receive 100 percent payment over the long run, while work at the RQL (50 percent defective) can expect to receive only 70 percent over the long run. Work below the RQL always has some value, even if only as a base upon which to apply an immediate repair in the form of an overlay to raise the pavement cross section to its design performance potential. Expected payment curves of the type shown in Figure 7 can be obtained by

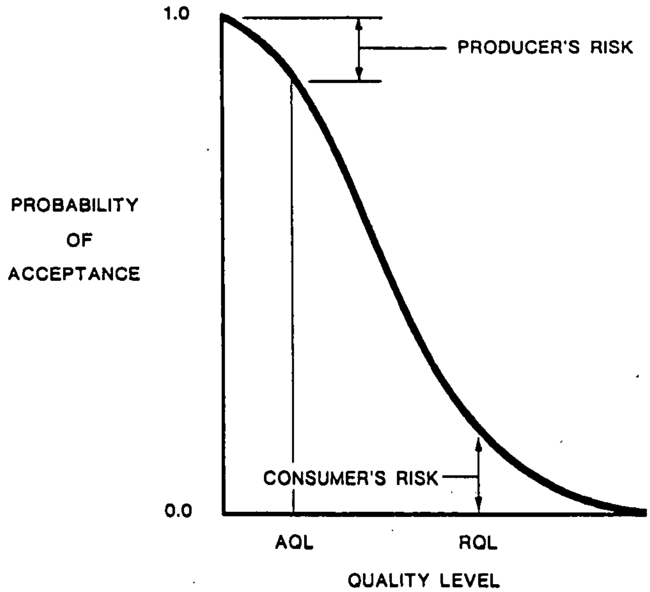


FIGURE 5 Conventional accept/reject OC curve (*31*).

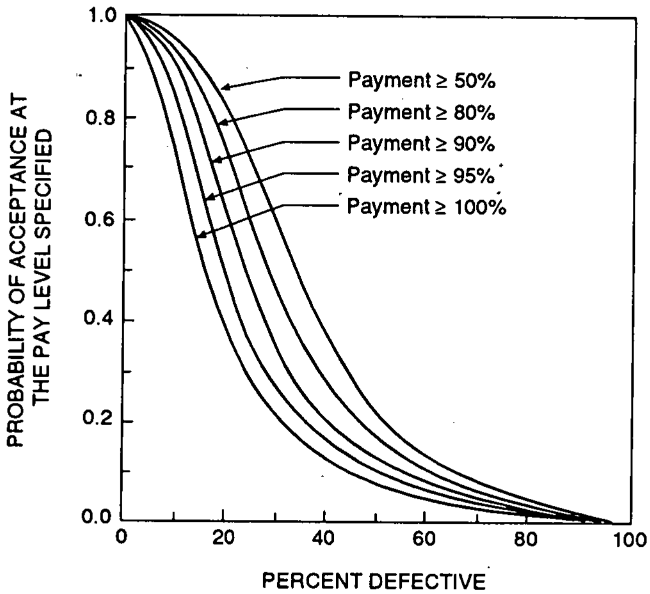


FIGURE 6 OC curves for adjustable payment acceptance plan.

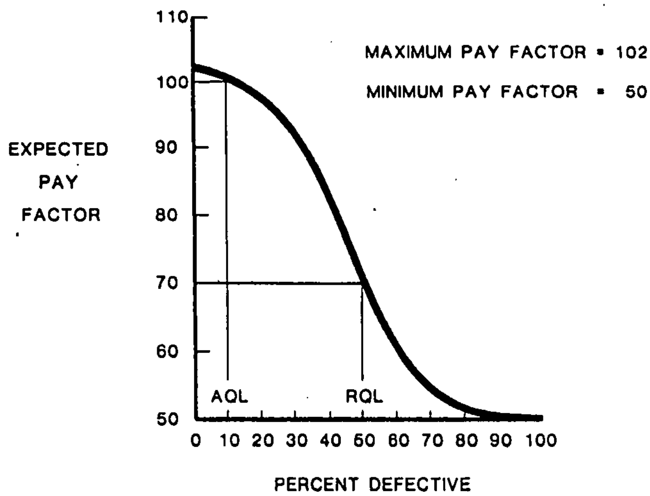


FIGURE 7 Expected payment curve for statistical acceptance procedure with an adjusted pay schedule (*31*).

using software designed for the purpose. Typically, such software is based on computer simulation. Development of OC and expected payment curves is the only way of knowing in advance whether or not the payment plan will function as intended and be fair to both parties (*31*).

The legal basis for withholding full payment when quality is deficient is the principle of liquidated damages (*72*). The courts have held that when actual damages are uncertain in nature or amount or are difficult to ascertain, two parties may agree on an amount to be withheld in the event of contractual noncompliance, provided the amount is reasonably consistent with the actual damage and provided there is no element of deception, either willful or by mistake (*73*). Payment schedules derived from performance algorithms that are part of PRS and which attempt to recover future losses that must be estimated at the time of construction clearly meet these criteria. Positive pay factors consistent with the enhanced worth of the work can be established to assure that 100 percent payment will result when the work is (on average) at the target AQL (*72*). This element overcomes one of the major concerns of the contracting industry to specifications that include payment adjustment plans (*53*); even though such specifications are enforceable because they are contractual, many are considered to be onerous because the arbitrary nature of the adjustable payment schedule is perceived to be unfair.

Weed (*31,72*) has summarized the advantages to the liquidated damages approach as follows:

> Because the pay adjustments are based on the economic impact of departures from the specified quality level, they may be positive as well as negative. For quality in excess of the design level, the transportation agency receives a tangible benefit in terms of greater performance or service life and, accordingly, the method awards a small bonus. . . [The] procedure equates the pay adjustment directly to the estimated gain or loss experienced by the transportation agency which . . . is a fair and equitable approach. And finally, because it is based on the well-established principle of liquidated damages, it is believed to be more defensible than some of the earlier methods.

CHAPTER FOUR

CURRENT STATUS OF PERFORMANCE-RELATED SPECIFICATIONS

While the concepts of PRS development are generally applicable to both manufactured highway products and project-produced items, they have been applied only to the latter category, primarily to highway pavement components. As noted earlier, the mainstream of PRS development in the United States has been advanced under the auspices of a limited number of programs, including those of the New Jersey DOT, the FHWA's Nationally Coordinated Program E8, "Construction Control and Management," and *NCHRP Report 332*. In addition, other research and model specifications development has supported the development of specific components of PRS. The purpose of this chapter is to review these activities, focusing on the performance-related materials and construction (M&C) variables, the performance models (or algorithms), and the adjustable payment plans. Specific aspects of each of the programs are found in the cited references.

NEW JERSEY DOT STANDARD SPECIFICATION FOR PCC STRENGTH

Over a period of more than 10 years, the New Jersey DOT has been developing the concepts for both statistical end-result and performance-related M&C specifications (*8,31*). After several field trials in 1989, New Jersey DOT implemented its first operational version of a performance-related specification (*74*). Designed initially for portland cement concrete (PCC) pavement, the new specification has subsequently been adopted for structural concrete as well (*8*). Details of the New Jersey DOT specification and its development can be found in several reports (*8,11,12,31,74*).

The New Jersey specification for PCC is based on three quality characteristics: slump, air content, and 28-day compressive strength. Because slump and air content can be measured when the concrete arrives at the job site, these characteristics are used to screen the concrete at that time, using tolerances based on historical data on variability. Final acceptance is judged on the basis of 28-day compressive strength with provision for both positive and negative pay adjustments. The pay adjustment corresponds to the present worth of the anticipated future cost difference between the as-designed and the as-constructed work, based on the legal principal of liquidated damages. This difference is calculated from service life predictions based on the AASHTO rigid pavement design model (*54*); while that model applies only to concrete pavement, a rationale based on engineering judgment has been used to justify applying the same methodology to concrete construction items other than pavement (*8*).

In practice, concrete from a stratified random sample of individual trucks is tested for slump and air content, and cylinders are molded for 28-day strength tests. The specification includes guidelines under which additional testing of the plastic concrete, either with or without retempering, may be permitted when the first sample is out of compliance for slump or air content. Those batches that are tested and ultimately found deficient are rejected. The others are allowed to remain at the contractor's discretion.

The strength requirements of the New Jersey specification were developed to control five different classes of concrete (Table 2). Each class is identified by a structural design strength set by the design engineer to assure structural integrity (commonly designated f'_c) and by a class design strength chosen to obtain other benefits that may be desired such as impermeability, durability, and abrasion resistance. Differences in these strength requirements reflect different design requirements and different levels of criticality. Final acceptance of concrete under the New Jersey specification is based on both strength values.

Because the class design strength reflects all of the design considerations, the acceptable quality level (AQL) has been set at 10 percent defective (i.e., 10 percent below the class design strength), which is consistent with guidelines of the American Concrete Institute (ACI) (*75*) and the American Society for Testing and Materials (ASTM) (*76*) for tolerable deficiency levels. Thus, if it is estimated that less than 10 percent of the concrete in a lot is below the class design strength, the lot is eligible for a positive pay adjustment. Correspondingly, if the estimate indicates more than 10 percent is below the design strength, a pay reduction is assessed down to the rejectable quality level (RQL), which is set at 10 percent below the structural design strength (for all concrete classes except C and S, where it is 20 percent). For lots estimated to be at or below the RQL, the contractor is offered the option to remove the work or accept 50 percent payment.

The payment factor (PF) under the New Jersey specification is calculated from a version of Equation 1 (see Chapter 3), simplified for field use.

$$PF = 102.0 - 0.2\ PD \qquad (3)$$

in which:

- PD = lot percent defective (estimated from standard tables for different sample sizes and specific values of Q),
- Q = quality index = $(X - L)/S$,
- X = mean lot strength,
- L = class design strength, and
- S = lot standard deviation.

This simplified field version of the pay function is shown in Figure 8 to closely approximate the theoretical equation. Also, the close match between the operating characteristic (OC) curve for the specification (with the retest provision) and the pay function, up to a point just beyond 30 percent defective where it drops rapidly to the minimum pay factor of 50 percent, illustrates the strong incentive provided by the specification for the contractor to meet or exceed the AQL of 10 percent defective (i.e., below the class design strength).

TABLE 2
28-DAY COMPRESSIVE STRENGTH REQUIREMENTS FOR NEW JERSEY CONCRETE (*8*)

Class	Typical Use	Class Design Strength (psi)	Structural Design Strength (psi)
P	Prestressed Beams	5500	5000
A	Bridge Decks	4200	3600
B	Pavement	3700	3000
C	Foundations	3200	3000
S	Seal Concrete	2000	2000

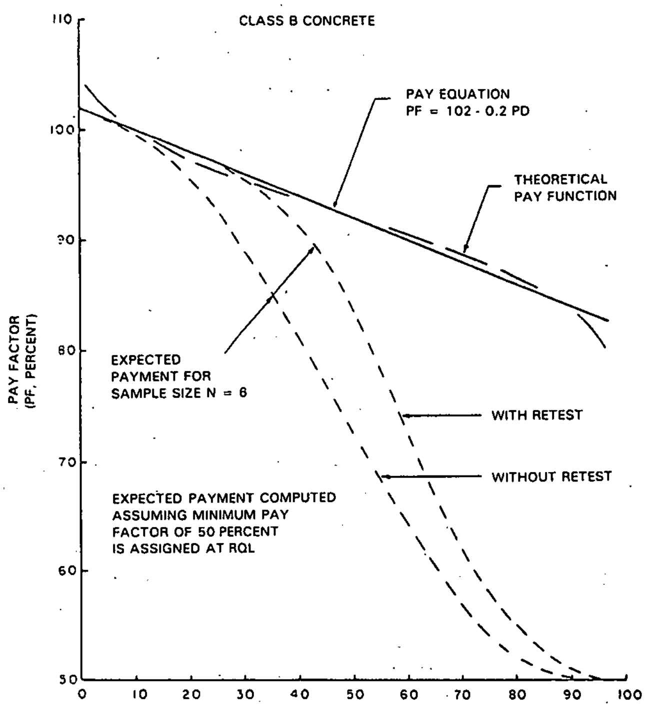


FIGURE 8 Pay relationships for New Jersey PCC specification (*8*).

The New Jersey specification for PCC may be the only version of a performance-related specification in operational use. The specification is based on a strong theoretical foundation, yet is relatively easy to apply in practice. It has been tested extensively, with the aid of both computer simulation and field trials and has been shown to produce results that are reasonable and fair to both parties. It has been used on actual jobs where it has improved the degree of contract compliance (*8*). As important and as practically beneficial as this specification has been, when measured against the standard of what has come to be expected of a true performance-related specification, it has limitations. Because it is important for those wishing to adopt or build on the New Jersey experience to understand those limitations, they have been identified by other researchers and are summarized below (*12*).

- The AASHTO rigid pavement design equation, on which the specification relies to predict service life, has acknowledged shortcomings of its own. Principal among these are its reliance on a relatively small set of variables which, even conceptually, are not in themselves sufficient to completely define performance. Also, at the practical level, the AASHTO design equation has not been shown to be applicable to design, materials, and climatic conditions in New Jersey.
- Even if the AASHTO model were shown to be valid for New Jersey conditions, the New Jersey specification considers only one of the model's performance predictors, concrete strength, to the exclusion of the other factors in the model.
- The concrete strength used in the specification is based on laboratory-cured cylinders rather than on the actual strength of the material in place.
- The validity of the extrapolation of the strength-performance relationship of the model to structural elements other than pavements is intuitive and has not been validated.

NEW JERSEY DOT EXPERIMENTAL SPECIFICATION FOR PCC PAVEMENT

More recently, the New Jersey DOT developed an experimental specification for PCC pavement that expands on the concepts embodied in the earlier specification for concrete strength. As with the earlier specification, plastic concrete is screened on the basis of its slump and air content; statistical sampling with provision for retesting is employed. However, the new specification includes two quality characteristics—slab thickness and smoothness—in addition to strength upon which final acceptance and payment are based. The AQL and RQL for each of these characteristics are shown in Table 3. The pay function of the new specification includes a combination of all three characteristics weighted according to a performance model that is also based on the AASHTO design equation. Details of the experimental specification are provided in several reports (*11,12,77*). A brief description of the design equation's development follows.

The AASHTO design equation (*54*) expresses the number of applications of an equivalent 18-kip load (W) that the pavement can sustain as a function of slab thickness (D), concrete working stress (f_t), concrete modulus of elasticity (E), and modulus of subgrade reaction (k):

$$W = f(D, f_t, E, k). \tag{4}$$

New Jersey researchers have demonstrated that the AASHTO equation is significantly more sensitive to thickness and working stress than to subgrade modulus or concrete modulus, as small percentage changes in either of the first two variables produce relatively large changes in the load bearing capacity of the pavement (Figure 9), while changes in the latter two do not (*78*). As a result, New Jersey developed a rationale for acceptance of the structural aspects of concrete pavement based on thickness and working stress alone. Working stress, defined by AASHTO as 75 percent of the modulus of rupture (MR), is calculated from results of 28-day compression tests using the following relationship:

$$f_t = 0.75\ \text{MR} = 0.75k\,(f'_c)^{1/2}\ (75) \tag{5}$$

where,

k = working stress constant, usually between 8 and 10,

TABLE 3
QUALITY CHARACTERISTICS AND LEVELS FOR THE NEW JERSEY EXPERIMENTAL SPECIFICATION FOR CONCRETE PAVEMENT (*77*)

Quality Characteristic	Quality Measure	Acceptable Quality Level (AQL)	Rejectable Quality Level (RQL)
Thickness*	Average length of randomly located cores	10 inches	9.5 inches
Strength*	Average compressive strength of 6" x 12" cylinders**	5,000 psi	4,000 psi
Smoothness	Percent of pavement length defective***	5.0 percent	15.0 percent

*A deficiency in one may offset a surplus in the other provided that neither is less than the rejectable quality.
**Or cores when retesting provision is applied.
***100 percent sampling as measured by the procedure specified in Section 405.15 (rolling straight edge).

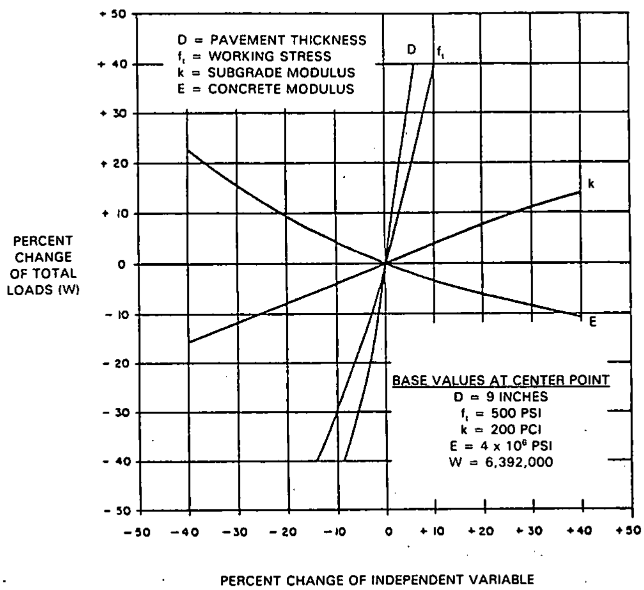


FIGURE 9 Sensitivity analysis of the four independent variables in the AASHTO equation for rigid pavement (*78*).

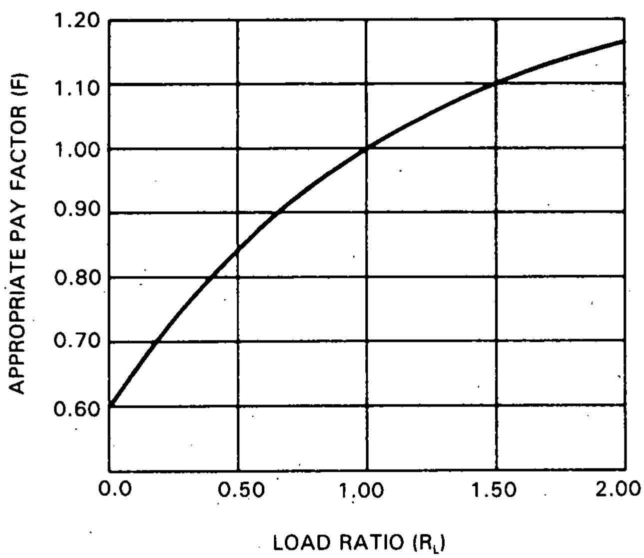


FIGURE 10 Typical pay function curve for the New Jersey experimental specification for PCC pavement (*78*).

and

f'_c = compressive strength of concrete (psi).

Acceptance under the New Jersey procedure is based on a calculated load ratio—the ratio of the as-built load capacity to the design load capacity, both calculated from the AASHTO design equation in which concrete modulus of elasticity, modulus of subgrade reaction, and the working stress constant are held at nominal values. Treatment of the latter properties in this manner is supported by further sensitivity analyses that have shown load ratio is relatively insensitive to changes in the properties's value within their normal ranges (*78*).

Using conventional principles of engineering economics, New Jersey has employed this model to develop rational pay schedules for concrete pavement based on the concept of liquidated damages (Chapter 3), reasoning that: "The appropriate pay adjustment is . . . the present worth of any expense or savings expected to occur in the future as the result of a departure from the specified level of quality and may be positive or negative" (*58*).

Because the New Jersey approach is based on a performance model (AASHTO rigid pavement equation) that includes both thickness and strength, it allows for a deficiency in one of the quality characteristics to be offset by an excess in the other (*78*). The payment function curve developed by New Jersey is shown in Figure 10 (*78*), and can be used to calculate both stepped or continuous pay schedules, the latter being preferred because it permits a more precise determination of the compensation rate.

For practical purposes, the following simple linear equation can be used, in lieu of the relatively complex AASHTO relationship, to arrive at pay factors for individual acceptance lots (*79*):

$$PF = 100 + 15\ (THK - 10) + 0.01\ (STR - 5000) \quad (6)$$

in which,

PF = pay factor (percent),
THK = average lot thickness (in.), and
STR = average lot compressive strength (psi).

Subsequently, another term was added to the pay factor equation to include the smoothness specification (*77*):

$$PF = 100 + 15\ (THK - 10) + 0.01\ (STR - 5000) + SPA \quad (7)$$

in which,

SPA = smoothness pay adjustment = 5 − PDL,

and

PDL = average percent defective length for smoothness; and the pay factor was subjected to the following limitations (*77*).

Value of the Quality Measure	Maximum Pay Factor (Percent)
PDL* 0–15	103-0.08(PDL)(PDL)
>15**	85
THK: <9.5 in**	75
STR: <4000 psi**	75

* Average percent defective length for smoothness
** Rejectable quality level

The smoothness (i.e., roughness) pay adjustment factor in Equation 7 was tailored to roughly correspond to the cost incurred from premature failure inferred from the AASHTO design equation, and was integrated into the payment equation so that it would control the maximum amount that the equation would pay for specific levels of smoothness; the logic is that regardless of how thick or how strong the pavement structure, it is inadequate unless it is smooth. Thus, for lots of superior strength or thickness, a pay factor of up to 103 percent is allowed, the maximum being controlled by the level of surface smoothness (PDL). For lots of deficient quality, but not below the rejectable quality level, the pay factor may be as low as 85 percent for smoothness or 75 percent for thickness and strength. Figure 11 shows a family of expected payment curves for the experimental specification, which is currently being subject to field trials (personal communication, Richard M. Weed, New Jersey DOT, April 1994).

Many of the limitations cited for New Jersey's standard specification for concrete strength apply equally to the newer experimental specification. The newer specification has also been criticized for being based on mean concrete strength and mean pavement thickness (*12*) which, unlike percent defective, does not encourage control of both the process mean and variability. Notwithstanding, the new specification represents a significant theoretical and practical advance in development of PRS for pavements.

MULTICHARACTERISTIC PLAN FOR PCC PAVEMENT

In a recent paper, Weed (*71*) discusses New Jersey DOT's approach to acceptance/payment plans for PCC pavement. The author proposes a four-step process for combining acceptance requirements for several quality characteristics into a single pay equation (Equation 2) and uses, as an example, an updated version of the multicharacteristic payment plan from New Jersey DOT's experimental specification. Specifically, the new version replaces mean value with percent defective (PD) as the operative quality measure for each characteristic, and introduces a slightly different pay equation.

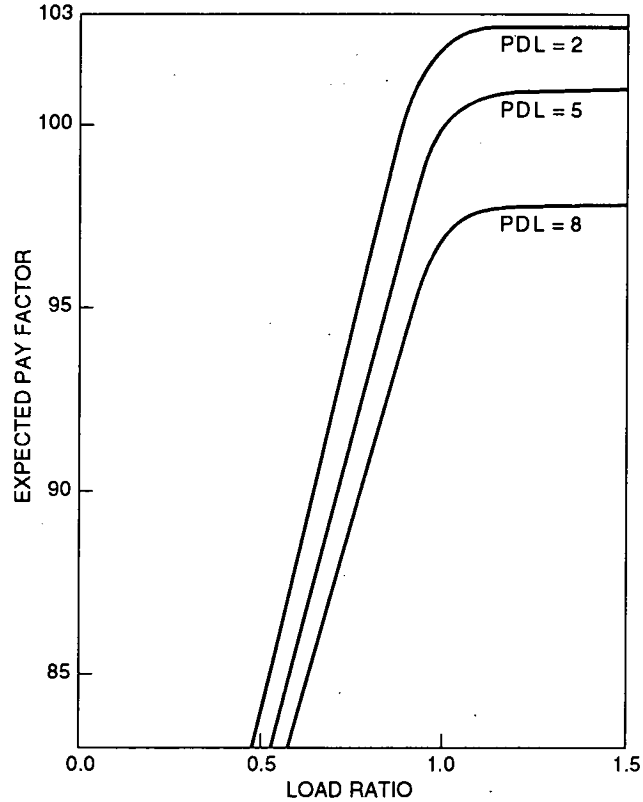


FIGURE 11 Expected payment curves for the New Jersey experimental specification for PCC pavement. (Source: New Jersey DOT)

This recent version of the New Jersey specification is based on the same five quality characteristics as the experimental specification, using slump and air content to screen, and thickness, strength, and smoothness for acceptance and payment. The pay equation is based on two performance models, the AASHTO rigid pavement design equation and a new model developed by New Jersey researchers that links smoothness with expected life (Le). The AQL, RQL, and minimum pay factor for each of the quality measures in the newer version are given in Table 4. The revised pay function is given by the following equation:

$$PF = 105 - 0.12\ PD_{thk} - 0.10\ PD_{str} - 0.11\ (PD_{smooth})^2. \quad (8)$$

In those instances where all three quality measures have zero PD, Equation 8 awards a maximum pay factor of 105 percent. For different levels of percent defective among the three quality measures, down to the RQL, the equation assigns pay factors between 105 and 65 percent, the latter occurring when all three are at their respective RQL values. An exception occurs when the

TABLE 4
QUALITY CHARACTERISTICS, LEVELS, AND RQL PAY FACTORS FOR THE WEED MULTICHARACTERISTIC ACCEPTANCE/PAYMENT PLAN (*71*)

	Allowable Percent Defective		
Quality Characteristic	Acceptable Quality Level (AQL)	Rejectable Quality Level (RQL)	RQL Pay Factor (percent)
Thickness	10	70	65
Strength	10	70	65
Smoothness	5	15	65

ROUTE 123 SECTION 10B LOT 21 DATE 6/1/93

START STATION 12+34.56 END STATION 22+34.56

TEST VALUES AND PD COMPUTATIONS

THICKNESS: 9.987, 10.623, 10.152, 10.229, 10.386

STRENGTH: 3825, 4230, 3870, 4520, 4015

SMOOTHNESS: 4, 3, 4, 2, 1, 3, 1, 4, 2, 4, 4, 3, 3, 4

THICKNESS	STRENGTH	SMOOTHNESS
Limit 10	Limit 3700	Total Length = 1000
N = 5	N = 5	Defective Length = 42
$\bar{x}$ = 10.275	$\bar{x}$ = 4092	PD = 4.20
s = 0.242	s = 286.7	
Q = 1.14	Q = 1.37	
PD = 12.37	PD = 6.56	

RQL LIMITATIONS

THICKNESS	STRENGTH	SMOOTHNESS
PD < 70?	PD < 70?	PD < 15?
Yes ✓	Yes ✓	Yes ✓
No* __	No* __	No* __

(a) Removal and replacement, corrective action, or PF = 65. Skip pay factor computation.

PAY FACTOR COMPUTATION

PF = 105 - 0.12 $PD_{THICKNESS}$ - 0.10 $PD_{STRENGTH}$ - 0.11($PD_{SMOOTHNESS}$)^2

= 105 - 0.12(12.37) - 0.10(6.56) - 0.11(4.20)(4.20)

= 105 - 1.48 - 0.66 - 1.94 = 100.92

FINAL DISPOSITION OF LOT

Remove/Replace: Yes __ No ✓ Corrective Action: Yes __ No ✓

If both "No", enter pay factor: PF = 100.92

FIGURE 12 Sample worksheet for Weed's multicharacteristic acceptance plan (*71*).

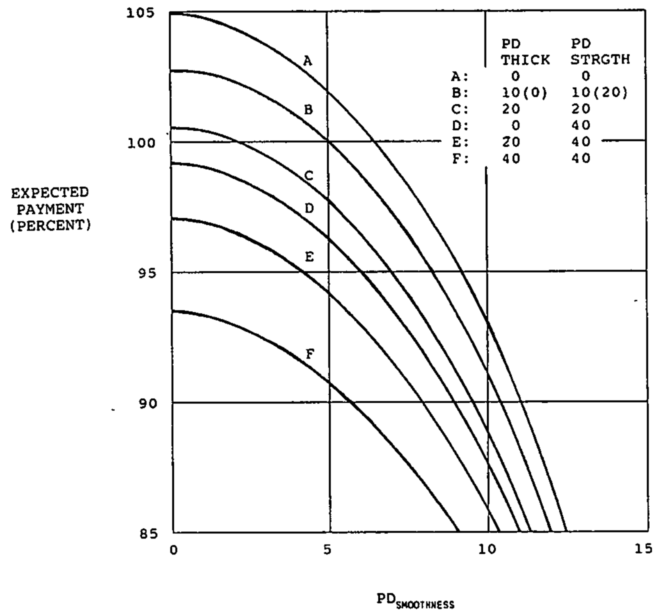


FIGURE 13 Expected payment curves for selected combinations of quality levels for Weed's multicharacteristic acceptance plan (*71*).

RQL is reached on any one of the quality measures, in which case the agency has the option to require removal and replacement, corrective action, or payment at 65 percent. Administratively, the procedure is easy to apply as illustrated by the sample worksheet shown in Figure 12.

As with the earlier version, the coefficients assigned to thickness and strength weight those two measures in approximate proportion to their relative importance in the AASHTO rigid pavement design equation, as described above. When all of the quality measures are below their RQL values, the procedure permits surpluses and deficiencies in thickness and strength to offset one another. Also, by using the second power of smoothness PD, the equation requires that relatively high levels of riding quality be achieved to trigger any appreciable bonus. Expected payment curves for the pay equation for selected quality levels of thickness and strength are shown in Figure 13.

The smoothness element of the pay equation is based on a performance model that was developed to satisfy the following assumptions, which were derived from a combination of experience and engineering judgement and were intended to apply equally to both rigid and flexible pavement:

Design life = 20 yr;
When PD_{smooth} = 0, life expectancy = 25 yr;
When PD_{smooth} = 5 (AQL), life expectancy = 20 yr;
When PD_{smooth} = 15 (RQL), life expectancy = 0 yr; and

The smoothness/performance curve should be S-shaped and approach the X-axis asymptotically.

The model itself, which appears below,

$$L_e = 25\ e^{-0.001785(PD_{smooth})^3} \tag{9}$$

when combined with Equation 1, yields a smoothness term for the pay function that satisfies the five assumptions listed above (Figure 14).

Weed's proposal for further refinement of New Jersey DOT's specification for PCC pavement represents another stage in the evolution of that agency's continuing attempt to link the contractor's level of compensation to the actual worth of the finished work. While the present iteration embodies many of the shortcomings cited above for the earlier versions, the New Jersey effort as a whole represents a unique case that demonstrates the feasibility of an operating agency producing a technically sophisticated performance-related specification that is based on sound engineering and statistical principles, yet, incorporates enough accommodations to practicality that it is administratively easy to apply.

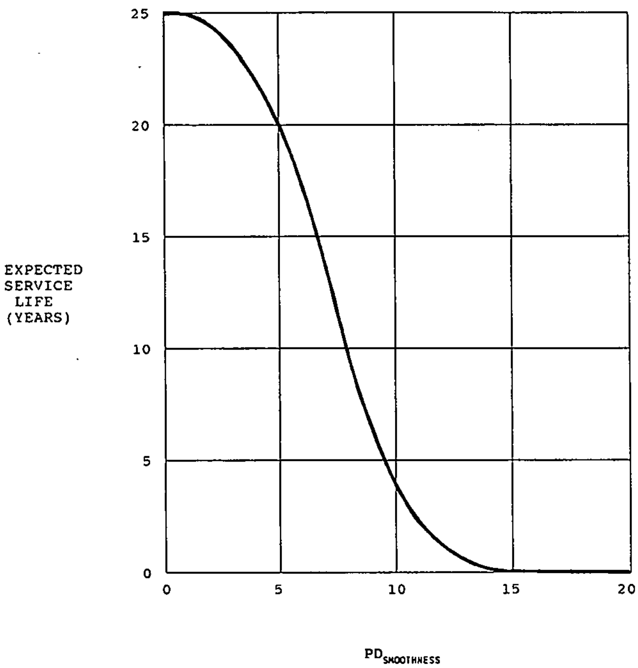


FIGURE 14 Approximate performance model for pavement smoothness (*71*).

DEMONSTRATION SPECIFICATION FOR PCC PAVEMENT

The New Jersey DOT approach to developing PRS for PCC pavement has been one of incrementally improving existing acceptance and payment practices, based largely on the AASHTO rigid pavement design model. The New Jersey DOT has been willing to accept the limitations of that model in return for a more sophisticated and more defensible rationale for their payment adjustment practice. In contrast, research sponsored by FHWA (*9,11,12*) has taken a much broader and more inclusive approach to the development of PRS that includes consideration of all of the variables that define performance. Working from a variation of the conceptual framework (Figure 15) described in Chapter 3, Irick, who developed the original framework, and other researchers at ARE Inc., Austin, Texas, have identified from the research and engineering literature selected primary and secondary performance relationships, as well as performance-related M&C variables, for use in developing a more comprehensive specification for the surfacing layer of PCC pavement (*9*).

The primary relationships, selected by ARE researchers and listed in Table 5, are those that link the key distress/performance indicators (e.g., cracking, faulting, and present serviceability index (PSI)) to the key distress/performance predictors (e.g., slab thickness, flexural strength, and modulus of elasticity). They are also the underlying relationships that, when combined with appropriate economic factors, allow differences in quality levels to be interpreted in terms of differences in worth. The models themselves are not shown in Table 5; but they can be found in several publications (*54,80–82*). Among these publications, *NCHRP Report 277: Portland Cement Concrete Pavement Evaluation System (COPES)* (*81*) is particularly important because it includes 40 new distress/performance models, developed from condition evaluations of 418 sections (2,101 km (1,305 mi)) of heavily trafficked PCC pavement in six states, to quantify the relationships with design, traffic, climate, and other variables.

The secondary relationships identified by ARE researchers are too numerous to include here, but are provided in an FHWA report (*9*). Secondary relationships are those that link the M&C variables that are amenable to control (e.g., concrete air content) to the distress/performance indicators, the stress/performance predictors, or their surrogates. The M&C variables that appear in the secondary relationships, or that are candidates for useful relationships not yet developed, are identified and classified in Table 6. In addition to identifying existing secondary relationships from the literature, existing data bases were evaluated for their potential use in developing new secondary relationships. However, all of these data bases were rejected because of a variety of deficiencies. As an alternative, a laboratory experiment of concrete material properties was planned and executed to improve at least one set of secondary relationships, those that involve concrete flexural strength.

In an independent activity, the researchers developed a limited demonstration PRS in the form of a computer spread sheet, based on the AASHTO rigid pavement design model (*54*) and the COPES distress prediction equation (*81*). Use of the spread sheet allows computation of pay factors based on the following: performance predictions of both as-designed and as-constructed pavements from three primary quality characteristics: slab thickness, concrete compressive strength, and initial serviceability (Table 7); a variety of other design, construction, traffic, environmental, distress, and economic factors (Table 7); and life-cycle cost estimates that include construction, maintenance, overlay, and salvage costs.

Because the purpose of the demonstration PRS presented in this study was to illustrate the development process, the specification itself was not fully elaborated, and neither a pay factor equation (similar to Equation 8) nor an OC curve was developed. However, in terms of the conceptual development of PRS, the FHWA/ARE effort represents some advances over earlier work. Specifically, it illustrates a method for introducing distress mechanisms other than those related to traffic into the computations, as well as other design, traffic, and environmental factors.

PROTOTYPE SPECIFICATION FOR PCC PAVEMENT

In a follow-up study, also sponsored by FHWA (*12*), researchers from ERES Consultants, Inc., Savoy, Illinois, refined the list of distress/performance indicators and M&C variables listed in Tables 5 and 6, extended the conceptual basis of PRS, continued to improve the secondary relationships for PCC pavement through a series of designed laboratory experiments, and developed a prototype specification that builds on the earlier work. This specification makes it possible to consider any number of quality characteristics and their within-lot variability on the pay factor. Both means and variances are considered.

From a comprehensive list of distress/performance indicators and associated M&C variables compiled by the researchers, an expert panel identified those variables under the contractor's control that are thought to be of sufficient importance to include in a PRS. The 12 M&C variables that appear in the second column of Table 8 represent those quality characteristics that the researchers believe should be considered for inclusion in a comprehensive

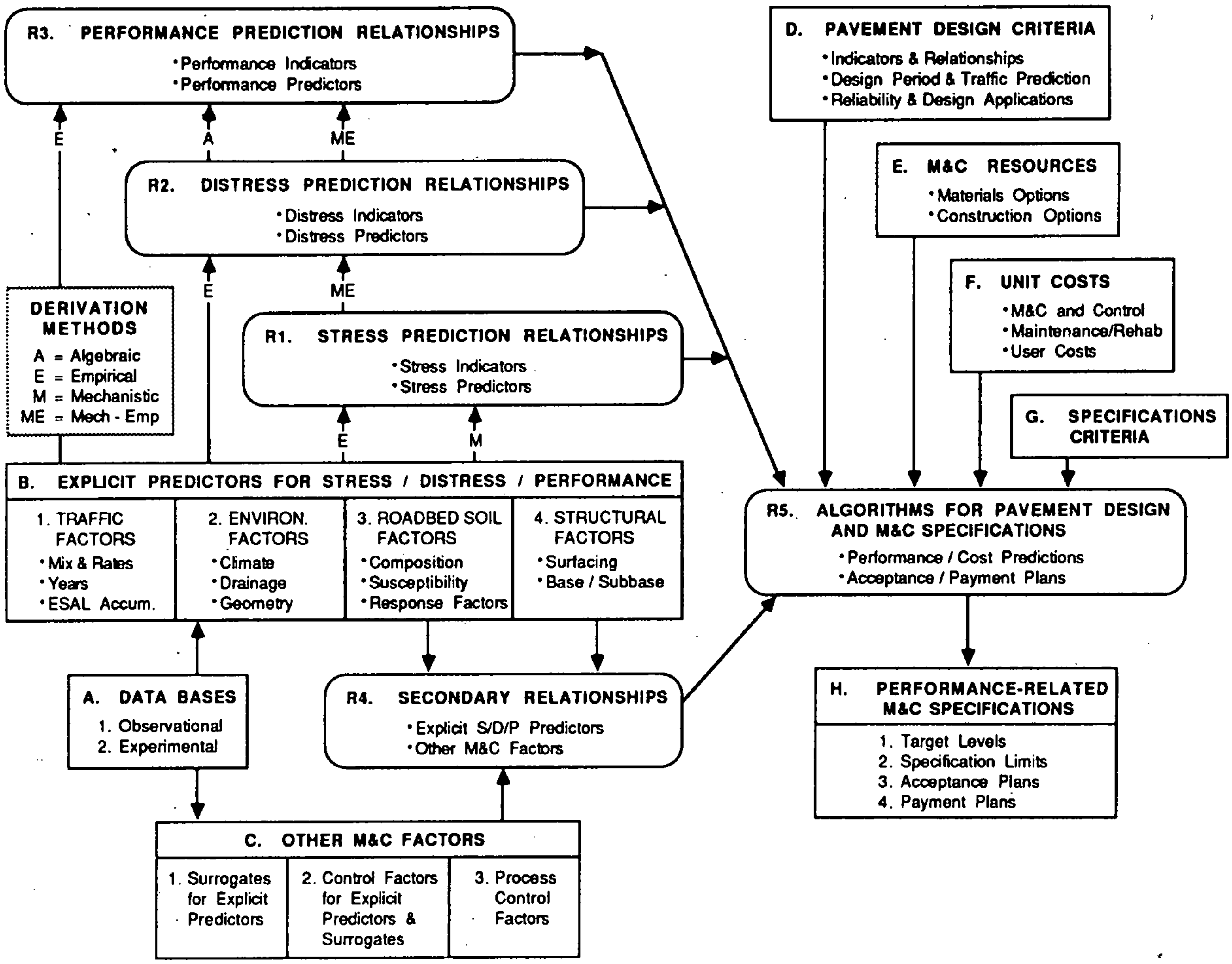


FIGURE 15 FHWA/ARE framework for development of performance-related M&C specifications (*9*).

TABLE 5
PRIMARY RELATIONSHIPS FOR CALCULATING DISTRESS/PERFORMANCE DIFFERENTIALS FOR PCC PAVEMENT SURFACING LAYER (after *9*)

Distress/Performance Indicator	Source for Distress/Performance Prediction Model
Stress	ELSYM5 (*80*)
Pumping	COPES report (*81*)
Cracking	COPES report
Faulting	COPES report
Joint Deterioration	COPES report
CRCP Distress	TxDOT report (*82*)
Serviceability Loss	COPES report
Performance	AASHTO (*54*)

PRS and for which an appropriate standard test must be available, a test that is rapid, repeatable, and suitable for field use.

The prototype specification is based on measuring four quality characteristics of the in-situ pavement: 28-day concrete flexural strength, slab thickness, in-situ concrete air content, and surface smoothness. The flexural strength is estimated by a two-step process from either the compressive or the splitting tensile strength of cores removed from the pavement after a minimum of 72 hours. The 72-hour strengths are first adjusted to 28-day strengths under standard laboratory-cured conditions using maturity methods and relationships developed from actual on-site project materials, and then converted to flexural strengths (third-point loading) through an approved relationship developed for the specific concrete mixture. Slab thickness is measured in the usual manner from the same cores used for testing strength. Concrete air content may be measured from cores of the hardened concrete using microscopical methods (ASTM C 457), from samples of plastic concrete removed from the consolidated in-place slab using AASHTO T-152 or ASTM C 231, or in situ from the plastic concrete using any other approved method capable of making such determinations. Riding

TABLE 6
CLASSIFICATION OF M&C VARIABLES FOR PCC PAVEMENT SURFACING LAYER

General Classification	Variable(s)
Surfacing Layer Variables	Profile Thickness Reinforcement Variables Joint Geometry Variables Load Transfer Variables Shoulder Variables
Properties of Hardened PCC	Flexural Strength Compressive Strength Tensile Strength Elastic Modulus Freeze-Thaw Resistance Shrinkage Thermal Coefficient Air Bubble Distribution Gel Space Ratio Scaling Resistance Abrasion Resistance Permeability
Placement and Curing Variables	Placement Temperature Curing Time Curing Temperature Curing Humidity
Properties of Plastic PCC	Slump Air Content Unit Weight Yield Mixing Time Time of Set Heat of Hydration
Coarse Aggregate Properties	Type Gradation Soundness Reactivity Quantity D-Cracking Potential
Fine Aggregate Properties	Type Gradation Sand Equivalent Fineness Modulus Soundness Reactivity Quantity
Cement Properties	Type Cement Factor Alkali Content
Water Variables	Chemical Composition Water/Cement Ratio Water Content
Additive Type and Content	AE Agent Fly Ash Superplasticizer Accelerator Retarder

surface smoothness is measured after completion of any required grinding.

The four quality characteristics (including their means and standard deviation) are combined into a single quality measure, the future life-cycle cost (LCC) of the pavement, calculated over the design period and expressed as a present worth. Values of LCC for both the target as-designed and the as-constructed conditions are calculated with the aid of a computer software routine called PAVESPEC, which uses five complex distress and rideability models (Table 9), appropriate cost factors and cost models, and other traffic/design/climate/materials inputs.

Payment factors (PFs) for the prototype specification are expressed in terms of the difference between the estimated LCCs of the as-designed and as-constructed pavements (*12*):

$$PF = 100\ (\text{Lot Bid} + \text{Diff})/(\text{Lot Bid}); \qquad (10)$$

in which,

PF = Payment factor, percent of original lot bid price,
Lot Bid = Contractor's lot bid price, and
Diff = (As-designed LCC) − (As-constructed LCC).

The objective of PAVESPEC is to compute payment factors by simulating pavement construction parameters for each lot, sampling these parameters, and predicting performance and costs (Figure 16). For the as-designed pavement, input values for the simulation are the design mean targets for the quality characteristics and their design variances. For the as-constructed pavement lot, input variables are the results of individual acceptance tests. Other inputs are constants between the two cases and include design, traffic, climate, and materials variables. PAVESPEC predicts the key distress indicators (faulting, cracking, spalling, present serviceability rating (PSR)) for both the as-designed and as-constructed pavements over the analysis period, applies appropriate rehabilitation policies, estimates the difference in the present worth of the LCCs, and calculates pay factors using Equation 10. The use of LCC as the key overall quality measure provides for direct consideration of the effects of the measured quality characteristics on a single pay factor. No arbitrary averaging or multiplication of individual pay factors is needed.

PAVESPEC designers point out that at this point in the development of PRS for concrete pavement, PAVESPEC is a research tool and is not intended for commercial use. A complete display of the prototype specification is given in the project report (*12*).

DEMONSTRATION SPECIFICATION FOR ASPHALT CONCRETE (AC) PAVEMENT

There has been a comparable effort to develop PRS for AC pavement, paralleling the program of broad-based research on PRS for PCC pavement. The conceptual framework for both programs has evolved from a common source (*3*), and the research approaches have been similar. Sponsored first by NCHRP (*10*) and more recently by FHWA (*13*), researchers have identified from the literature primary and secondary relationships, as well as performance-related M&C variables, for use in developing PRS for AC pavement, and have conducted research to develop new secondary relationships.

The primary objective of the NCHRP study (*NCHRP Report 332*), conducted by the Pennsylvania Transportation Institute (PTI) at The Pennsylvania State University, was to develop a generalized

TABLE 7
INPUT DATA FOR THE FHWA/ARE DEMONSTRATION SPECIFICATION FOR PCC PAVEMENT (9)

		Design Pvt. (DES)	Constructed Pvt. (CON)
A.	Primary PCC Specifications Factors		
	1. Initial PSI (P_o)	4.3	4.0
	2. Slab Thickness (D_c)	9.0 in	8.5 in
	3. 28-day Compressive Strength (F'_c)	4000 psi	3500 psi
	4. 28-day Flexural Strength (S'_c) (estimated from F'_c by equation 35)	614 psi	557 psi
	5. PCC Elastic Modulus (E_c) (estimated from F'_c by equation 36)	4.17 mpsi	3.96 mpsi
		DES & CON	
B.	Non-PCC M&C Factors		
	1. Load Transfer Coefficient (J)	3.2	
	2. Drainage Coefficient (C_d)	1.0	
	3. Subbase Thickness	6.0 in	
	4. Joint Spacing	20 ft	
	5. Subbase Type (0 = Gran, 1 = Stab)	1 (Stab)	
	6. Shoulder Type (0 = AC, 1 = PCC Tied)	0 (AC)	
	7. Dowel Bar Diameter	1.25 in	
	8. Reinf. Steel Quantity	0.12 in^2/ftwidth	
	9. Type of Joint Filler (0 = None, 1 = Unitube)	1 (Unitube)	
	10. Modulus of Subgrade Reaction (k)	60 pci	
C.	Traffic Factors		
	1. Initial 4-lane ESAL (W_o)	500,000	
	2. Direction Distribution Factor	50%	
	3. Lane Distribution Factor	90%	
	4. Annual Growth Rate (r)	5%	
D.	Environmental Factors		
	1. Freeze Index	625	
	2. Avg. Monthly Temperature	18°C	
	3. Max. Annual Temp. Range	33°C	
	4. Avg. Annual Precipitation	25 in	
E.	Other Distress Factors (for COPES equations)		
	1. D-Crack Potential (0 = No, 1 = Yes)	0	
	2. Reactive Aggregates (0 = No, 1 = Yes)	0	
	3. Incompressible Potential (0 = No, 1 = Yes)	0	
	4. Joint Damage Potential (0 = No, 1 = Yes)	0	
F.	Economic and Cost Factors		
	1. Interest Rate (i)	6%	
	2. Cost of PCC Construction (Bid Price)	$30.00/sy	
	3. Annual Maintenance Costs when PSI = 2.5 (m in equation 37)	$0.28/sy	
	4. Percent of Vehicle Operating Costs (q in equation 38)	10%	

TABLE 8
DISTRESS/PERFORMANCE INDICATORS AND CORRESPONDING M&C VARIABLES FOR PCC PAVEMENTS (*12*)

PERFORMANCE INDICATOR	MEASURED QUALITY CHARACTERISTICS(S)
Transverse cracking caused by loading and thermal curling	• Flexural strength • Slab thickness
Transverse joint spalling	• Air void system • Timing of joint sawing • Dowel bar alignment • Improper densification of concrete surrounding dowel bars
Longitudinal joint spalling	• Air void system • Timing of joint sawing • Depth/alignment of tiebars
Random transverse cracking	• Timing of joint sawing • Depth of joint sawing
Surface roughness	• Initial surface profile
Low surface friction	• Initial surface friction
Scaling/spalling throughout slab	• Depth of reinforcement
Punchouts and crack spalling	• Depth of reinforcement (CRCP only)
Transverse joint spalling, blowups, and bridge pushing problems	• Improper joint sealant installation

TABLE 9
DISTRESS/PERFORMANCE MODELS USED IN THE FHWA/ERES PROTOTYPE SPECIFICATION FOR PCC PAVEMENT

Distress/Performance Indicator	Model Source
1) Transverse Joint Faulting	FHWA-RD-89-138 (*83*)
2) Transverse Cracking	NCHRP/COPES (*81*)
3) Transverse Joint Spalling	FHWA-RD-89-138 (*83*), as modified in the research
4) Pumping (feeds back into the cracking prediction model)	NCHRP/COPES (*81*)
5) Present Serviceability Rating (PSR) (as a function of initial smoothness, cracking, spalling, and faulting)	FHWA-RD-89-138 (*83*)

conceptual framework for PRS and to apply that framework to the development of PRS for hot-mix asphalt materials and construction. Working from the Irick paper (*3*) (discussed in Chapter 3), the NCHRP/PTI researchers prepared the generalized conceptual framework shown in Figure 17.

The key features of this framework, listed below, are appropriate to all pavement types and were subsequently used in the development of Figure 15, discussed earlier in connection with the development of PRS for PCC pavement (*10*):

- A payment schedule that is related to the difference between the projected performance of the target and as-constructed pavements;

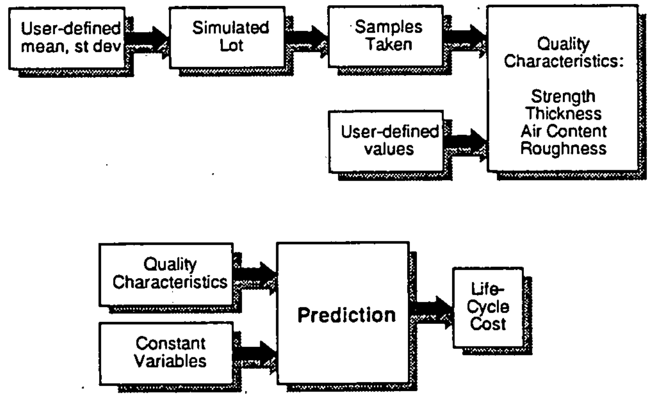


FIGURE 16 Acquiring quality characteristics (top), and their use in predicting LCC (bottom) with PAVESPEC (*12*).

- The use, for payment and quality assurance purposes, of only those M&C variables that are performance-related and that can be controlled by the contractor;
- The use of fundamental mixture response variables to predict the performance of the target and as-constructed pavements;
- The incorporation of the pavement design algorithm into the schedule used to pay the contractor;
- The use of predicted equivalent uniform annual cost, or some other economic factor, to express LCC as a basis for determining any payment adjustment; and
- The use of stochastic variables and statistical concepts and methodologies wherever appropriate.

Application of the generalized framework to hot mix AC pavement is diagramed in Figure 18. The key elements of that application are (*10*):

- Target design values, which include the pavement design (i.e., thickness, percent compaction, allowable roughness), as well as the target values for the mixture (i.e., percent asphalt cement, gradation, Marshall stability). These are the target M&C variables;
- A characterization of the M&C variables for the as-constructed pavement. These are the measured values of the as-constructed M&C variables;
- The algorithms that are used to determine LCC;
- Predicted LCC for the target and as-constructed pavement; and
- An acceptance plan and payment schedule.

A second research objective was to demonstrate the validity of the conceptual framework by designing a demonstration PRS for hot-mix AC. The demonstration was not expected to produce a working version of a PRS, but rather to illustrate the recommended methodologies. Accordingly, the research team selected from the literature those primary relationships thought to best predict the deterioration of pavement condition or service with increasing axle load applications (Tables 10 and 11). Unfortunately, few of the primary relationships were found to include M&C factors of the type for which specifications are normally developed, that is, that are amenable to control by the contractor. Thus, much of the balance of the research consisted of demonstrating various techniques that can be useful in developing such relationships,

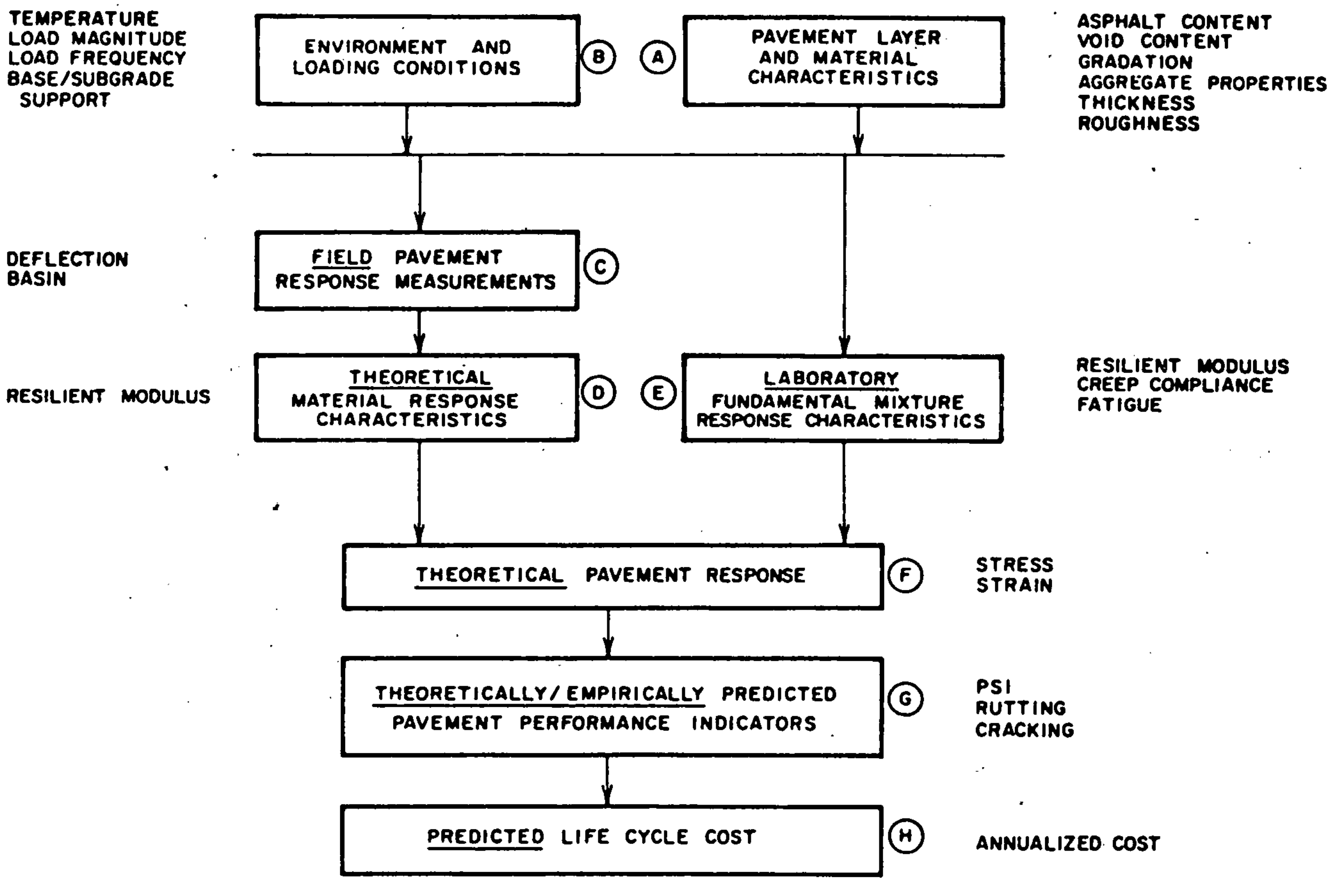


FIGURE 17 Generalized conceptual framework for PRS (*10*).

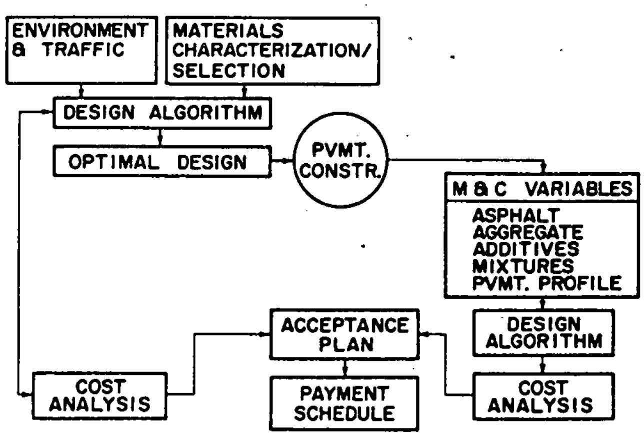


FIGURE 18 Generalized framework for a performance-related specification for hot-mix asphalt concrete (*10*).

including design of field and laboratory experiments, evaluation of observational and experimental data bases, use of expert systems, and sensitivity analysis. The resulting demonstration PRS used distress models for cracking, rutting, and roughness but without any multicharacteristic condition indicator, such as those discussed for PCC pavement.

An important feature of the PRS demonstration was a method for predicting performance-period costs based on a LCC analysis that includes maintenance, rehabilitation, and user costs. The approach employs the concept of economic life, illustrated in Figure 19, which is the time within the initial performance period at which the equivalent uniform annual cost has a minimum value. The annualized cost (A_n) is computed as follows:

$$A_n = (\text{Cumulative Present Worth of Total Costs}) \times [(1-r)/(1-r^n)]; \quad (11)$$

in which,

A_n = Annualized total cost at year "n",
r = 1/(1+i), and
i = Interest rate.

The payment factor (PF) is calculated as follows:

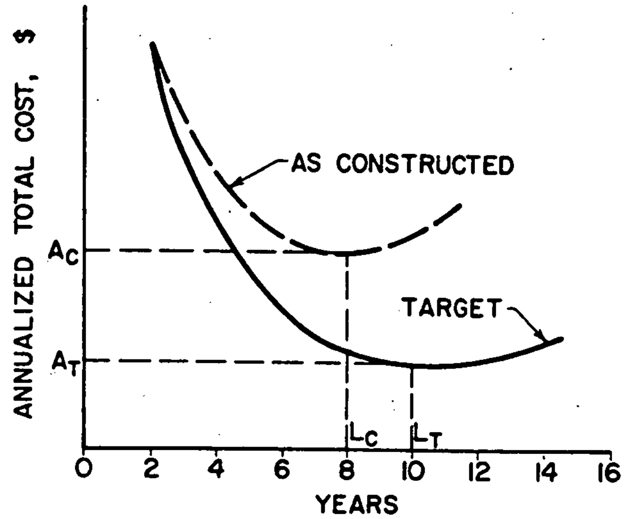
$$PF = 100\ (LBP-C)\ /\ LBP; \quad (12)$$

in which,

LBP = Lot bid price,
$C = (A_c-A_t)\ \{[(1+i)L_c-1]\ /\ [i(1+i)L_t]\}$,
A_c = Annualized total cost at economic life of as-constructed pavement,
A_t = Annualized total cost at economic life of target pavement,
L_c = Economic life of as-constructed pavement, and
L_t = Economic life of target pavement.

TABLE 10
PRIMARY RELATIONSHIPS FOR CALCULATING DISTRESS/PERFORMANCE DIFFERENTIALS FOR AC PAVEMENT SURFACING LAYERS

Distress/Performance Indicator	Source for Distress/Performance Prediction Model
Fatigue Cracking	ARE (*84*) Asphalt Institute (*85*) VESYS Cracking Model (*86*)
Low Temperature Cracking	Cold (*87*) Shahin-McCullough Model for Low-Temperature Cracking (*88*)
PSI/Roughness	PDMS (*89*) AASHTO (*54*) VESYS Roughness Model (*86*) Fernando (*90*)
Rutting	VESYS Rut Depth Model (*86*) Shell (*91*) AGIP (*92*)
Skid Resistance	See Table 11
Thermal Fatigue Cracking	Lytton-Shanmugham (*86*) Shahin-McCullough Model for Thermal Fatigue Cracking (*93*)



A_c = annual cost at end of economic life (as-constructed pavement)
L_c = economic life of as-constructed pavement
A_T = annual cost at end of economic life (target pavement)
L_T = economic life of target pavement

FIGURE 19 Economic life of as-constructed versus target pavement (*10*).

TABLE 11
EMPIRICAL MODELS FOR PREDICTING PAVEMENT FRICTION AT 40 MPH FROM GENERAL AGGREGATE TYPE AND NUMBER OF LOAD REPETITIONS (*6*)

Aggregate Hardness	Description	Friction Model
Soft	TX Georgetown Limestone	$SN = 34.6\ (N/10^6)^{-0.136}$
Soft	Central and Northern FL	$SN = 45.4\ (N/10^6)^{-0.222}$
Soft	VA Limestone	$SN = 44.7\ (N/10^6)^{0.1964}$
Soft	TX Burnett Dolomite	$SN = 40.4\ (N/10^6)^{-0.121}$
Soft	KY Limestone	$SN = 46.9$ at $N = 10^6$
Soft	WI Dolomite	$SN = 43.1$ at $N = 10^6$
Soft	GA Limestone	$SN = 72.5\ (N/10^6)^{-0.128}$
Hard	TX Traprock	$SN = 43.5\ (N/10^6)^{-0.096}$
Hard	WI Igneous Rock	$SN = 49.5$ at $N = 10^6$
Hard	TX Iron Slag	$SN = 46.4\ (N/10^6)^{-0.063}$
Hard	VA S4, S5 Nonpolishing Aggregate	$SN = 52.1\ (N/10^6)^{-0.058}$
Hard	GA Siliceous Aggregate	$SN = 54.8\ (N/10^6)^{-0.044}$

It has been noted (*9,10*) that while the economic life approach is frequently used for replacement analyses in industrial applications, there may be a significant problem in applying it to pavements because of the short economic lives that appear to result at a time when serviceability is still quite high.

DEVELOPMENT OF NEW PRS COMPONENTS FOR AC PAVEMENTS

The work on PRS for AC pavements continued under FHWA sponsorship at ARE Inc., and focused on identifying secondary relationships that could be used as the basis for prediction equations in a PRS, and subsequently on laboratory studies to develop new equations. However, the project resources limited that activity to M&C variables directly related to the surfacing layer of AC pavements only, to the exclusion of those related to roadbed soil properties, base/subbase properties, and shoulder construction.

The secondary relationships identified from the literature by the researchers were assessed with regard to their use in developing a PRS system. Those selected for consideration are too numerous to include here in their entirety but can be found in the literature (*13*), and their various elements are compared with one another in Table 12. The first column of Table 12 cites the literature source of the relationship; the second column, the dependent variable; and the third through fifth columns, the independent variables. The last column lists the statistics for those equations for which they are available. Because none of the relationships included all of the potential independent M&C variables, because almost one-half included variables not directly controllable during construction, and because only one-third included statistical parameters (coefficient of determination and standard error of estimate), the researchers assessed the extant secondary relationships to be deficient from the standpoint of their usefulness in developing a PRS system. Accordingly, they designed and executed a partial factorial laboratory experiment to develop the requisite relationships.

The intent of the experimental design was to link as many as possible of the M&C predictors shown in Pool A of Figure 20 with as many as possible of the response variables shown in Pool B. The specific variables and their levels were selected by the research team in consultation with the project's advisory panel to conform to the resources available to the study. Seven of the 20 M&C variables were included in the experiment at either two or three levels. Techniques of stepwise multiple regression tempered by engineering judgment were used in the data analysis phase to make the final selection of variables to be employed in the secondary prediction relationships. The equations themselves are given in Table 13 and include as dependent variables compaction index (CI), resilient modulus (MR) in which the asphalt is represented by either type or penetration, direct tensile strength (TS) in which the asphalt is represented by either type or penetration, age susceptibility in terms of either modulus or tensile strength ratios, moisture susceptibility in terms of either index of retained modulus (IRM) or index of retained strength (IRS), and fatigue resistance (log (N)). CI is also used as an independent variable in other equations.

The secondary equations in Table 13 permit resilient modulus, tensile strength, and fatigue resistance to be adjusted from optimum conditions for variations in aggregate gradation, asphalt content, and compaction that occur at the job site. The former properties are pavement response variables that appear in most primary prediction relationships for pavement service life. After considering several of these primary relationships, the researchers chose the AASHTO equations (*53*) to use with the secondary relationships developed in this study.

In the performance algorithm developed by the FHWA/ARE researchers, service life is predicted from the AASHTO design guide as the number of load repetitions (ESALs) to produce a terminal present serviceability index for certain fixed pavement design and materials factors, and for as-designed or as-constructed levels of selected M&C variables. The variables included in the performance algorithm are: asphalt content, percent passing the #30 sieve, percent passing the #200 sieve, percent voids in mineral aggregate (VMA), and percent air voids (% VOIDS).

The service life estimates of the AASHTO equation are linked to these M&C variables through the layer coefficient for asphalt concrete, which is, in turn, a function of the resilient modulus of the layer that is estimated by the secondary equations for compaction index (CI) and resilient modulus (MR) (Table 13). The independent variables in the CI and MR equations are the five cited in the previous paragraph.

Two different methodologies were employed to calculate pay factors, both based on the concept of present worth of differences in estimated life:

1) A variation of the method adapted by New Jersey DOT (*8,31*), and represented by Equation 3 in which the mean and standard deviation of test values for a given lot are used to estimate the percent of predicted pavement life values that lie at or above the 100 percent pay limit. Pay factors are based on the percent of predicted life at or above the 100 percent pay limit:

$$PF = 105.0 - 0.5\ (PD). \tag{13}$$

The formula permits a maximum payment of 105 percent, paying 100 percent when 90 percent of the lot is within the limit, and 55 percent when 0 percent is within the limit.

2) A method represented by Equation 1 in which only values of mean predicted lives are used. This method does not consider the effect of the distribution of test values.

OTHER STUDIES

The research reviewed in this chapter represents the mainstream of PRS development in the United States. These projects are all linked either programmatically or through an informal network of investigators whose focus is on developing the technology and the processes for implementing PRS. However, the reviewed studies do not, by themselves, include all of the work that has contributed to individual elements of PRS development. This is particularly true with respect to the relationship between M&C variables and performance.

Several recently drafted statistical end-result specifications have attempted to incorporate some of the key elements of a working PRS, particularly composite pay factors, including: the Western Association of State Highway and Transportation Officials' (WASHTO) specification for PCC pavement (*94*), Oklahoma Department of Transportation's specification for PCC pavement (*95*), and AASHTO's draft specification for PCC pavement (*96*). Each of these specifications is reviewed critically in an FHWA report (*12*).

TABLE 12
SELECTED SECONDARY PREDICTION RELATIONSHIPS FOR AC PAVEMENT SURFACE LAYERS (AFTER *13*)

Reference Citation	Dependent Variable (Primary Predictor in PPR)	Independent Variables that Are also Primary Predictors of Pavement Performance						Materials and Construction Variables																	Other Variables		Statistics		
		ATS	DEN	LMS	PAV	TH	VMA	ACP	AGG	APN	ATY	AV	AVC	DV	GTM	LAV	P2	PAW	PVB	RBS	SAG	SB	T	VAG	f	q	R^2	SEE	n
(10)	SM				X																	X		X					
"	DM											X					X		X				X		X				
(84)	AE																						X						
(89)	PFD														X														
"	SM																					X				X			
(10)	SM						X												X			X							
(86)	SM							X	X		X												X		X				
"	SM								X				X																
(87)	MS							X																					
"	HVS							X																					
"	PRD							X																					
"	TDF					X																	X				.797	.048	
"	DM					X																	X				.931	.0728	
(88)	MR		X							X											X						.659	.680	35
"	DM				X							X				X	X	X					X				.968	.0889	
"	DM				X							X				X	X	X					X				.971	.0849	
"	DM			X										X													.900	.1514	
"	DM	X												X													.744	.2844	
(10)	N*																		X	X									

Dependent Variables
AE = Asphalt Concrete Modulus
DM = Dynamic Modulus
HVS = Hveem Stability
MS = Marshall Stability
N = Number of Applications(=1x10⁴)
MR = Resilient Modulus
PRD = Percentage of real density
SM = Stiffness of the mix
TDF = Total deflection

Independent Variables
ATS = Asphalt Concrete Tensile Strength
DEN = Density
LMS = Log10 of Marshall Stability (lbs) divided by 100 times Marshall flow (0.01 in.)
PAV = Percent air voids
TH = Thickness
VMA = Volume of mineral aggregate

Materials and Construction Variables
ACP = Asphalt content percentage
AGG = Aggregate gradation
APN = Asphalt penetration
ATY = Asphalt type
AV = Absolute viscosity
AVC = Air void content
DV = Percentage of voids for the modulus specimen minus percent air voids for Marshall Test specimen
GTM = GTM revolutions
LAV = Log10 viscosity of asphalt
PAW = Percentage asphalt by weight
PVB = Percentage volume of binder
P2 = Percentage aggregate passing #200
RBS = Ring and ball softening point
SAG = Percentage of sand in aggregate
SB = Stiffness modulus of bitumen
T = Temperature
VAG = Volume concentrations of aggregates

Other Variables
f = Frequency
q = Mix stiffness/bitumen stiffness

Statistics Variables
R^2 =Coefficient of determination
SEE =Standard error of estimate
n =Number of cases (samples)

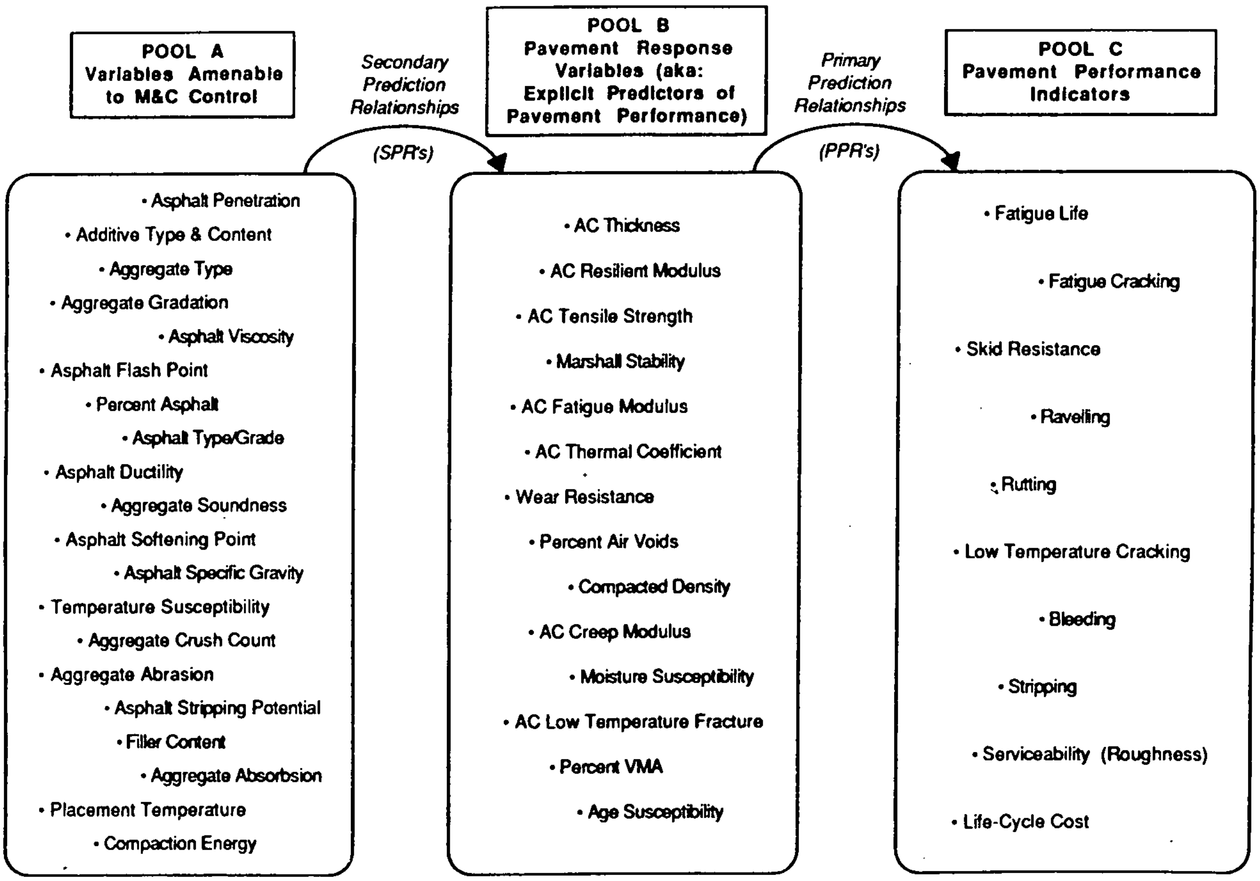


FIGURE 20 Connection among variables associated with an AC pavement surface PRS (*13*).

TABLE 13
FINAL REGRESSION EQUATIONS (SECONDARY RELATIONSHIPS) FOR DEVELOPING PRS FOR AC PAVEMENT SURFACES (*13*)

DEPENDENT VARIABLE	EQUATION	N	R'	SE
Compaction Index (CI)	2.19087-0.05206(VMA) - 0.23405(%VOIDS) + 0.00340623(%#30)(%VOIDS) - 0.02298(%#200)(%ASPHDEV) - 0.00882088(%#30)(%ASPHDEV)	105	0.85	0.34898
AC Type ln (MR)	5.32928+0.64468(CI) + 0.94522(ASPHTYP) - 0.03965(VMA) + 0.02207(%ASPHDEV) - 0.26202(%ASPHDEV)^2 - 0.0012691(%#200) + 0.001484(%#200)(VMA)	108	0.84	0.38278
AC Type ln (TS)	3.47901 + 0.74038(CI) + 0.51266(ASPHTYP) + 0.02932(VMA) + 0.12752(%ASPHDEV) - 0.15695(%ASPHDEV)^2 + 0.04984(%#200) - 0.001939(%#200)(VMA)	107	0.87	0.27457
AC Penetration ln (MR)	7.60425 + 0.02189(%ASPHDEV) - 0.26264(%ASPHDEV)^2 - 0.02624(ASPHPEN) - 0.03926(VMA) + 0.64515(CI) - 0.000543256(%#200) + 0.001453686(%#200)(VMA)	108	0.84	0.38258
AC Penetration ln (TS)	4.71325 + 0.12722(%ASPHDEV) - 0.15764(%ASPHDEV)^2 - 0.01423(ASPHPEN) + 0.02949(VMA) + 074065(CI) + 0.05005(%#200) - 0.00194589(%#200)(VMA)	107	0.87	0.27440
ln MR (32 days) / MR (1 day)	0.18977 + 0.0020579(%#200)(VMA)- 0.01049(%ASPHDEV)(VMA) + 0.00046623(%#30)(VMA)	95	0.42	0.2307
ln TS (32 days) / TS (1 day)	0.50560 - 0.0091774(CI)(%#30) - 0.0052624(VMA)	93	0.29	0.278
IRM	41.42601 - 69.58340(ADITV) + 34.55498(ASPHTYP)(ADITV) + 3.69456(VMA) + 28.91298(CI)(ADITV)	97	0.44	29.615
IRS	85.78256 - 1.52260(%#30)(ADITV) + 3.86562(ASPHTYP)(VMA) - 1.89002(ASPHTYP)(%#30)	96	0.37	35.608
log (N)	2.92100 - 2.6401 log (S) + 2.22575 log (TS)	96	0.69	0.48751

CI = Compaction index; MR = Resilient modulus; TS = Tensile strength; IRM = Index of retained modulus; IRS = Index of retained strength; log (N) = Fatigue resistance; VMA = Percent voids in mineral aggregate; % VOIDS = Percent air voids; % ASPHDEV = Percent deviation from optimum asphalt content; ASPHTYP = Asphalt type (temperature susceptibility; 0 = low, 1 = high); ASPHPEN = Penetration value @ 77 F (25 C); ADITV = Presence of lime (0 = yes, 1 = no); and S = Applied stress level for fatigue analysis.

CHAPTER FIVE

CURRENT PRACTICE

THE UNITED STATES AND CANADA

Questionnaire Design

A questionnaire (Appendix A) was mailed in the spring of 1992 to identify highway performance-related construction materials or construction element specifications, conforming to the definition of PRS developed for the synthesis (and repeated below), that are either currently in use or are in the process of being implemented.

> Performance-related specifications (PRS) in the highway industry are specifications for key materials and construction quality characteristics (M&C factors) that have been demonstrated to correlate significantly with long-term performance of the finished work. They are based on *quantified relationships* (models) between such characteristics measured at the time of construction and subsequent performance. They include sampling and testing procedures, quality levels and tolerances, and acceptance (or rejection) criteria. Typically, they also include payment schedules with positive and/or negative adjustments that are directly related *through the performance models* to changes anticipated in worth of the finished work as a result of departure from the quality level defined as acceptable.

The questionnaire sought examples of specifications based on quantitative rationales for the acceptance criteria and for the incentive/disincentive payment clauses. The definition of PRS used for this synthesis was worded carefully with specific phrases highlighted to emphasize this focus. Without these essential elements, a specification was not considered to be performance-related in terms of the definition.

Copies of the questionnaire, appropriately modified, were provided for each of the following seven topic areas:

1) Portland cement concrete (PCC) pavement;
2) Asphalt concrete (AC) pavement;
3) PCC and concrete materials;
4) AC and other asphalt paving materials;
5) Elements of concrete, steel, or timber structures, and structural materials other than concrete;
6) Soils, subgrades, subbases and bases; and
7) Drainage, geosynthetics, traffic control devices, paints and coatings, highway appurtenances, and other elements.

Questionnaire Responses

A total of 53 responses were received including 42 from state departments of highways or transportation, the District of Columbia, and Puerto Rico; 4 from Canadian provinces and territories; and 7 from various transportation authorities. Telephone follow-ups with state highway agencies produced another 10 responses, for a total of 63 (see Table 14).

Although much care was taken in drafting the definition of PRS and, in particular, to emphasize the essential element of quantification, the questionnaire apparently failed to convey to many (about three-quarters of respondents) just what was sought. As a result, many respondents provided great detail on quality levels, sampling plans, and decision criteria of specifications. However, they revealed that those specifications were in fact not supported by the quantitative models sought and, therefore, were not (in the definition of PRS) performance-related. For instance, in identifying the "performance model" that supports a density requirement for AC, one respondent cited the "recommended acceptance practices of the Asphalt Institute"; another noted the conventional understanding that "departures from the level of density specified result in diminished service life." Likewise, the details of incentive/disincentive payment schedules given were typically not supported by quantitative rationales provided. It should be noted that the terminology itself may have been misleading because many agencies believe that their specifications are in fact performance-related, even though their ability to quantitatively demonstrate the performance relationship is lacking.

Collectively, these responses are taken as evidence that the term "performance-related specifications" does not evoke a consistent understanding within the highway construction community at large, as it does within the more restricted research community. Even though PRS as a "sanctioned term" is at least 16 years old (*55*), it appears to be confused by many with "end-result specifications." This was reinforced through conversations held with respondents during the course of the project. Confusion with terminology is not totally surprising. Quality assurance (QA) in the construction management field has been an evolutionary process with new terms emerging and old terms taking on new meanings, as new awarenesses develop. A still often-cited publication on QA (*15*), for example, uses the terms "end-result specifications" and "performance specifications" interchangeably. As described elsewhere, usage has since evolved that distinguishes between these two.

In response to the question on quantitative relationships (models), 13 agencies cited one or more performance models for various measured attributes (see Table 15). Each of those responses was evaluated against the definition of PRS adopted for this synthesis. Many of the citations did refer to quantitative relationships that incorporate one or more factors perceived by their users to be performance-related materials and construction (M&C) variables. In PRS terminology, these would be secondary relationships, with the exception of the AASHTO design equation, which is a primary relationship. Significantly, variance estimates had not been developed for any of the models; only one of the models had been used to develop an adjusted payment schedule, even though such schedules were frequently associated with the particular M&C variable. The exception was New Jersey DOT's experimental specification for PCC pavement thickness, strength, and smoothness, discussed in Chapter 4. Some of the relationships cited were not models at all, in the sense that the term is usually understood, and this fact reinforces the perception of inconsistency within the highway construction community with regard to its understanding of PRS.

OTHER THAN THE UNITED STATES AND CANADA

A limited number of inquiries regarding the status of PRS outside of the United States were made, primarily in the United Kingdom, Australia, and Europe. While each evoked enthusiasm for the concepts represented by the synthesis definition, none resulted in the identification of a working PRS. Not unlike the United States, many jurisdictions have implemented statistical specifications and are experimenting with adjustable payment. However, most of the payment schemes include penalties only and quantitative relationships between pay factors and diminished worth are recognized as important, but are generally absent.

The Australia Road Research Board Ltd. provided the most technically detailed response. While PRS as here defined are not used in Australia, most Australian states do employ a reduced payment plan, promulgated at the national level, for deficiencies in the thickness of pavement base and subbase layers. Reductions in functional life associated with thickness deficiencies are estimated from a graphical performance model, whose basis was not given. Laboratory experiments have recently been completed to develop relationships between compactive effort (repeated load triaxial tests) and performance for common granular materials, so that payment reduction schedules could be developed that also include the degree of compaction (personal communication, A. Auff, Principal Research Scientist, Australian Road Research Board Ltd., Nunawading, Australia, April 1992).

In contrast, the trend reported by the United Kingdom is toward end-result specifications with payment reductions based on primary prediction factors, such as stiffness and fatigue resistance (personal communication, R.R. Addis, Pavement Engineering Division, Transport and Road Research Laboratory, Crowthome, Berkshire, United Kingdom, 1992).

TABLE 14
SUMMARY OF QUESTIONNAIRE RESPONSES

Source	Number Sent	Number Received
United States	50	50
District of Columbia and Puerto Rico	2	2
Canadian Provinces and Territories	10	4
Transportation Authorities	15	7
Total	77	63

TABLE 15
PERFORMANCE MODELS CITED FOR PRS

Construction Element	Attribute	Model Cited	Citing Agencies*
AC Pavement	Abrasion resistance	"CA model"	CA
AC Pavement	Aggregate gradation	AASHTO	KS
AC Pavement	Density	"Oregon model" TRR 1217 (*97*) AASHTO	CA NY IA
AC Pavement	Roughness	AASHTO Des Eq (*54*)	IA,KS
AC Pavement	Voids	Asph Inst MS-2	MN
PCC	Air Content	PCA Research (*98*) R-73-1 (*99*)	MN PA
PCC	Strength	ACI 212/214	MDTA
PCC	Aggregate (pavement vulnerability factor)	Wallace (*100,101*)	KS
PCC Pavement	Roughness	AASHTO Des Eq (*54*) NY RR 16 (*102*)	KS,NJ NY
PCC Pavement	Strength	AASHTO Des Eq (*54*)	NJ
PCC Pavement	Thickness	AASHTO Des Eq (*54*) "Pay form"	DE,KS,MN,NE,NJ,OR ISTHA
Polymer Overlays		Local experience	VA

*State highway agencies identified by standard two-digit abbreviations; MDTA = Maryland Transportation Authority; ISTHA = Illinois State Toll Highway Authority

CHAPTER SIX

CONCLUSIONS

An effort has been made in the preparation of this synthesis to describe the historical imperatives that have compelled the highway industry to consider performance-related materials and construction specifications, the conceptual basis on which they are founded, and the current status of their development and implementation. In so doing, the individual components of performance-related specifications (PRS) (e.g., statistical sampling, performance modeling, rapid on-site testing, operating characteristic (OC) curves, adjustable payment), as well as the mathematical aspects of PRS development, have generally been treated lightly, or by reference. The intent here has been to keep the focus on PRS as a design/specification/acceptance process, rather than on its details.

A concern has emerged, however, that while the research community involved in the development of PRS is well versed in both its theory and practice, awareness within the highway construction community at large seems quite low. This situation is reflected in the responses to the agency questionnaire and in the virtual absence of PRS development programs within highway agencies. With the exception of the New Jersey DOT, PRS development to date has been advanced almost exclusively by a small number of university and industry consultants. The risk in not broadening the base of participation in this work to include more of the agencies that will ultimately be responsible for its implementation is that the prototype specifications that are developed may not adequately reflect the needs and constraints of operating agencies.

The following general conclusions are drawn from the literature that was reviewed in the preparation of this synthesis and from the statements of practice that were obtained from highway agencies in the United States and elsewhere.

- A general process through which concepts of design and performance can be used to develop rational materials and construction specification for engineered highway elements has been demonstrated.
- That process has been employed to produce a conceptual framework for PRS development for materials and construction (M&C) factors for asphalt concrete (AC) and portland cement concrete (PCC) pavements.
- Demonstration and prototype specifications that employ some of the performance-related M&C factors for AC and PCC pavement surface layers have been developed. These specifications illustrate the general approach to PRS development as well as specific techniques, including identification of M&C factors, performance modeling, sensitivity analysis, economic modeling, pay factor development, and OC curves.
- The only operational versions of PRS identified for any manufactured or site-produced highway construction element were those of the New Jersey DOT for PCC, which has been a standard since 1989, and for PCC pavement, which has had experimental status since 1990 and has been subject to field trials.
- Adjustable payment plans are commonly used by highway agencies to enforce specification compliance including those that offer positive incentives only, those that offer negative incentives only, and those that offer both. Because few have OC curves, little is known about their fairness; and because few have been developed from performance and economic models, little is known about the extent to which their pay factors reflect enhanced or diminished worth of the as-constructed work.
- The term "performance-related specification" does not evoke the same consistency of understanding within the highway construction community at large that it does within the more restricted community. Many in the former appear to interpret the term to mean a statistical end-result specification with an adjustable payment schedule.

In consideration of the national priority that has been accorded PRS development among research and development needs in the management of highway construction, the following recommendation for further research and developmental work are offered:

- Continue PRS research and development at the national level with emphasis on a greater range of construction elements, including concrete, steel, or timber structures; soils, subgrades, subbases, and bases; and drainage, geosynthetic, traffic control devices, paints and coatings, and highway appurtenances.
- To the extent possible, highway agency research and development that supports PRS should be coordinated to ensure that state programs complement work at the national level effectively.
- Investigate methods so that the national effort on PRS development can be integrated with state programs to educate highway agency personnel on the concept, development, and implementation of PRS and to encourage their participation in the development of experimental specifications. The New Jersey DOT experience, though still evolving, can be helpful in this regard.
- Because of the wide use already made of adjustable payment acceptance plans, and the controversy they evoke within the construction industry over the issue of fairness, further research on this element of PRS alone could benefit the highway construction field.
- To the extent possible, include representation by the construction industry in PRS development, but particularly in the development of payment plans.

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LIST OF ACRONYMS

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
ACI	American Concrete Institute
AQL	Acceptable Quality Level
ASTM	American Society for Testing and Materials
CBR	California Bearing Ratio
CI	Compaction Index
COPES	Portland Cement Concrete Pavement Evaluation System
CRCP	Continuously Reinforced Concrete Pavement
ERS	End-Result Specifications
ESAL	Equivalent Single Axle Load
FHWA	Federal Highway Administration
IBTTA	International Bridge, Tunnel and Turnpike Association
IRM	Index of Retained Modulus
IRS	Index of Retained Strength
LCC	Life-Cycle Cost
LTPP	Long-Term Pavement Program
M&C	Materials and Construction
MR	Modulus of Rupture
NCHRP	National Cooperative Highway Research Program
OC	Operating Characteristic
PCC	Portland Cement Concrete
PF	Payment Factor
PRS	Performance-Related Specifications
PSI	Present Serviceability Index
PSR	Present Serviceability Rating
PTI	Pennsylvania Transportation Institute
QA	Quality Assurance
QC	Quality Control
RQL	Rejectable Quality Level
SHRP	Strategic Highway Research Program
TRB	Transportation Research Board
TRIS	Transportation Research Information Service
TS	Tensile Strength
VMA	Voids in Mineral Aggregate
WASHTO	Western Association of State Highway and Transportation Officials

APPENDIX A

QUESTIONNAIRE
NCHRP Project 20-5, Topic 23-05
"Performance-Related Specifications"

PORTLAND CEMENT CONCRETE PAVEMENT

"Performance-related specifications (PRS) in the highway industry are specifications for materials and elements of construction that have been demonstrated to correlate significantly with performance of the finished work. They are based on quantified relationships between attributes measured at the time of construction (through either process control or acceptance testing) and performance. They include sampling and testing procedures, quality attributes, quality levels and acceptance (or rejection) criteria. They may also include payment schedules, with both positive and negative price adjustments, that are directly related through quantitative models to changes in worth of the finished work, anticipated as a result of departure from the quality level defined as acceptable."

Name of Agency ______________________________

Address of Agency ______________________________

Person completing questionnaire:

Name ______________________________

Title ______________________________

Telephone Number ______________________________

1. Please note the specific attribute for which this part of the questionnaire is being completed (e.g., thickness, roughness, friction, etc.) Please use a separate set of forms for each attribute. ______________________________

2. Is the above attribute measured as part of the contractor's quality control, or as part of your agency's acceptance (or rejection) procedure? ______________________________

3. What quality/acceptance level (or range) is specified for this attribute? If codified in your specifications or in published operating procedures, please enclose a copy.
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Name of Agency ______________________________

4. What sampling plan and testing method is used to assess this attribute? If there are written procedures, please enclose a copy (only cite AASHTO, ASTM, etc. procedures).
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5. What are the acceptance (or rejection) criteria for this attribute (for example, is there a certain proportion of samples which must meet, or be within specified limits of, the quality/acceptance level or range specified in Question 3)? If they are written, please enclose a copy.
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6. Describe the quantitative relationship (model) between the measured attribute and performance of the finished work. Please enclose any documentation (reports, memoranda, data, etc.) that support the relationship. ______________________________
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7. Is there an incentive/disincentive payment schedule for this attribute? If yes, please enclose a copy with an explanation of how it is applied. ______________________________

8. Is there a quantitative basis for the incentive/disincentive schedule? If yes, please enclose any documentation (reports, memoranda, data, etc.) that support the relationship between the quality levels obtained and the worth of the finished work. ______________________________

Thank you for taking the time to thoughtfully complete this questionnaire. **Please return it with enclosures to the synthesis consultant:**

William P. Chamberlin, P.E.
292 Washington Avenue Extension
Albany, New York 12203
Phone: (518) 452-8786
FAX (518) 452-8776

QUESTIONNAIRE

NCHRP Project 20-5, Topic 23-05
"Performance-Related Specifications"

ASPHALT CONCRETE PAVEMENT

"Performance-related specifications (PRS) in the highway industry are specifications for materials and elements of construction that have been demonstrated to correlate significantly with performance of the finished work. They are based on quantified relationships between attributes measured at the time of construction (through either process control or acceptance testing) and performance. They include sampling and testing procedures, quality attributes, quality levels and acceptance (or rejection) criteria. They may also include payment schedules, with both positive and negative price adjustments, that are directly related through quantitative models to changes in worth of the finished work, anticipated as a result of departure from the quality level defined as acceptable."

Name of Agency ______________________________

Address of Agency ______________________________

Person completing questionnaire:

Name ______________________________

Title ______________________________

Telephone Number ______________________________

1. Please note the specific attribute for which this part of the questionnaire is being completed (e.g., thickness, roughness, friction, etc.) Please use a separate set of forms for each attribute. ______________________________

2. Is the above attribute measured as part of the contractor's quality control, or as part of your agency's acceptance (or rejection) procedure? ______________________________

3. What quality/acceptance level (or range) is specified for this attribute? If codified in your specifications or in published operating procedures, please enclose a copy.

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Name of Agency ______________________________

4. What sampling plan and testing method is used to assess this attribute? If there are written procedures, please enclose a copy (only cite AASHTO, ASTM, etc. procedures).

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5. What are the acceptance (or rejection) criteria for this attribute (for example, is there a certain proportion of samples which must meet, or be within specified limits of, the quality/acceptance level or range specified in Question 3)? If they are written, please enclose a copy.

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6. Describe the quantitative relationship (model) between the measured attribute and performance of the finished work. Please enclose any documentation (reports, memoranda, data, etc.) that support the relationship. ______________________________

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7. Is there an incentive/disincentive payment schedule for this attribute? If yes, please enclose a copy with an explanation of how it is applied. ______________________________

8. Is there a quantitative basis for the incentive/disincentive schedule? If yes, please enclose any documentation (reports, memoranda, data, etc.) that support the relationship between the quality levels obtained and the worth of the finished work. ______________________________

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QUESTIONNAIRE

NCHRP Project 20-5, Topic 23-05
"Performance-Related Specifications"

PORTLAND CEMENT CONCRETE AND CONCRETE MATERIALS

"Performance-related specifications (PRS) in the highway industry are specifications for materials and elements of construction that have been demonstrated to correlate significantly with performance of the finished work. They are based on quantified relationships between attributes measured at the time of construction (through either process control or acceptance testing) and performance. They include sampling and testing procedures, quality attributes, quality levels and acceptance (or rejection) criteria. They may also include payment schedules, with both positive and negative price adjustments, that are directly related through quantitative models to changes in worth of the finished work, anticipated as a result of departure from the quality level defined as acceptable."

Name of Agency ______________________________

Address of Agency ______________________________

Person completing questionnaire:

Name ______________________________

Title ______________________________

Telephone Number ______________________________

1. Please note the specific attribute for which this part of the questionnaire is being completed (e.g., strength, air content, cement content, etc.). Please use a separate set of forms for each attribute. ______________________________

2. Is the above attribute measured as part of the contractor's quality control, or as part of your agency's acceptance (or rejection) procedure? ______________________________

3. What quality/acceptance level (or range) is specified for this attribute? If codified in your specifications or in published operating procedures, please enclose a copy.
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Name of Agency ______________________________

4. What sampling plan and testing method is used to assess this attribute? If there are written procedures, please enclose a copy (only cite AASHTO, ASTM, etc. procedures).
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5. What are the acceptance (or rejection) criteria for this attribute (for example, is there a certain proportion of samples which must meet, or be within specified limits of, the quality/acceptance level or range specified in Question 3)? If they are written, please enclose a copy.
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6. Describe the quantitative relationship (model) between the measured attribute and performance of the finished work. Please enclose any documentation (reports, memoranda, data, etc.) that support the relationship. ______________________________
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7. Is there an incentive/disincentive payment schedule for this attribute? If yes, please enclose a copy with an explanation of how it is applied. ______________________________

8. Is there a quantitative basis for the incentive/disincentive schedule? If yes, please enclose any documentation (reports, memoranda, data, etc.) that support the relationship between the quality levels obtained and the worth of the finished work. ______________________________

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QUESTIONNAIRE

NCHRP Project 20-5, Topic 23-05
"Performance-Related Specifications"

ASPHALT CONCRETE AND OTHER ASPHALT PAVING MATERIALS

"Performance-related specifications (PRS) in the highway industry are specifications for materials and elements of construction that have been demonstrated to correlate significantly with performance of the finished work. They are based on quantified relationships between attributes measured at the time of construction (through either process control or acceptance testing) and performance. They include sampling and testing procedures, quality attributes, quality levels and acceptance (or rejection) criteria. They may also include payment schedules, with both positive and negative price adjustments, that are directly related through quantitative models to changes in worth of the finished work, anticipated as a result of departure from the quality level defined as acceptable."

Name of Agency ____________________

Address of Agency ____________________

Person completing questionnaire:

Name ____________________

Title ____________________

Telephone Number ____________________

1. Please note the specific paving material and attribute for which this part of the questionnaire is being completed (e.g., AC/void content). Please use a separate set of forms for each material/attribute combination. ____________________

2. Is the above attribute measured as part of the contractor's quality control, or as part of your agency's acceptance (or rejection) procedure? ____________________

3. What quality/acceptance level (or range) is specified for this attribute? If codified in your specifications or in published operating procedures, please enclose a copy.

Name of Agency ____________________

4. What sampling plan and testing method is used to assess this attribute? If there are written procedures, please enclose a copy (only cite AASHTO, ASTM, etc. procedures).

5. What are the acceptance (or rejection) criteria for this attribute (for example, is there a certain proportion of samples which must meet, or be within specified limits of, the quality/acceptance level or range specified in Question 3)? If they are written, please enclose a copy.

6. Describe the quantitative relationship (model) between the measured attribute and performance of the finished work. Please enclose any documentation (reports, memoranda, data, etc.) that support the relationship. ____________________

7. Is there an incentive/disincentive payment schedule for this attribute? If yes, please enclose a copy with an explanation of how it is applied. ____________________

8. Is there a quantitative basis for the incentive/disincentive schedule? If yes, please enclose any documentation (reports, memoranda, data, etc.) that support the relationship between the quality levels obtained and the worth of the finished work. ____________________

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QUESTIONNAIRE

NCHRP Project 20-5, Topic 23-05
"Performance-Related Specifications"

ELEMENTS OF CONCRETE, STEEL OR TIMBER STRUCTURES
AND STRUCTURAL MATERIALS OTHER THAN CONCRETE

"Performance-related specifications (PRS) in the highway industry are specifications for materials and elements of construction that have been demonstrated to correlate significantly with performance of the finished work. They are based on quantified relationships between attributes measured at the time of construction (through either process control or acceptance testing) and performance. They include sampling and testing procedures, quality attributes, quality levels and acceptance (or rejection) criteria. They may also include payment schedules, with both positive and negative price adjustments, that are directly related through quantitative models to changes in worth of the finished work, anticipated as a result of departure from the quality level defined as acceptable."

Name of Agency ______________________

Address of Agency ______________________

Person completing questionnaire:

Name ______________________

Title ______________________

Telephone Number ______________________

1. Please note the structural element or material and the specific attribute for which this part of the questionnaire is being completed (e.g., bridge decks/concrete cover, steel/tensile strength, etc.). Please use a separate set of forms for each element/attribute combination. __________

2. Is the above attribute measured as part of the contractor's quality control, or as part of your agency's acceptance (or rejection) procedure? __________

3. What quality/acceptance level (or range) is specified for this attribute? If codified in your specifications or in published operating procedures, please enclose a copy.

Name of Agency ______________________

4. What sampling plan and testing method is used to assess this attribute? If there are written procedures, please enclose a copy (only cite AASHTO, ASTM, etc. procedures).

5. What are the acceptance (or rejection) criteria for this attribute (for example, is there a certain proportion of samples which must meet, or be within specified limits of, the quality/acceptance level or range specified in Question 3)? If they are written, please enclose a copy.

6. Describe the quantitative relationship (model) between the measured attribute and performance of the finished work. Please enclose any documentation (reports, memoranda, data, etc.) that support the relationship. __________

7. Is there an incentive/disincentive payment schedule for this attribute? If yes, please enclose a copy with an explanation of how it is applied. __________

8. Is there a quantitative basis for the incentive/disincentive schedule? If yes, please enclose any documentation (reports, memoranda, data, etc.) that support the relationship between the quality levels obtained and the worth of the finished work. __________

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QUESTIONNAIRE

NCHRP Project 20-5, Topic 23-05
"Performance-Related Specifications"

SOILS, SUBGRADES, SUBBASES AND BASES

"Performance-related specifications (PRS) in the highway industry are specifications for materials and elements of construction that have been demonstrated to correlate significantly with performance of the finished work. They are based on quantified relationships between attributes measured at the time of construction (through either process control or acceptance testing) and performance. They include sampling and testing procedures, quality attributes, quality levels and acceptance (or rejection) criteria. They may also include payment schedules, with both positive and negative price adjustments, that are directly related through quantitative models to changes in worth of the finished work, anticipated as a result of departure from the quality level defined as acceptable."

Name of Agency ______________________

Address of Agency ______________________

Person completing questionnaire:

Name ______________________

Title ______________________

Telephone Number ______________________

1. Please note the earth material and the specific attribute for which this part of the questionnaire is being completed (e.g., subbase/moisture content, base course/percent passing #200 sieve, etc.) Please use a separate set of forms for each material/attribute combination. ______________________

2. Is the above attribute measured as part of the contractor's quality control, or as part of your agency's acceptance (or rejection) procedure? ______________________

3. What quality/acceptance level (or range) is specified for this attribute? If codified in your specifications or in published operating procedures, please enclose a copy.

____

Name of Agency ______________________

4. What sampling plan and testing method is used to assess this attribute? If there are written procedures, please enclose a copy (only cite AASHTO, ASTM, etc. procedures).

____

5. What are the acceptance (or rejection) criteria for this attribute (for example, is there a certain proportion of samples which must meet, or be within specified limits of, the quality/acceptance level or range specified in Question 3)? If they are written, please enclose a copy.

____

6. Describe the quantitative relationship (model) between the measured attribute and performance of the finished work. Please enclose any documentation (reports, memoranda, data, etc.) that support the relationship. ______________________

7. Is there an incentive/disincentive payment schedule for this attribute? If yes, please enclose a copy with an explanation of how it is applied. ______________________

8. Is there a quantitative basis for the incentive/disincentive schedule? If yes, please enclose any documentation (reports, memoranda, data, etc.) that support the relationship between the quality levels obtained and the worth of the finished work. ______________________

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QUESTIONNAIRE

NCHRP Project 20-5, Topic 23-05
"Performance-Related Specifications"

DRAINAGE, GEOSYNTHETICS, TRAFFIC CONTROL DEVICES, PAINTS AND COATINGS, HIGHWAY APPURTENANCES AND OTHER ELEMENTS

"Performance-related specifications (PRS) in the highway industry are specifications for materials and elements of construction that have been demonstrated to correlate significantly with performance of the finished work. They are based on quantified relationships between attributes measured at the time of construction (through either process control or acceptance testing) and performance. They include sampling and testing procedures, quality attributes, quality levels and acceptance (or rejection) criteria. They may also include payment schedules, with both positive and negative price adjustments, that are directly related through quantitative models to changes in worth of the finished work, anticipated as a result of departure from the quality level defined as acceptable."

Name of Agency

Address of Agency

Person completing questionnaire:

Name

Title

Telephone Number

1. Please note the element and the specific attribute for which this part of the questionnaire is being completed. Please use a separate set of forms for each element/attribute combination.

2. Is the above attribute measured as part of the contractor's quality control, or as part of your agency's acceptance (or rejection) procedure?

3. What quality/acceptance level (or range) is specified for this attribute? If codified in your specifications or in published operating procedures, please enclose a copy.

Name of Agency

4. What sampling plan and testing method is used to assess this attribute? If there are written procedures, please enclose a copy (only cite AASHTO, ASTM, etc. procedures).

5. What are the acceptance (or rejection) criteria for this attribute (for example, is there a certain proportion of samples which must meet, or be within specified limits of, the quality/acceptance level or range specified in Question 3)? If they are written, please enclose a copy.

6. Describe the quantitative relationship (model) between the measured attribute and performance of the finished work. Please enclose any documentation (reports, memoranda, data, etc.) that support the relationship.

7. Is there an incentive/disincentive payment schedule for this attribute? If yes, please enclose a copy with an explanation of how it is applied.

8. Is there a quantitative basis for the incentive/disincentive schedule? If yes, please enclose any documentation (reports, memoranda, data, etc.) that support the relationship between the quality levels obtained and the worth of the finished work.

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The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Harold Liebowitz is president of the National Academy of Engineering.

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Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

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