NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT **17**

DEVELOPMENT OF GUIDELINES FOR PRACTICAL AND REALISTIC CONSTRUCTION SPECIFICATIONS

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RALEIGH, NORTH CAROLINA

RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY OFFICIALS IN COOPERATION WITH THE BUREAU OF PUBLIC ROADS

SUBJECT CLASSIFICATION:
CONSTRUCTION

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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

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

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

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

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

This report is one of a series of reports issued from a continuing research program conducted under a three-way agreement entered into in June 1962 by and among the National Academy of Sciences-National Research Council, the American Association of State Highway Officials, and the U. S. Bureau of Public Roads. Individual fiscal agreements are executed annually by the Academy-Research Council, the Bureau of Public Roads, and participating state highway departments, members of the American Association of State Highway Officials.

This report was prepared by the contracting research agency. It has been reviewed by the appropriate Advisory Panel for clarity, documentation, and fulfillment of the contract. It has been accepted by the Highway Research Board and published in the interest of an effectual dissemination of findings and their application in the formulation of policies, procedures, and practices in the subject problem area.

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FOREWORD

By Staff

Highway Research Board

This report will be of interest to highway engineers and contractors because it specifically concerns the definition of work and materials, the basis for acceptance or rejection of these, and a philosophy for modernizing the preparation of construction specifications. Although the study was conducted with the highway transportation industry principally in mind, other disciplines will find this useful because of the mutual interests in materials and methods common to a variety of construction. The philosophy postulates that practical and realistic specifications will result only when recognition is given to the intrinsic variability in workmanship and materials under even the most ideal conditions and when specifications are designed to account for the variability unique to particular circumstances. Many existing specifications do not meet these criteria and are therefore not of sufficient scope to bring about a realistic balance between owner and contractor interests such that maximum economy and performance will be characteristics of contruction and utility of the end product. This research report surveys current specifications and develops guidelines for designing practical and realistic construction specifications with due consideration being given to purpose, format, language, objectivity, comprehensiveness in scope and design, and application to the fullest extent of such concepts as value engineering, statistical analysis, and the theory of inherent risks associated with making decisions based on acceptance samples. Although the study was not intended to account for all facets of a complete highway specification, it is comprehensive to the point of providing a significant base from which further developments may originate.

The dynamic evolution of science and technology has been a driving force behind a steadily increasing challenge to engineering proficiency in many areas. Insofar as the highway transportation field is concerned, an area of major significance in which evolution has been described as something less than dynamic is that concerned with the development of practical and realistic construction specifications. The question frequently arises as to whether or not the existing specifications are adequate for the many accomplishments for which they are intended, in terms of both present and long-range applications. The answer is in the negative in many cases, and it is held that the deficiency becomes more prominent with the continuing advancement of technology, even though frequent updatings have occurred. The basic cause is attributed to the need for a universally accepted philosophy for the preparation of specifications—one which acknowledges and places in proper perspective the variations in workmanship and materials which cannot be avoided. It is proposed that these variations can be adequately provided for by the adoption of scientific techniques successfully used in other fields. Specifications thus prepared would tremendously challenge the experience and versatility of the writer, for it would be necessary to thoroughly comprehend the facets of each project so that the specifications could be designed to meet specific needs rather than consisting of a compilation of more-or-less standardized terminology. It has been stated that this practice results in shortcomings such as ambiguity and conflict. Specifications properly designed and implemented could have impact on socioeconomic benefits because the requirements of the design engineer could be explicitly stated to insure support of the design criterion; economy could accrue from the contractor's complete knowledge of the conditions on which he is bidding and the latitude of his operation in providing the end product; and the owner and user could realize improved performance of the end product due to having been protected from inferior workmanship and materials.

This research report contains the results of the Miller-Warden Associates' efforts directed to the provision of guidelines for preparing designed construction specifications which are practical and realistic. Specifically, the reseach consisted of first reviewing the generic considerations in the broad field of highway materials and construction specifications and then placing particular emphasis on (a) surface smoothness requirements, (b) thickness requirements, and (c) aggregate gradation requirements. Questionnaires and interviews brought to light information that engineers will find of considerable interest concerning present practices throughout the country. Attempts have been made to present new points of view on subjects in controversy. New approaches to problems have been hypothesized and supported by citing practical examples which illustrate the utility possible with an appropriate blend of theoretical engineering concepts, engineering experience, and statistical concepts. In this latter regard, the research agency had previously conducted research concerned with the application of statistics in highway acceptance specifications. This provided a fund of knowledge for extension in the current research and led to a comprehensive outline of the relationship of statistical methods to many phases of the development and enforcement of specifications. A glossary is included which will materially aid the individual being introduced for the first time to these concepts. The report also contains a discussion of the ASTM work in regard to application of statistical techniques and the development of precision statements, and guides are suggested for implementing cooperative testing for development of test methods. Conclusions are drawn concerning the status quo of existing specifications and further work necessary to bring these to the desired stage of development. Ideally, this will provide for continued and complete utilization of the applicable features of developing science and technology.

This is a final report on one year of research. Considerable effort is necessary in completely overhauling specifications in general and is beyond the intended scope of this project. It is, however, difficult to approach limited aspects of the total problem in subject matter of this type without at the same time developing features which are universally applicable. In conducting this research Miller-Warden Associates have taken a significant forward step toward solving both the limited and the broad aspects of this controversial problem, and it is hoped that the research will evoke the continued response necessary to a total solution.

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ACKNOWLEDGMENTS

The roster of the many persons and agencies involved in the conduct of the project and the preparation of this report is too extensive to mention each individually. Nevertheless, the assistance and cooperation of these contributors is gratefully acknowledged.

Special mention is due the following for their participation in the work:

As principal authors of the report—Schuyler B. Hudson, Warren B. Warden, and H. Fred Waller, Jr., respectively chief engineer, proprietor, and staff engineer, Miller-Warden Associates.

For invaluable assistance in formulating statistical concepts—Dr. Arnold Grandage, Professor of Statistics, North Carolina State University; and Dr. Norbert L. Enrick, Associate Professor of Business Administration, University of Virginia.

For editorial contributions and guidance—Archibald De Groot, formerly Director, School of Civil Engineering, International Correspondence Schools; and Dr. E. P. Dandridge, Associate Professor of English, North Carolina State University.

For the summary of ASTM D-4 test methods containing precision statements—L. D. Hicks, formerly Soils Engineer, North Carolina State Highway Department.

Special thanks also are extended to the Portland Cement Association for permission to use its copyrighted material on state highway department concrete pavement aggregate standards as contained in Appendix B.

DEVELOPMENT OF GUIDELINES FOR PRACTICAL AND REALISTIC CONSTRUCTION SPECIFICATIONS

SUMMARY

A highway construction specification is a means to an end. Its mission is to provide the traveling public with an adequate and economical pavement on which vehicles can move easily and safely from point to point. A practical specification is one that is designed to insure adequate performance at minimum cost. A realistic specification is one that recognizes that there are variations in materials and construction which are inevitable and characteristic of the best construction possible today. The purpose of this report is to present guidelines for the preparation of a complete specification meeting these requirements.

Parts of specifications should be arranged in logical order in general conformance with Bureau of Public Roads Policy and Procedure Memoranda 40-3.1, 40-3.1(1) and 40-3.2. Full decimal systems of numbering paragraphs should be used. Specifications should be of the "end result," "materials and methods," or "restricted performance" types, depending on the conditions of acceptance. Only directions should be given, requirements should not be repeated, and the basis of acceptance or rejection should be clearly stated. Each statement should mean one thing only. The limits of the engineer's authority should be clearly defined. The numerical limits and tolerances established must be economically attainable, and acceptance plans should be designed, by use of the given methods, to have a known risk of accepting material or construction not within these limits. Risks should be based on criticality of requirements for significant characteristics.

To achieve maximum economy, specification requirements must be geared to policy and cost considerations. To insure practicality, the given administrative and engineering guidelines should be consulted.

Gradation requirements for aggregates and mixtures of aggregates with other materials should be based on the control of size and quantity of voids, as determined by the given theoretical method, modified to include variations to be expected under normal construction conditions. Pavement smoothness requirements should be based on both the deviations from a straightedge, and their span, in accordance with slope-variance criteria developed at the AASHO Road Test. Tolerances and penalties for deficiency of thickness of pavement courses should be related to reduction in service life in terms of daily traffic. Theoretical loss of performance is twice the cost, on a fractional-inch basis, for flexible pavements and five times the cost for rigid pavements.

In addition to being technically competent, accurate and complete, specifications must be written as clearly and concisely as possible. The text should employ simple language, with contemporary usage and grammar, as suggested in the given editorial guidelines.

CHAPTER ONE

INTRODUCTION *

In developing guidelines in accordance with the research problem statement, the research agency has taken cognizance of the many facets involved as well as the specific objectives listed. The whole area pertaining to highway specifications has been explored, first by means of an intensive literature search, and then by special studies, questionnaires and interviews.

Within the limits of the funds available it has not been possible to develop all of the facets completely. However, an attempt has been made to present new points of view on controversial subjects and to exemplify new approaches with practical problems. Basically the role of the research agency has been one of selection, interpretation, and presentation of those concepts deemed most appropriate for the up-to-date specifications writer. Among other items, this has required a careful review of some 400 literature references, analysis of a number of questionnaires and personal interviews, and a concentrated study of certain theoretical, mathematical, and statistical relationships. For ease of reference the items of literature consulted were classified into several categories from which the major sections of the report were developed.

An effort has been made to bring together the theoretical concepts, engineering experience, and statistical considerations necessary for a complete, realistic and practical specification. A discussion is provided on the essential generic considerations which apply to any complete highway specifications are included. It is believed that this section will plored and those concepts which appeared to be most appropriate for initial application to construction problems have been translated into highway terms and illustrated by examples. There has been no attempt to write a texbook, but rather to simplify some highly complex and difficult concepts so as to make them understandable and usable by the average highway engineer. Several types of selected acceptance plans are presented and other statistical methods associated with the development and enforcement of specifications are included. It is believed that this section will be one of the most valuable to the specification writer.

A questionnaire-type survey was conducted among 17 state highway departments and public agencies to determine their specification requirements in the particular areas cited in the project statement. In addition, a number of equipment manufacturers, contractors, materials suppliers and trade association representatives were contacted for a determination of how their particular area of operations fitted into the specifications picture. Data obtained from these sources were essential to the development of policy and cost considerations as well as general engineering guidelines. The report is rounded out with editorial and grammatical guidelines.

Although the broad field of highway materials and construction has been reviewed, specific emphasis has been directed toward those items specifically named in the project statement; namely, (1) surface smoothness requirements; (2) thickness requirements; and (3) aggregate gradation requirements. Likewise, examples used to illustrate concepts presented have been selected to best suit conditions of the project statement. However, the basic principles and guidelines are easily adaptable to many other materials and items of construction.

The ideas and concepts contained in these guidelines should suggest to the specification writer ways of developing construction specification requirements that will be both practical and realistic.

RESEARCH APPROACH

Planning

Initial analysis of the requirements outlined by the project statement indicated that, inasmuch as no experimental work was involved, a great deal of literature would have to be reviewed to define *all* elements of specifications, including current practice and appropriate mathematical concepts. Accordingly, the various areas pertinent to the project objectives were defined approximately and the results of a preliminary search of the contents of the information storage and retrieval system operated by the research agency were used to categorize the types of literature to be included in a comprehensive search.

Literature Search

The comprehensive literature search, performed by use of the facilities of North Carolina State College, located approximately 400 items which appeared to be of interest. Each of these was scanned and classified for detailed study in connection with the preparation of the different parts of the report.

Survey of ASTM Statistical Tolerances

As a former leader in the area of developing precision statements for ASTM test methods, Dr. A. B. Brown was invited to participate in this phase of the work. His contribution, included in Chapter Ten, shows a summary of the status of all ASTM D-4 test methods with respect to precision statements.

Questionnaires

To determine specification requirements regarding smoothness and thickness currently being enforced, a sampling

*The material presented here is intended solely for the information and assistance of those persons engaged in preparing construction specifications. This report is not intended as a manual and the suggestions put forward by the research agency are to be considered as guidelines only.

consisting of 17 public agencies was selected. These agencies are not identified by name in the various tables, charts, and other references in this report, but include California, Colorado, the U.S. Corps of Engineers, the Federal Aviation Agency, Illinois, Michigan, Minnesota, Mississippi, Montana, New Jersey, New Mexico, New York, Ohio, Oklahoma, Pennsylvania, Texas, and Wisconsin. This sampling is believed to represent a typical cross section of the highway industry.

Specification Wording and Format

Initial studies and literature reviewed indicated that format and editorial considerations played an important part in maximizing usability of specifications. Accordingly, Archibald DeGroot, formerly Director, School of Civil Engineering, International Correspondence Schools, was requested to prepare material covering this area. The results of his work have been incorporated in Chapters Two and Eight, which have been amplified and edited by Dr. E. P. Dandridge, Jr., Associate Professor of English and Director of Composition Program, North Carolina State College.

Statistical Techniques

The research agency had previously prepared a report for the Bureau of Public Roads entitled "A Plan for Expediting the Use of Statistical Concepts in Highway Acceptance Specifications." Knowledge gained during the preparation of this report was used as a starting point for developing statistical guidelines for the current project. A comprehensive outline of the relationship of statistical methods to all phases of the development and enforcement of specifications was prepared by Dr. Arnold Grandage, Professor of Statistics, North Carolina State College. Using this as a working basis, a variety of statistical methods was examined, and scrutinized for adaptability to the project objectives. From a large quantity of material assembled from various sources, those methods which appeared to be most appropriate, in view of space limitations, were selected. The selected methods and acceptance plans were adapted to highway problems and illustrated by practical examples. This material appears in Chapter Three.

Process Control

The customary division of responsibility between contractors, producers, and public agencies was studied. It was apparent that more practical specifications could be developed if process control could be divorced from acceptance testing. However, time and available funds did not permit a detailed presentation of the uses of process control methods by contractors and producers.

Cost-Benefit and Cost-Tolerance Study

To obtain relevant cost factors, contractors, equipment manufacturers, and representatives of trade associations were interviewed. Specific questions concerning relationships between specification requirements and costs were standardized by the use of a questionnaire (interview outline). Through the cooperation of the National Limestone Institute, questionnaires concerning the problems of aggregate producers were circulated to its 600 members. The findings from these questionnaires and interviews are summarized in Chapter Five.

Special Studies

In addition to the study and adaptation of statistical methods, special mathematical studies were conducted in other areas. These included the relationship of thickness of pavement courses to performance, the relationship of AASHO slope-variance criteria to straightedge measurements, and the relationship of aggregate gradation to both the significant characteristics of construction and the characteristics of mixtures of aggregate with other materials. It was found that, for optimum application of statistical techniques and acceptance plans, gradations should be characterized as a single number. Existing indices were found appropriate for certain applications but not for others. Preliminary studies were made to determine the suitability of the Hudson $\bar{A}$ as a significant index of the effects of variations of aggregate gradation in applications where surface area of aggregate is of prime importance.

Glossary

From the literature review it was apparent that many relatively new terms and statistical symbols were not defined uniformly. To avoid misunderstanding, the most important of these are given in small capital letters where they first appear in the text and are collected in Appendix A for ready reference. No attempt has been made to devise precise definitions, but the meanings are explained in the sense that they were used in this report.

CHAPTER TWO

GENERIC CONSIDERATIONS

THE RATIONALE OF PRACTICAL AND REALISTIC SPECIFICATIONS

A highway specification is a means to an end. Its mission is to provide the traveling public with an adequate and economical pavement on which vehicles can move easily and safely from point to point. On this premise, the cost of each specification requirement must be justified with respect to the functional quality of the highway.

A practical specification is one that is designed to insure the highest overall value of the resulting construction. To define value meaningfully it must be divided into three parts, as follows:

1. USE VALUE,* based on both immediate serviceability and safety and on longevity in terms of years of service before replacement and the maintenance required during that period.
2. COST VALUE, based on the dollar investment and on the depletion of natural resources such as certain types of locally available aggregates.
3. AESTHETIC VALUE, based on intangible benefits to the traveling public.

To realize the highest overall value, the desired use value should be defined precisely so that this value can be obtained by incorporating economical materials into the construction by the most efficient methods. The additional cost to the taxpayer of aesthetic values should then be weighed against benefits to the occupants of high-speed vehicles, rather than to the design or construction engineer.

A realistic specification is one that recognizes that there is a cost associated with every specified limit and that the characteristics of all materials, products, and construction are inherently variable. It is certainly unrealistic to set an unnecessarily restrictive limit and then require that all measurements and observations conform to it precisely.

FUNCTIONS OF SPECIFICATIONS

Purpose

The purpose of a highway specification is to define explicitly each item which the contractor agrees to construct or supply for a stated price. This definition usually includes a description of the essential characteristics of the item and establishes requirements for attributes and measurable properties. In cases where the essential properties are unknown or immeasurable, it is necessary to define the desired result by comparison with satisfactory materials or construction or by description of the method of accomplishment.

In any case, the definition must insure that the use value of the item will be neither too high nor too low, and that the balance of quality of the composite construction is maintained.

*Throughout this report key words are printed in small capital letters at their first appearance. Definitions of these words as used in this report are given in Appendix A, as are the definitions of the various symbols used.

Uses

The uses of highway specifications are to:

1. Provide the contractor a definite basis for preparing his bid.
2. Inform all representatives of the buyer as to what the contractor is obligated to do.
3. Describe required procedures.
4. State the basis for acceptance or rejection of the completed work, including sampling and testing methods.
5. Provide rules for decision on matters referred to the engineer.

In conjunction with the contract and the plans, the specifications are contract documents. Therefore, many existing highway specifications function as a means of setting forth legal and business requirements. The interpretation of some of these articles is not within the province of the engineer's or contractor's representatives on the job. It would be more practical to cover such requirements in the advertisement and instructions to bidders, and in the contract itself.

Practical specifications can best fulfill their primary functions if they contain only those matters pertaining to the actual construction of the highway.

PARTS OF PRACTICAL AND REALISTIC SPECIFICATIONS

Divisions

A practical highway construction specification must be as brief as is consistent with clarity. Also, repeating the same requirement in different places in the specification can lead to confusion and possibly establish a basis for a claim by the contractor. To accomplish these objectives the specifications are divided into parts, called *divisions.* A suggested arrangement of these divisions is contained in Bureau of Public Roads Policy and Procedure Memoranda 40-3.1, 40-3.1(1), and 40-3.2. The format outlined in these standards is intended as a guide and reasonable, minor, departures from this arrangement may be considered for approval by the Bureau. For example, inclusion of a separate subdivision for equipment has received Bureau approval and inclusion of a separate materials division is optional.

DIVISION I—GENERAL REQUIREMENTS

This division should cover all matters which relate to the construction work as a whole, except that, as previously stated, legal and business requirements should be given only in the contract, which is a stronger legal document. Any requirements, phrases, or wording, that would otherwise require repetition in the other divisions, should be covered by articles or paragraphs in this division.

Great care must be taken in establishing the requirements of this division, because they will affect the cost value of the project more than will requirements in other divisions.

DIVISION II—CONSTRUCTION DETAILS

Details of construction of the various items of work should be described by the articles in this division, roughly in sequence of construction, as follows:

Part 1. Earthwork.
Part 2. Base Courses.
Part 3. Surface Courses.
Part 4. Structures.
Part 5. Incidentals.

DIVISION III—PRODUCT AND MATERIAL REQUIREMENTS

This division should cover products manufactured by combining materials at or near the job site. Examples are portland cement concrete, bituminous concrete, or plant-mixed stabilized base. Requirements for component materials, such as cement, asphalt, or reinforcing steel, should also be included in this division.

DIVISION IV—EQUIPMENT REQUIREMENTS

Requirements for items of equipment referred to in other divisions should be detailed in this division.

DIVISION V—DEFINITIONS

Because a practical specification should have a much more extensive list of definitions than most existing specifications, a separate division should be set aside for this purpose. This division should have two parts:

(a) Definition of words and terms.
(b) Abbreviations (ASA) used in the specification.

Parts

Each division should be divided into parts within which are grouped items of like nature. Examples of arrangement of subdivisions are given in the Bureau Memoranda.

Subsections

Each part should be divided into subsections, each dealing with a particular item of construction, material, or equipment.

Articles

Each subsection should be divided into articles which define the phases of the work. For example:

236 Base Course—Penetration Macadam

Article	236-01	Description
Article	236-02	Materials
Article	236-03	Construction Requirements
Article	236-04	Methods of Measurement
Article	236-05	Basis of Payment

Paragraphs

Each article should be divided into paragraphs, each of which should deal with one, and only one, material or specific operation.

Subparagraphs

For ease in reading and understanding, long paragraphs should be divided into shorter paragraphs, each of which should be set up as a subparagraph.

DESIGNATION OF PARTS OF SPECIFICATIONS

Titling System

In assigning titles to parts, subsections and articles, the generic name should be given first, followed by the key word for alphabetical indexing; for example, 236 Base Course—Penetration Macadam.

Indexing Numbering System

The full decimal numbering system should be used. The features of this system are:

1. The 100 numbers run consecutively from the beginning to the end of the specification book.
2. A block of 100 numbers is assigned to each division. For example, numbers 200 to 299, inclusive, may be assigned to Division 2.
3. Part numbers are formed by adding multiples of 10 to the 100 number of the division; for example, 230 Base Courses.
4. Subsections are numbered by adding digits to the part number; for example, 236 Base Course—Penetration Macadam.
5. Article numbers are formed by placing a hyphen after the subsection number and numbering the articles consecutively from 01 to 99; for example, 236-02 Materials.
6. Paragraph numbers are formed by placing a decimal point after the article number and numbering the paragraphs consecutively from 01 to 99; for example, 236-02.01 Bituminous Material.
7. Subparagraph numbers are formed by placing a decimal point after the paragraph number and numbering the subparagraphs consecutively from 01 to 99; for example, 236-02.01.02 Preparation.
8. An exception to the consecutive numbering of paragraphs occurs when an article does not contain an item which appears in similar articles. In this case, the other paragraphs should be numbered the same as if the missing paragraph were present. For example, if Article 236 is silent as to materials, the article number 236-02 would be followed by "Materials (not specified)." Construction requirements, which would normally follow, would still be numbered 236-03. In other words, paragraphs having the same titles should have the same two numbers following the hyphen throughout the specification book.

TYPES OF SPECIFICATIONS

Construction specifications may be classified as being of three general types, as follows:

1. Performance or "end result" specifications.
2. Materials and methods specifications.
3. Restricted performance specifications.

Performance or "End Result" Specifications

With this type of specification the contractor or producer takes the entire responsibility for supplying an item of construction, or a product, that meets the specification requirements. The specification places no restrictions on the materials to be used or the methods of incorporating them into the completed work or product. This type of specification is suitable for use only if (a) the essential characteristics of the end result are known and are measurable, (b) a quick method of test is available, and (c) deficiencies can be corrected by reprocessing.

The last is a practical rather than a theoretical condition. The principal objection to this type of specification is that a large quantity of construction or material in place may be found to be defective and no correction is possible. In theory the contractor can be forced to remove and replace the defective item, but in practice this may be unrealistic because of various pressures and exigencies. The situation is embarrassing to both the contractor and the engineer. There is no satisfactory solution and often the substandard work is accepted, with or without a token penalty. For this reason, performance specifications are most suitable for such items as the construction of embankment. Where a definite density can be specified, the density of a compacted lift can be readily measured. No restrictions need be placed on the contractor as to moisture content or equipment, because if the required density is not obtained it is not impractical to recompact the material.

Materials and Methods Specifications

This type of specification is customarily used for most items of highway construction and must be used when (a) the essential characteristics of the completed work are not known or are not measurable, (b) no quick method of acceptance test is available, or (c) it is impractical to remove and replace defective work.

The contractor or producer is directed to combine specified materials in definite proportions, using approved equipment, or to place a specified material or product in a specified way. Normally the operations must at all times be under the surveillance of inspectors who represent the engineer. Although some specifications hopefully state that the contractor or producer is responsible for the end result, this statement is not usually legally enforceable if the materials and methods requirements have been met.

Probably the best example of this type of specification is that for the production of portland cement concrete. The component materials—cement, aggregates, water, and air-entraining agents—must be pretested and approved. These materials must be combined in specified proportions, mixed in a certain way. The mixture must meet further requirements as to consistency and air content.

In this case it is necessary to use the materials and methods specification because quick tests for compressive strength have not been adopted, and because there is no definitive test for the second essential characteristic of concrete, which is durability.

The weakness of the materials and methods specification is that it may not always produce the desired end result. It is based on past experience, and if variables unknown to the specification writer change under new conditions, the end result may not be satisfactory.

A common example is subbase material that, although constructed of the specified aggregate, meeting all requirements as to gradation and Atterberg limits, and compacted to the specified density, may not provide a stable working platform for subsequent construction.

In this situation the engineer is in an awkward position, because any effort to force the contractor to take remedial measures may result in a claim at the end of the job.

Restricted Performance Specifications

Essentially a combination of the previous two types, this is probably the most practical and realistic type of specification. The desired end result is stated and the contractor or producer is allowed the fullest possible latitude in obtaining it. However, certain restrictions are included so as to insure at least a minimum level of quality and to prevent the construction or production of a large quantity of work before defects are discovered. In the example under "Performance Specifications" it would be advisable to limit the moisture content of certain types of materials so that an elastic condition would not be created in the embankment. It also would be necessary to stipulate that the lifts be limited in thickness and that each lift be tested for density and found acceptable before another lift was placed on it.

In the first example under "Materials and Methods Specifications" a concrete producer operating under a quality control system might be allowed to supply concrete under a specification which required only that the concrete attain a specified 28-day strength, within statistical tolerances. Other requirements might be that the concrete contain at least a minimum quantity of cement and when delivered be workable and be within specified limits for slump, wet density, and air content.

In the second example the contractor might be required to construct a stable subbase capable of supporting all necessary construction equipment without rutting. Additional requirements of the material in place might be a limit on the minus No. 200 material, and limits on the liquid limit and plastic limit of the minus No. 40 material.

It should be noted that in most cases restrictions on a performance specification can be written in such a way that the contractor is not entirely relieved of responsibility, but minimum acceptable quality is insured and the engineer has some protection against being confronted with an impossible situation.

REQUIREMENTS FOR PRACTICAL AND REALISTIC SPECIFICATIONS

Basic Requirements

COMPLETENESS

Except for information set forth on the plans or standard drawings, or contained in standard specifications or test methods referred to by number and date, the specifications must be complete. Each article should describe its subject matter unequivocally. If the specification is silent as to a requirement, the contractor cannot be expected to meet that requirement without additional payment. However, it must be realized that it is not practical to cover all unimportant details or to provide for every possible contingency.

TECHNICAL ADEQUACY

It is the specification writer's responsibility to include in each article the really essential characteristics of the subject matter, along with realistic numerical limits if such limits are required. He must make sure that requirements taken from other specifications are appropriate to the actual conditions covered by the specification he is writing. The fact that a specification has been in force for a number of years does not necessarily insure technical adequacy, because field practice may in the past have included conditions that resulted in adequate performance. A difference in these conditions may result in unsatisfactory work unless essential characteristics are spelled out in the specifications.

All requirements must be based on adequate reference information. Such references may consist of numerical or factual data exemplified by tables of values of a material characteristic necessary for design performance. Other references may be descriptive information, such as the best way to obtain completed construction which will meet serviceability requirements.

In all cases, the data and the descriptive information should be checked carefully to make sure that they are realistic. This means that data values should represent what can actually be expected in good construction under average job conditions. Basing requirements on what *might* be obtainable under special conditions leads to unnecessary construction costs, or to difficulties in enforcement.

ECONOMICALLY JUSTIFIABLE

As stated previously under "Rationale," the use value and aesthetic value of each requirement must be balanced against the cost value. Every requirement has some direct or indirect cost associated with it; and whenever specifications are written or revised each requirement should be scrutinized with respect to its essentiality and its effect on cost. Innocent appearing requirements may affect costs appreciably. For example, the specifications may require that a certain gradation of stone be used in combination with other aggregates to produce a bituminous paving mixture. This has no use value because the gradation of the combined aggregate is specified; but if the hot-plant operator has to haul the material a long distance because his local supplier is out of that particular size, the requirement is going to affect the cost value. Another size of aggregate, or blend of aggregates, could have been used to obtain the same result, and the savings in cost should be reflected in the bid price.

Another aspect of justification of requirements is the availability of local materials. In many areas the sources of good aggregates are rapidly becoming depleted. If these aggregates are wasted in the lower pavement courses where their quality is not required, the cost of construction will eventually rise due to the necessity of importing aggregates of like quality. This waste may occur because the specification writer and his immediate associates are too far separated from the field to be aware of the relationship between requirements and costs. True economy of construction comes from specifying only requirements appropriate to the need.

For this reason, meetings with contractors' groups and field engineers should be scheduled before specification revisions are finalized. Every specification item should be studied with a view to eliminating non-essential requirements and permitting the use of new materials, methods, and equipment. Any item that requires hand labor should be given particular scrutiny with a view to eliminating it or of changing the design so that machine equipment can be used. An example is a taper at the beginning of a turn-out from a highway. Here, hand-raking is both expensive and unsatisfactory. A square-ended deceleration lane can be built with a paving machine cheaply and quickly, and will have better riding qualities. Contractors, producers, and highway employees should be consulted and encouraged to volunteer cost-cutting ideas, and these suggestions should be given high-level consideration. This approach, which has resulted in millions of dollars of savings in industry and which has been called the greatest thing since mass production, is VALUE ENGINEERING.

ENFORCEABILITY

A contractor or producer cannot be expected to accomplish the impossible. The fact that contractors have been "living with" a requirement for a number of years does not necessarily mean that it is fully enforceable. It may be that "field tolerances" have been applied. For example, 98 percent of Marshall density might be required for a bituminous surface course. If obtaining this density resulted in overrolling and degradation of the aggregate, a conscientious inspector might protest the requirement and, on being given the "brush-off" by his superiors, proceed to apply a "field tolerance" and become selective in what tests were reported. This type of procedure produces construction of adequate quality, but creates an embarrassing situation when an investigation is made by parties not aware of the circumstances.

Any indication that there is difficulty in meeting specification requirements should receive immediate attention. All requirements must be realistic and represent what it is practical to obtain, and has been obtained, in construction of adequate quality.

FAIR AND JUST

The contractor's obligations and known risks should be clearly stated. A requirement should not be designed to "get something for nothing" from a contractor by concealing its intent. For example, if all-crushed aggregate is required in a bituminous pavement course, the specification should so state, rather than specifying such a high Marshall stability that it will be necessary to use all-crushed aggregate to obtain the required test values.

Also, a requirement should not be so written as to force the contractor to obtain material or equipment from a single source. Such "sleepers" may be hidden in model specifications volunteered by vendors of materials and equipment. All such model specifications should be carefully compared with those for competitive items before being included in materials or construction specifications.

GIVING DIRECTIONS ONLY

In writing specifications, include only information that is needed by the contractor in order to prepare his bid and to perform the work satisfactorily. Other information, such as a reason for the requirement or a suggestion for complying with the requirement, does not belong in specifications. If an additional statement is given in connection with a requirement, the person who uses the specifications may consider that statement to be a controlling part of the requirement. In other words, the presence of the additional explanation may obscure the clarity of the requirement itself. Instructions associated with the enforcement of specifications properly belong in a construction manual.

Admonitions characterized by the use of the word "should" are often the cause of controversy between the contractor and engineer. Specifications should state definitely what shall or shall not be done.

AVOIDING REPETITION OF REQUIREMENTS

Do not try to include in the specifications information that can be given better on the plans. Because a requirement should be covered only once, information that is given on the plans should not be included also in the specifications. In general, the plans should show all dimensions of parts of a structure, whereas the specifications show properties of materials and quality of workmanship.

Also, certain broad requirements are given best in Division I, which covers the general requirements. A single statement can then apply to a number of different kinds of work. If a certain requirement is covered by a provision in the general requirements, that requirement should not be repeated in Division II under construction details.

BASIS OF ACCEPTANCE OR REJECTION CLEARLY STATED

The only way to insure equitable and uniform enforcement of specification requirements is to spell out the acceptance procedure in detail. Otherwise, controversy may arise as the result of different procedures being applied on similar projects. Each article should state the point at which the material or construction item will be inspected or tested for acceptance. The characteristics or attributes that will be inspected or tested should be stated, as well as the number of samples that will be taken, the sampling plan, and the quantity of material or construction that will be represented by each sample or group of samples. The article should state definitely what action, practical of enforcement, will be taken if the material or construction is not found acceptable, and should also state what penalties will be applied if the material or construction is found to be *substantially* acceptable. For example, if a bituminous surface course was unacceptable, because of surface texture or smoothness, the action might be to require that the contractor remove and replace with the option of adding an additional inch of satisfactory course at his expense. If the course was satisfactory in all respects except a minor density deficiency, the contractor might be required to apply a fog seal, with sand cover, to insure the durability of the construction.

Legal Requirements

The principal legal requirement for a specification is that each statement be incapable of misinterpretation by meaning one thing and that only. All requirements should be clearly stated in words familiar to the contractor and the engineer. Legal phraseology, if necessary at all, should be confined to the contract, which will be interpreted by lawyers. Long compound sentences capable of more than one meaning will not be interpreted by a court in favor of the originator's intent, because it is the responsibility of the originator to make the meaning clear. Also, words of the correct meaning must be used. For example, in a recent case a court refused to issue an injunction against a producer who had erected a concrete plant in a municipality. The local ordinance specified that no "cement" plants be erected. The judge threw the case out with the comment that "cement is to concrete as flour is to cake." (See Chapter Nine, Editorial Guidelines)

When modifying performance specifications by restrictions or additional requirements, care must be taken that the legal responsibility of the contractor is not lessened thereby. Because the specification functions in part as a legal document, its requirements are always subject to review by a court or a board of arbitration. When new requirements are inserted in a specification, trouble may arise because of the tenet of past practice. The contractor may plead in court that the requirement did not apply on previous similar work in the area, and that when making up his bid he did not expect the requirement to be enforced on his project. For this reason, a clause should be inserted in the contract or general provisions stating that prior practice does not apply.

Special Requirements

AUTHORITY OF ENGINEER

Probably there is no phrase commonly used by specification writers that is so severely criticized by contractors as is "as directed by the engineer." Obviously, when the contractor is preparing his bid he has no way of knowing what the engineer is going to direct him to do, so must try to second guess the situation, then add a contingency item to his bid.

Although contractors may sometimes accuse specification writers of being either ignorant or lazy, it is often impossible for the specification writer to foresee every possible contingency, so some things must be left to the judgment of someone who can properly assess each situation when it arises. The engineer, because of his experience background and professional standing, is the one best qualified to make the decision as to what action should be taken.

However, the contractor should have some assurance that he will not be penalized because of whims or personality conflicts. The objectionable wording previously discussed can usually be rephrased to "in a manner approved by the engineer," which allows the contractor a choice of the method to be used.

BASIS FOR RULINGS BY THE ENGINEER

On any construction work, especially where specification requirements are arbitrary and unrealistic, there will be a certain percentage of the work that will not meet the requirements. It then becomes the duty of the engineer to determine if the work is "within reasonably close conformity" with the plans and specifications or if "reasonably acceptable work has been produced."

To give the contractor advance assurance that these vague terms will be interpreted fairly, the general provisions should contain a statement similar to the following:

> In all matters requiring a ruling by the engineer it will be understood that his decision will be his professional engineering judgment based on evidence. This evidence may take the form of,
>
> (a) Results of Physical and Chemical Tests
> The engineer will take into consideration the inherent variations of materials and processes and the risks associated with drawing inferences from small samples. He may, where practicable, require that sufficient additional tests be made to provide a statistically sound basis for his ruling.
>
> Samples shall be of such size and number as to be truly characteristic of the materials which they represent. Satisfactory evidence of proper and adequate process control will be acceptable in lieu of samples.
>
> (b) Customary Practice
> In cases where it is impractical to measure a characteristic of construction, or to make a sufficient number of tests, the engineer's ruling will be based on experience. This may be the engineer's personal experience with the use of materials or methods which have produced acceptable results, or the reported experience of other competent engineers.

ESSENTIAL CONTENT OF ARTICLES

The articles in Division II should include the following:

1. A general description of the item.
2. Mandatory requirements of the completed work, materials, and equipment.
3. Additional requirements, arranged in the order of the class of work to which they apply.
4. The LOT quantity, or units of the work, that will be tested for acceptance or rejection.
5. The basis for acceptance or rejection, including the stage of construction during which the lot will be sampled, the acceptance plan, the number of samples, the method(s) of testing samples, the desired result, and the allowable tolerances from the desired result.
6. The limiting value which must be met by 100 percent of the material or construction. This is the value that will be the basis for rejection of any units found to be nonconforming by additional sampling and testing.
7. The action that will be taken if the lot does not fully comply with the requirements, and that which will be taken if it substantially meets the requirements.
8. The units of measurement used for the basis of payment and the subdivisions of these units to be used in making measurements. The subdivisions can be indicated by the number of zeros standing for significant figures in the units of measurement.
9. The method of payment.

CLASSIFICATION OF WORK

Inasmuch as the specifications will apply to projects having a wide range of cost and importance, provision should be made to formally match the requirements to the job.

Obviously, a culvert on a tertiary road does not require such an extensive testing and inspection program as a major bridge on an Interstate Highway. The cost of inspection and testing should be weighed against the consequences of inferior serviceability.

One way to do this would be to arrange requirements in order of importance, such as (a) mandatory requirements for essential characteristics, (b) desirable requirements related to longevity, and (c) optional requirements related to aesthetics. Special provisions could then delete requirements not appropriate to the class of work.

SETTING REALISTIC TOLERANCES

Realistic tolerances should be established for all requirements having numerical limits. It must be accepted that all measurements on samples are not going to fall within customary limits because of the inherent variation of materials and processes. Also, a failing test on a single sample does not necessarily mean that the material or construction is unacceptable, but may indicate only that the sample was faulty.

Whenever practical, specification limits should be established by statistical methods that will take into account the inherent variation of the material or process, and the sampling and testing error. When arbitrary or engineering limits are used, provision should be made to allow for a small percentage of measurements to fall outside the specification limits without penalty (see Chapter Three).

CHAPTER THREE

USE OF STATISTICAL METHODS*

APPLICATION OF STATISTICAL METHODS

Purpose of Making Tests on Materials and Construction

During construction of a highway many tests are made for two purposes; first, to make sure that unsatisfactory material or construction is not incorporated into the work, and second, to provide a permanent record evidencing that full value has been received for the monies expended on behalf of the taxpayer. Engineering and testing consume a significant part of the total cost of highway construction and the basic problem is how to best spend the testing dollar in order to afford the greatest protection of quality.

Obviously, it is not practical to test all of the material or construction items incorporated into a highway. When the tests are destructive, it would be impossible. For example, if all reinforcing steel were tested to the breaking point there would be no steel left for use in construction. The only feasible method of estimating quality is to make tests on samples of material or units of construction.

Currently, these samples or units are often chosen so as to be representative; that is, to show average conditions. The result of this procedure is commonly called a REPRESENTATIVE SAMPLE in connection with highway construction. The choice of the material in the sample depends on the judgment of the sampler and the results of tests on such samples can be BIASED by his attitude at the time of sampling. Also, because representative samples may show only one aspect of a variable condition, they seldom give a true picture of overall quality.

For these reasons, the term representative sample, as used in connection with highway construction, is often misleading, and tests made on such samples do not accomplish the basic purposes of testing.

The New Approach to Sampling

In military and industry situations similar to those that exist in connection with highway construction, it has been found that it is more efficient to use a statistically derived acceptance sampling plan instead of attempting to select representative samples.

This approach involves the concept of lot-by-lot testing for the purpose of protection against acceptance of unsatisfactory materials or construction. A lot is any well-defined quantity of material or construction produced by essentially the same process. Examples are the number of square yards of stone base constructed in a day, or the number of cubic yards of concrete in a continuous placement. The lot is also the unit of material or construction which is accepted or rejected when an ACCEPTANCE PLAN is used to determine compliance with specifications. *The purpose of an acceptance plan is to provide the basis for making a decision as to whether to accept or reject a lot.*

Under the concept of lot-by-lot testing the process of constructing a highway may be thought of as the production of a succession of lots, which are presented to the engineer for acceptance or rejection, as shown in Figure 1. By use of an acceptance plan the engineer protects the quality of the construction by rejecting any lots that the samples indicate are not of the specified quality.

To implement the acceptance plan, each lot must be considered to be made up of subdivisions of various sizes. The largest of these are the SEGMENTS, which may be well-defined subdivisions of a lot as in the case of mixer-truck loads of concrete, or whose limits are arbitrary as in the case of a square yard of base course.

A sample is that portion of the lot taken to represent the whole. Examples are the total number of groups of concrete test cylinders made during a day's placement or the total number of bags of samples obtained when sampling a sandpit.

Here the term sample is defined in the statistical sense. This term is often confused by engineers with the individual INCREMENTS which are small quantities of material taken from different segments in the lot.

Samples usually are made up of several increments, such as groups of concrete cylinders made during a day's placement, or density specimens removed from a lot of pave-

*The purpose of this chapter is to furnish guidelines for the application of statistical techniques in the development and interpretation of construction specifications. The examples given are illustrative only and it is not intended that they be applied directly or used as prototype specifications.

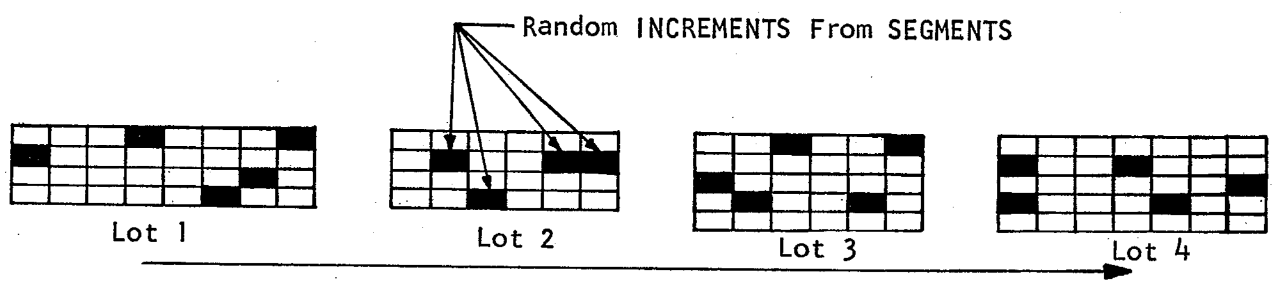


Figure 1. Production of lots (such as pavement placements).

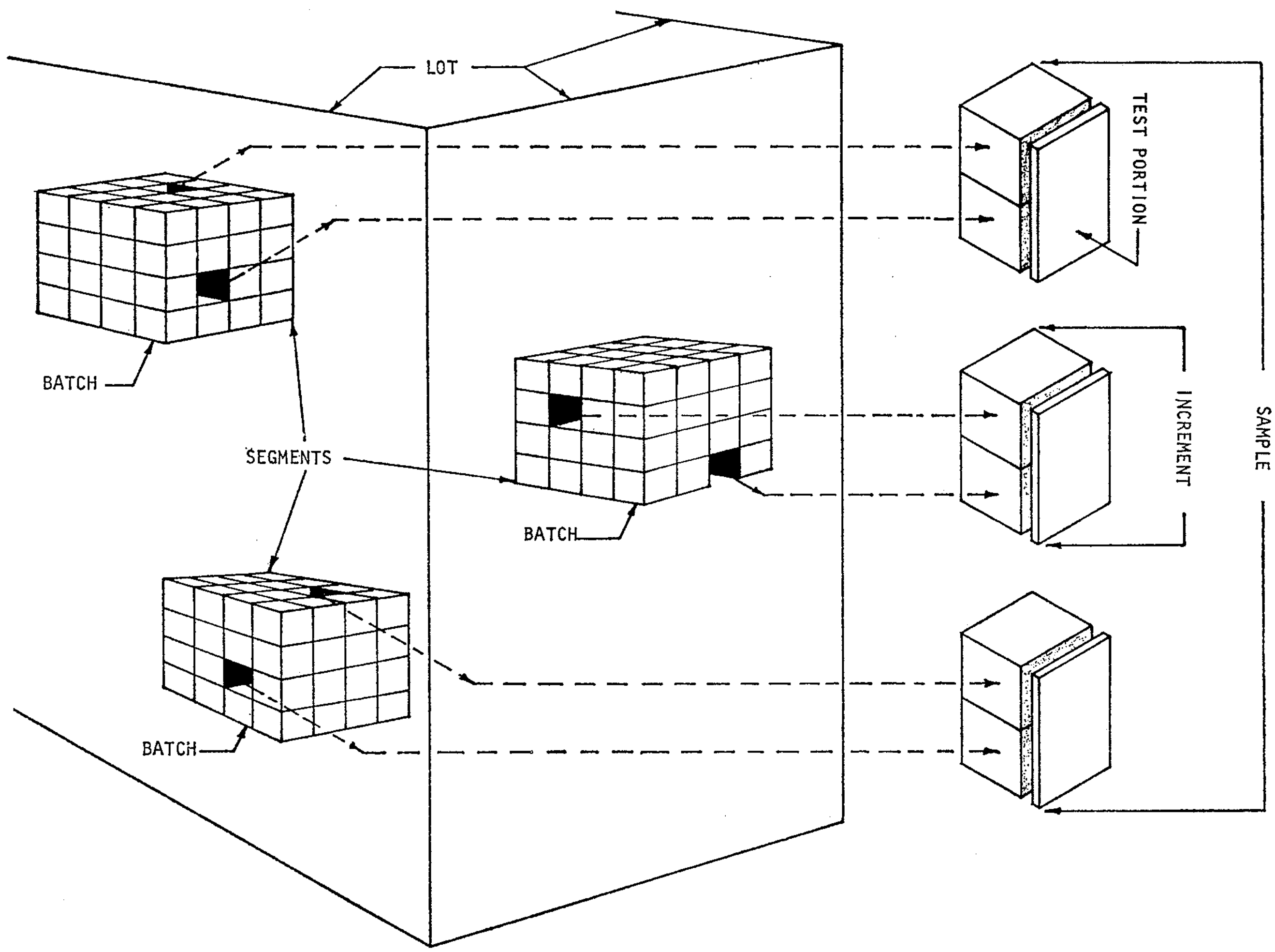


Figure 2. Test portions representing a lot.

ment. One increment represents one segment such as a square yard of pavement, or a batch, or a truckload. In the case of some materials, such as a batch of concrete or hot-mix, increments are made up of small portions taken from different locations in the batch, which is considered to be a segment.

When making some chemical and physical tests, where it is not practical to measure the entire bulk of the increment, the bulk is reduced by quartering or splitting. The part of an increment on which measurements are made is called a TEST PORTION.

The relationship of the lot and its subdivisions is shown in Figure 2. The advantages of lot-by-lot acceptance testing are:

1. A much better indication of the acceptability of lots of construction is obtained than by the method of representative sampling, as previously described.

2. Testing load is not affected by variations in rate of construction and inspector's time can be utilized more efficiently.

3. The quantity of testing required is related to the consequences of acceptance of a lot of material or type of construction of unsatisfactory quality.

4. Unsatisfactory lots are quickly detected, before a large quantity of unacceptable material or construction has been produced, and at a time when corrective action is most apt to be feasible.

These benefits can only be obtained if the acceptance plan is based on practical and realistic numerical limits with which the measurements on the sample from each lot are compared.

Realistic Limits and Acceptance Criteria

BASIC REQUIREMENTS FOR NUMERICAL LIMITS

One facet of the overall problem of designing an acceptance plan is how best to set numerical limits for measured characteristics of lots of materials and construction, and how to determine substantial compliance with these requirements. Appropriate limits must minimize risk of failure to meet performance standards and must insure maximum use value.

The associated acceptance criteria must provide a means of effective enforcement with reasonably low risks of either accepting poor material or rejecting good material. Also, the acceptance plan must be capable of discriminating between acceptable and unacceptable material by means of a practical number of samples and tests.

SOURCE OF DIFFICULTY

The principal obstacle to meeting these requirements easily is VARIATION. Many of the materials used in construction have characteristics that vary over wide limits. Construction equipment and methods have definite limitations as to how closely the exact plan grade and dimensions can be maintained. The methods of measuring the characteristics of materials and construction, in some cases, are in themselves inaccurate and a source of variation.

It is well recognized that measurements (the results of tests) made to determine compliance with highway specifications show some variation. However, the actual extent of this variation is not definitely known, due to the frequent practice of taking "representative samples," discarding measurements of test results that show unusually high or low values, or of combining several small samples to form an "average" sample. As a result, recorded data tend to reflect average values and the extent of variation normally associated with single measurements of a characteristic of a material or process is unknown. If independent measurements are made on a random basis, values may vary widely from that usually expected.

Although this variation exists, and tests made under some conditions appear to indicate a non-compliance with specification requirements, completed construction usually provides satisfactory performance. It is obvious that certain measurements or tests which show non-compliance with specification requirements indicate that further checking or action is necessary.

(a) PAVEMENT CORE THICKNESS (IN.)

1.8	2.1	2.0	2.0	1.9
2.0	2.0	1.7	2.1	2.0
1.9	2.2	2.0	2.0	2.1
2.2	1.9	2.0	2.0	2.0
1.8	2.2	2.1	2.0	2.1
2.1	2.2	2.3	1.8	2.0
2.1	2.2	1.9	2.0	2.0
1.9	2.0	2.0	2.0	2.1
2.1	1.9	2.0	2.1	2.0
2.0	2.1	2.1	1.9	1.9

(b) TALLY OF PAVEMENT CORE THICKNESS

(NO. OF MEASUREMENTS)

1.7	/			
1.8	///			
1.9	~~////~~	///		
2.0	~~////~~	~~////~~	~~////~~	~~////~~
2.1	~~////~~	~~////~~	//	
2.2	~~////~~			
2.3	/			

Figure 3. Example of measurement distribution by tally.

NEED FOR MEASUREMENT OF VARIATION

To evaluate measurements in such a situation realistically, there must be available some way of measuring variation and expressing it as a number. Furthermore, there should be some way of estimating what percentage of high or low values can be expected from RANDOM SAMPLES so that it can be estimated in advance about how many of a group of values will fall outside of some given limit, or limits.

With a method of measuring variation at hand, it is possible to distinguish between the normal variation that is, and always has been, present in acceptable construction, and an actual decrease in quality that would result in a loss of use value. When the pattern of normal variation is known, it is possible to design acceptance criteria that can be rigidly enforced to insure acceptable quality, and at the same time will allow for the always-present percentage of measurements (test results) that will fall outside of the specified numerical limits. The tool for accomplishing these objectives is already at hand in the methods of STATISTICS.

BENEFITS OF STATISTICAL METHODS

Statistics is a scientific method that deals with the analysis of averages and variation around the averages as found in numerical DATA. The methods of statistics provide an indispensable tool for dealing with variation and of estimating probabilities. When understood, these methods are easy to use, and a knowledge of arithmetic is all that is required to make the necessary computations. Realistic specification limits and tolerances can be set accurately, and statistical methods also establish guidelines for the practical interpretation and enforcement of specifications.

Basic Statistical Concepts

USE OF NORMAL DISTRIBUTION CURVE

Methods of Picturing Variation.—It is a common practice among engineers to plot individual measurements as points on some type of graph, then to fit the best possible curve to the scatter of points. Once this has been done it is possible to draw inferences from the curve, and to interpolate and extrapolate values that do not appear in the data. A very similar approach is used in statistics, but here the objective is to measure the variation of the individual measurements from their average. To do this, a special type of curve called a DISTRIBUTION CURVE must be fitted to the data. To understand how this is done the concept of a DISTRIBUTION must first be visualized.

One way to get a picture of variation is to place each value on a tally sheet. For example, if 50 cores are cut from an asphalt surface course at random locations and the thickness of each core is measured, the results might look like those in Figure 3a.

The tally in Figure 3b gives a picture of the way the data are grouped; that is, it shows the distribution of the measurements, but it is not to scale and does not provide a means of computing a numerical value which is a measure of the variation. A way to draw this picture to scale is to plot the data in the form of a bar chart, called a HISTOGRAM, so that each measurement is a unit of height of the bar representing a particular value of the measurement (Fig. 4).

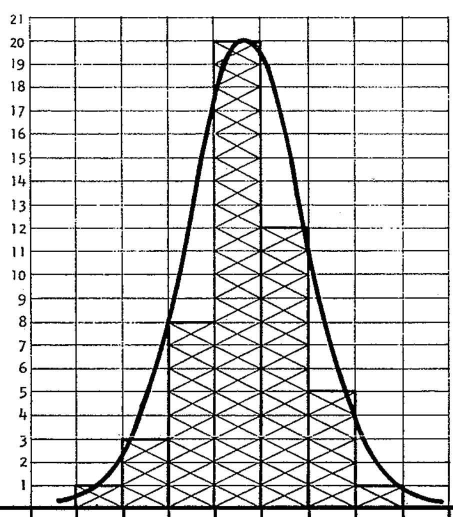
Figure 4 shows that once the data have been plotted to scale, in histogram form, a bell-shaped curve can be applied, and a fairly good fit obtained. This curve is called the NORMAL DISTRIBUTION CURVE. Although this curve retains its characteristic shape, the ratio of height to width of base can change radically, depending on the values of two PARAMETERS that completely define the shape and location of the curve. These parameters are the MEAN, $\bar{X}'$, which is a measure of central tendency, and the STANDARD DEVIATION, σ', which is a measure of variability.

Inasmuch as the shape of the curve, and its position on a numerical scale, can be changed by changing the values of $\bar{X}'$ and σ', the curve can be fitted to almost any set of data, and each set of data will have a unique distribution curve. The more measurements there are in a set of data, the better the fit will be. Sometimes a small set of data, when plotted in histogram form, will have a very irregular distribution and it appears that the normal curve cannot be fitted. However, it should be visualized that these few measurements are only a small part of a very large number of possible measurements, and that if all measurements were available and were plotted the normal curve would fit.

This is an important concept, as it can be seen that the individual values obtained by making a small number of measurements on a lot do not, in themselves, provide much information. If a large number of measurements were made there would be many both smaller and larger than those obtained from the sample. What is really important is the overall distribution of all possible measurements on the lot, and this can be estimated from the measurements on the sample by utilizing the properties of the normal curve, providing it can be assumed that the sample mean, $\bar{X}$, and the sample standard deviation, σ, are sufficiently good estimates of $\bar{X}'$ and σ', the true (unknown) values.

Properties of Normal Curve.—The objective of fitting the normal curve to data is to draw statistical inferences from the curve. One of the properties of this curve is that, regardless of its shape, a definite percentage of the total area beneath the curve is defined by vertical lines spaced a measured distance from the centerline of the curve. This distance must, however, be measured in standard deviation (σ) units. The approximate percentages of area that correspond to the standard deviation measurements of the normal curve are shown in Figure 5. As explained hereinafter, Figure 5 indicates that if a large number of pavement cores were taken and the thickness measured, about 95 percent of the measurements would be between 1.79 and 2.25 in.

Practical Application of Normal Curve.—To make use of the properties of a normal curve that has been fitted to a set of data, the standard deviation, σ, of the curve that



1. Pavement Thickness (in.)		1.7	1.8	1.9	2.0	2.1	2.2	2.3		Totals
2. Frequency		1	3	8	20	12	5	1		50
3. Frequency x (Line 1)		1.7	5.4	15.2	40.0	25.2	11.0	2.3		100.8
4. Deviation from Average		.316	.216	.116	.016	.084	.184	.284		
5. (Deviation)^2		.0999	.0467	.0135	.0002	.0071	.0339	.0807		
6. (Line 2) x (Line 5)		.0999	.1401	.1080	.0040	.0852	.1695	.0807		.6874

$$\text{Average} = \frac{\text{Total of Line 3}}{\text{Total Frequency}} = \frac{100.8}{50} = 2.016$$

$$\text{Standard Deviation} = \sqrt{\frac{\text{Total of Line 6}}{\text{Total Frequency}}} = \sqrt{\frac{.6874}{50}} = \sqrt{013748} = .11725$$

Figure 4. Normal curve fitted to histogram.

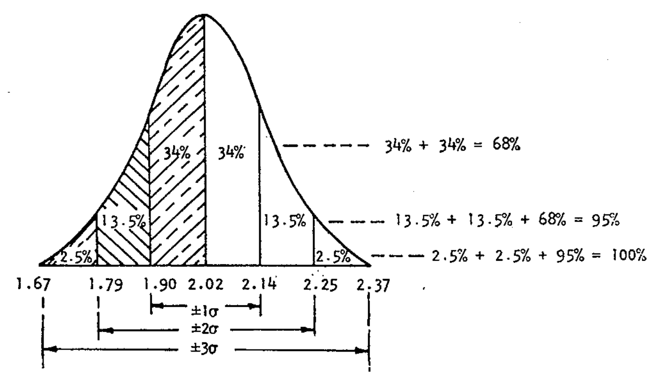


Figure 5. Approximate percentages of area within stated sigma limits.

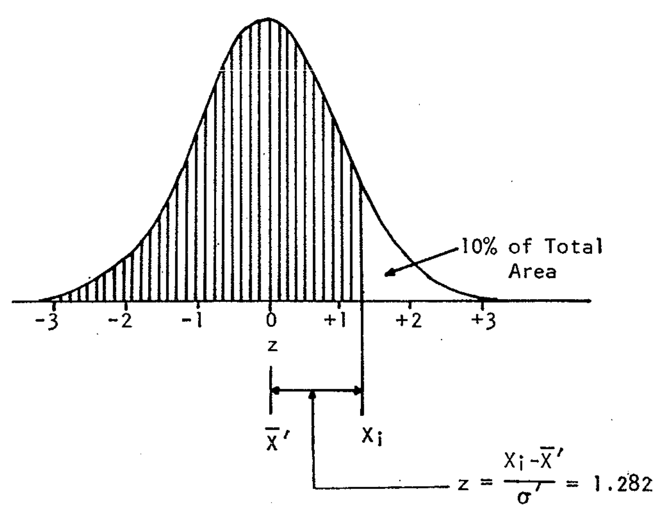
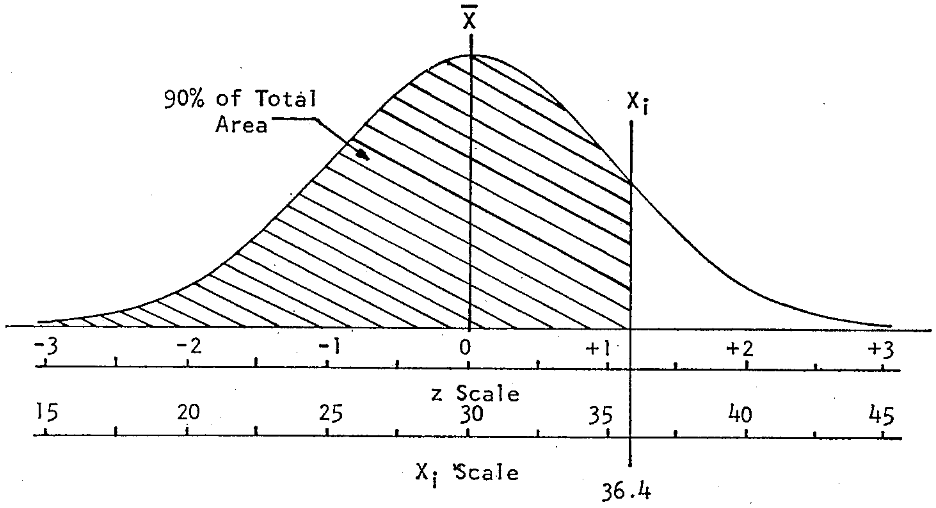


Figure 6. Elements of normal curve.



$\sigma = 5 \quad \bar{X} = 30$

X_i	$X_i - \bar{X}$	$z = \frac{X_i - \bar{X}}{\sigma}$	% of Area
15.0	- 15.0	- 3.00	0.135
23.6	- 6.4	- 1.28	10.0
25.8	- 4.2	- 0.84	20.0
27.4	- 2.6	- 0.52	30.0
28.75	- 1.25	- 0.25	40.0
30.00	0.00	0.00	50.0
31.25	+ 1.25	+ 0.25	60.0
32.6	+ 2.6	+ 0.52	70.0
34.2	+ 4.2	+ 0.84	80.0
36.4	+ 6.4	+ 1.28	90.0
45.0	+ 15.0	+ 3.00	99.865

Figure 7. Relationship of numerical (X_i) *scale to percent total area.*

would best fit the data must be computed from the data.

Once the value of σ has been estimated, data units such as pounds, inches, or percentages, can be converted to σ units by

$$z = \frac{X_i - \bar{X}}{\sigma} \tag{1}$$

in which z is a distance measured along the base of the normal curve in either direction from the centerline, in standard deviation units; X_i is a particular value, in data units; $\bar{X}$ is the average of the data, in the same units; and σ is the standard deviation, also in data units.

For example, Figure 6 shows that if $z = 1.282$, then from the table of areas of the normal curve (Fig. 7) 10 percent of the measurements would be expected to have a value greater than X_i. More detailed tables can be found in textbooks dealing with the subject of statistics.

Method of Utilizing Properties of Normal Curve.—The point has now been reached where practical applications of the properties of the normal curve can be made. These applications include the setting of realistic numerical specification limits and the design of acceptance plans that provide protection against large risks of either accepting poor material or construction or rejecting good material or construction. For example, suppose that from measurements on a sample it has been estimated that some characteristic of a lot has a standard deviation of five ($\sigma = 5$) and that the average value of the characteristic is 30 ($\bar{X} = 30$). By converting from the data scale to the z scale, as shown in Figure 7, the percentage of a large number of measurements that will be larger or smaller than a certain value (X_i) can be predicted. If the specification had an upper limit of 36.4 ($X_i = 36.4$), it can be seen from Figure 7 that 90 percent of the lot would be within this limit. The percentage of the lot that would be included by other limiting values also is shown in Figure 7.

A similar use of the normal curve is made to estimate the probable risks involved in making an acceptance decision.

Theory of Risks

Whenever a decision is made to accept or reject a material or item of construction on the basis of a sample, there are possibilities of making an error. The source of error stems

Actual Conditions	ENGINEER'S DECISION	
	Reject Material	Accept Material
Material Acceptable	Type I Error Engineer Incorrect Seller's Risk	Engineer Correct
Material Unacceptable	Engineer Correct	Type II Error Engineer Incorrect Buyer's Risk

Figure 8. Decision risks.

from the fact that it is not practical to make measurements on every increment in a lot. The average value of the sample measurements, $\bar{X}$, will almost never be the same as the mean, $\bar{X}'$, of the lot. Also, due to variations within the lot, the sample standard deviation will be different from the true standard deviation, σ'.

The error of decision may be one of two types. If a decision is made to reject a material when the material is actually satisfactory, a TYPE I ERROR has been made. The risk (probability) of making such an error is symbolized by alpha (α). In this report it is called the SELLER'S RISK, which means the risk a contractor, producer or manufacturer takes of having acceptable material rejected.

If a decision is made to accept a material when the material is actually unsatisfactory, a TYPE II ERROR has been made. The risk of making such an error is symbolized by beta (β). In this report it is called the BUYER'S RISK, which means the risk an agency such as a state highway department or commission, represented by the engineer, takes of accepting material which does not fully comply with the specification requirements.

As used here, "material" means all items, including manufactured products or completed construction, to which specification requirements apply.

The situation that exists when any acceptance or rejection decision is made is depicted in Figure 8.

It is important that the statistical method of making a decision that will minimize, within practical limits, the probability of making either Type I or Type II errors be fully understood. This general approach is the basis of all statistical acceptance plans and their related specification limits.

The relationships among the factors involved in making an acceptance decision (the buyer's risk; the seller's risk; the standard deviation, σ', of the measurements pertaining to the lot; the number of measurements, *n;* and the level of quality) are illustrated by the following case discussion. The most important relationships are:

(a) The chances of rejecting a lot of poor quality are many times greater than rejecting a lot of good quality.

(b) The seller's risk can be decreased by increasing either quality or uniformity, or both.

(c) The buyer's or seller's risk, or both, can be decreased by increasing the number of measurements or by increasing the precision of measurements.

CASE DISCUSSION

A discussion of risks is meaningless unless they are related to a situation in the real world. Consider the following situation:

A lot consisting of 1,200 tons of asphaltic concrete has been placed and compacted. Density specimens (increments) are to be sawed from this pavement course. On the basis of bulk specific gravity tests on this sample, the engineer must make a decision whether to accept this lot or to require the contractor to take remedial measures. It has been found from previous experience that it is practical to compact similar material to the point that air voids are reduced to 5 percent, corresponding to a bulk specific gravity of 2.40, and that the standard deviation of the measurements is 0.036. Accordingly, an acceptable pavement course can be described by a distribution of bulk specific gravity measurements having a mean ($\bar{X}'$) of 2.40 and a standard deviation (σ') of 0.036.

On the other hand, it has been found from experience that a pavement course having 9 percent air voids, corresponding to a bulk specific gravity of 2.30, is not serviceable. This unacceptable pavement course is described by a collection of bulk specific gravity measurements having a mean of 2.30 and the same standard deviation of 0.036. Knowing that there will always be an occasional high or low test value, and that there is considerable testing and sampling error involved, the engineer realizes that he must assume some risk of accepting unsatisfactory pavement (Type II error). At the same time, the seller (contractor) will be exposed to a related risk of having properly compacted pavement rejected (Type I error). The engineer must decide how to assign these risks fairly on the basis of measurements on a practical number of test specimens cut from the pavement.

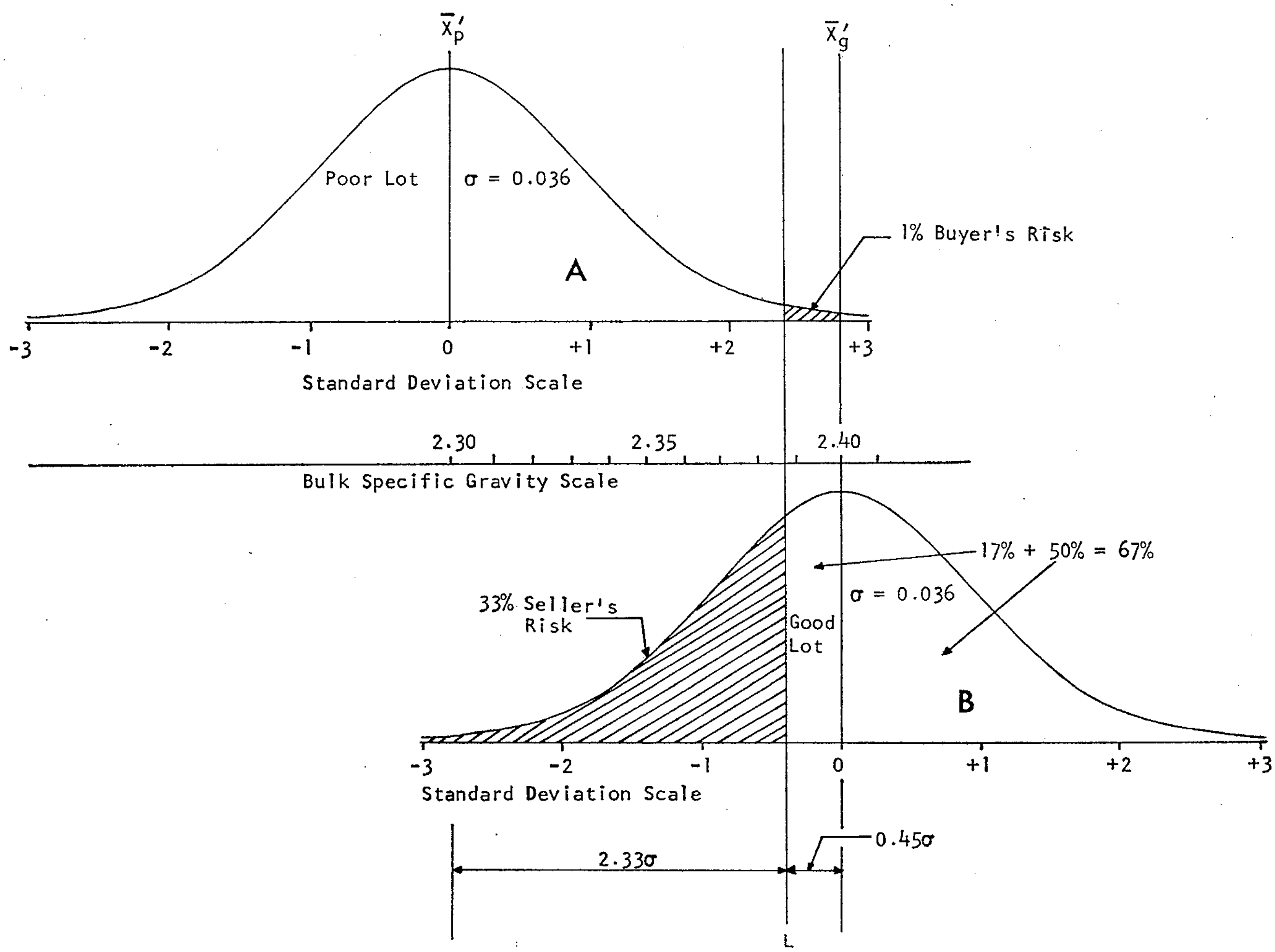


Figure 9. Acceptance and rejection based on individual measurements on one specimen only.

In graph form the situation looks like that in Figure 9, which shows the distribution of individual values of measurements on poor pavement (A) and good pavement (B).

ACCEPTANCE CRITERIA

The acceptance rule will be to take a definite number, n, of test specimens from the pavement, measure the bulk specific gravity (B.s.g.), and average the test results. If this sample average, $\bar{X}$, is above a certain value, L, the lot will be accepted. If the average is below this value the contractor will be required to take remedial measures, such as applying a fog seal with additional rubber-tired rolling, without additional payment. The L-value thus sets the acceptance (and rejection) criterion.

The basic problem is: What should be the value of L and how many measurements should be averaged? Suppose that the engineer is willing to take a 1 percent (buyer's) risk that he will accept poor pavement and will base his decision on a single measurement. Then L will be located at such a distance to the right of $\bar{X}'_p$ (the average of all possible measurements on a lot of poor or unacceptable material) that only 1 percent of the area under the distribution curve (A) will appear to the right of L. From a table of areas of the normal curve, this distance is found to be 2.33 standard deviation (σ) units. Because the standard deviation (σ) of the measurements is 0.036, this distance is $2.33 \times 0.036 = 0.084$ B.s.g. units, and L will be located at $\bar{X}'_p + 2.33\sigma$, or $2.30 + 0.084 = 2.384$.

With the buyer's risk set at 1 percent under these circumstances, what is the seller's (contractor's) risk of having good pavement rejected (Type I error)? The total distance between $\bar{X}'_p$ and $\bar{X}'_g$ (the average of all possible measurements on a lot of acceptable material) is 0.100 B.s.g. units, or $0.100/0.036 = 2.78\sigma$ units, so L is located $2.78 - 2.33 = 0.45\sigma$ units to the left of $\bar{X}'_g$. From a table of areas of the normal curve the area of distribution (B) between L and $\bar{X}'_g$ is found to be 0.17, so the area to the left of L is $0.50 - 0.17 = 0.33$ (or 33 percent), which is the producer's risk. This means that in one time out of three the engineer would reject satisfactory pavement (Type I error). Obviously, this is not a satisfactory acceptance plan, at least as far as the contractor is concerned. The contractor would prefer a value of L that reduces the Type I error, but such a change of L would increase the probability of erroneous acceptance of a poor product (Type II error).

REDUCING RISKS

Fortunately, the risks of making either a Type I or a Type II error, due to chance effects, can be reduced by increasing the numer of increments, n, taken, which in effect increases the amount of evidence on which a decision is made. As n increases, the variation in sample averages will decrease based on the relationship

$$\sigma/\sqrt{n}=\sigma_{\bar{x}} \qquad (2)$$

in which $\sigma_{\bar{x}}$ represents the standard deviation of sample averages.

The new distributions of the average values may be expected to have the same means, $\overline{X}'$, as the original, but will be narrower due to the smaller value of $\sigma_{\bar{x}}$. If acceptance is to be based on the average of four measurements, the situation in graph form would appear as in Figure 10. Assuming the same (1 percent) owner's risk, L will be located $2.33\sigma_{\bar{x}}$ units to the right of $\overline{X}'_p$. Inasmuch as $\sigma_{\bar{x}}=\sigma/\sqrt{n}=0.036/\sqrt{4}=0.018$, this distance will be $2.33\times 0.018=0.042$ B.s.g. units, and L will be located at $2.30+0.042=2.342$ B.s.g.

This point is $(2.400-2.342)/0.018=0.058/0.018=3.22$ units to the left of $\overline{X}'_g$, so there is practically no (actually less than 0.07 percent) risk of the engineer making a Type I error and rejecting a satisfactorily compacted pavement course.

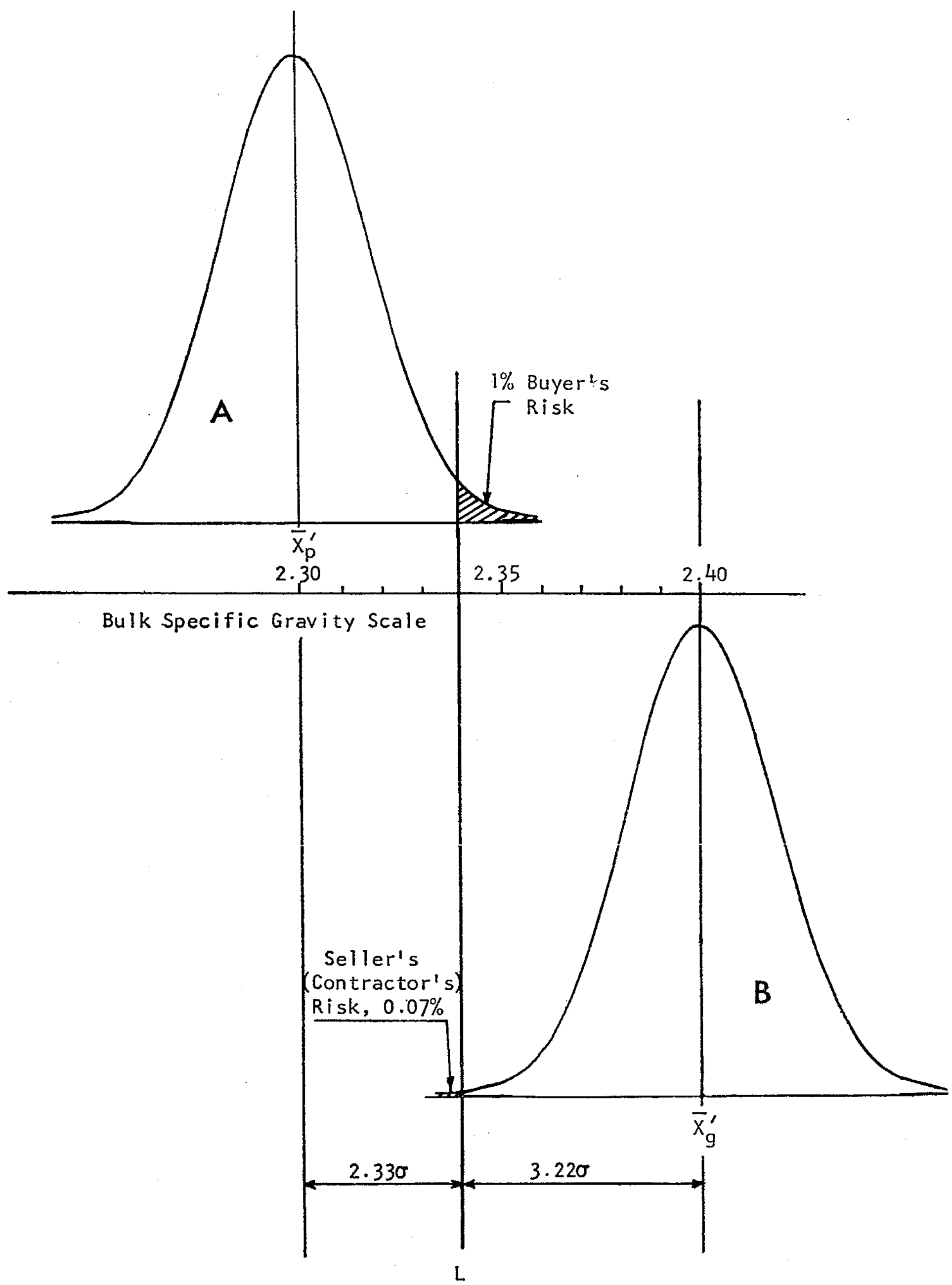


Figure 10. Distribution of averages of four measurements.

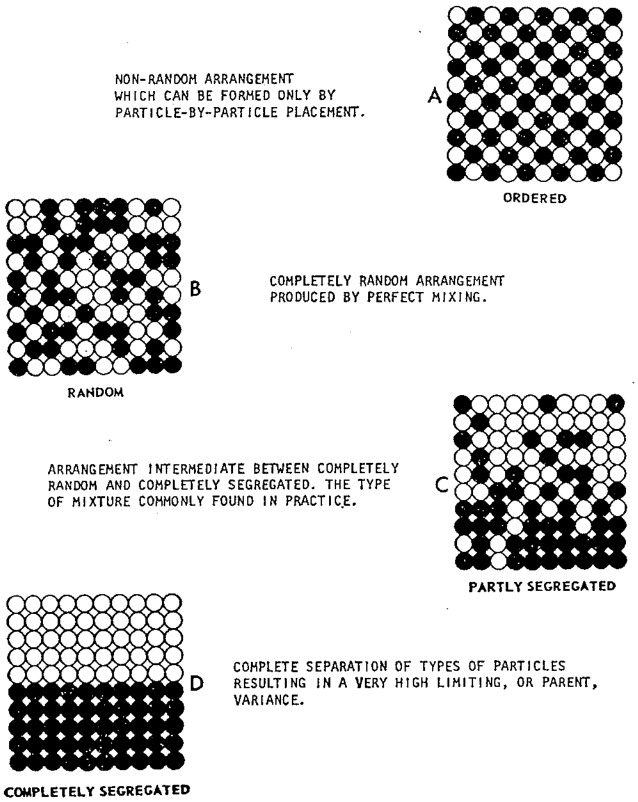


Figure 11. Particle arrangements. The white and black spots represent particles, or groups of particles, having unlike characteristics in an infinite population of combinations of such particles. The different arrangements represent the degree of dispersal of like particles throughout the mixture.

Another way of showing risks, and the probabilities of acceptance and rejection, is by the use of OPERATING CHARACTERISTIC (OC) CURVES. The possibility of using these curves for purposes of illustration was explored but, because a discussion of the construction and use of such curves was not considered essential to the objectives of this report, the OC curves that correspond to the various diagrams have not been shown.

Theory of Sampling

Positive assurance as to the value of the measurement of some characteristic of a lot can be obtained only by measuring each of the smallest subdivisions of the lot. Because this is impractical, particularly in the case of destructive tests, the value of the characteristic must be estimated from measurements on a sample, which has been defined as that portion of a lot taken to represent the whole.

The most important factor in obtaining information on which to base realistic specifications, or for the purpose of enforcing specifications, is the action of sampling. Although such action is often delegated to inexperienced and uninstructed personnel, it should be realized that precision of measurement and accuracy of computation are wasted effort if the sample is not taken in a way that will insure its function.

Life would be much simpler for the engineer if all materials, products, and construction were made up of bits having the uniform arrangement of (A) in Figure 11. If this were the case any test portion, wherever removed, would represent the entire lot. With the possible exception of some homogeneous materials, such as some kinds of well-mixed liquids, this is never the case. The best that can be hoped for is the RANDOM arrangement shown in (B) and even this is an idealized condition obtainable only under rare conditions. It must be accepted that the condition shown in (C) is the usual state of affairs in the real world and that a certain amount of SEGREGATION is inevitable in all lots of mixed material or product. The art of sampling is to recognize this fact and to take precautions that will overcome the effects of *temporary* segregation.

The objectives of sampling are to estimate from a limited number of measurements, the value of the mean, and the variation of measurements about the mean, in the lot itself. These objectives cannot be realized if "representative" samples are taken. For example, if an equal number of increments of white spots and black spots were taken from (D) in Figure 11 and these increments were combined to form a sample, measurements on the sample would yield the true mean value. However, the entirely segregated condition would not be revealed. In the case of (C) it is clear that no one increment can represent the lot and that many increments must be taken, and measured individually, to find the true mean value and the variation of the measurements.

The way that these increments are taken is extremely important. It must be clearly understood that unless the increments are chosen by PROBABILITY SAMPLING the methods of statistics cannot be applied. The locations or units from which the increments are obtained must be entirely random. Random in this case does not mean haphazard, but does mean that the locations be predetermined without bias, such as by the use of a table of RANDOM NUMBERS. In addition, every possible increment in the lot must have a known probability of being chosen. This means that a lot must be sampled at some stage of a process when all parts of the lot are accessible. For example, it is impossible to obtain a probability sample from a stockpile of aggregate because increments cannot be taken from the interior of the pile. To sample such material properly, it must be passed over a belt, and increments taken from the stream at randomly determined intervals.

Table 1 is a brief example of RANDOM NUMBERS which can be used to determine increment location. More extensive tables are available in textbooks and Federal publications. To use such a table to locate increments for a probability sample in space or time, the lot is divided into real or imaginary segments. If the segments are successive, as in the case of truckloads of material departing from a plant or arriving at a job site, the total number of truckloads in the lot is first estimated. The random numbers are considered as decimal fractions and, in any desired fashion, fractions equal in number to the intended number of increments are selected from the table. By multiplying the total number of truckloads by these fractions, and rounding the results, the sequence numbers of the truckloads from which increments are to be taken are designated. Similarly, the times at which increments are to be taken are found by multiplying the total time required for production of a lot by the decimal numbers.

If the lot exists in the form of an area, such as a day's construction of subbase, two random numbers are required to locate each increment. By multiplying the length of the construction by one set of decimals the stationing of the square yard of pavement is determined, and the offset from one side is found by multiplying the width of the construction by another set of decimals.

Sources of Variance

If increments are taken from widely separated parts of a lot, such as a day's production of asphaltic concrete, and some measurement, such as asphalt content, is made on these increments, the values of the measurements made on different increments may vary widely. In other words, the overall standard deviation, σ_o, of the measurements made on the sample will be large. The larger σ_o becomes, the greater will be the uncertainty as to the true average value of the measurement and the actual variation in the proportion of asphalt in the mixing placed on different parts of the roadway. For this reason, the relative sizes of the standard deviations that contribute to the size of σ_o should be determined and an effort made to reduce those which greatly affect σ_o. This can be accomplished by a sampling and testing program, followed by an ANALYSIS OF VARIANCE (ANOV) of the measurements on the samples.

The sources of variance of the gradation of a material such as a concrete aggregate are diagramed in Figure 12. It should be noted that standard deviations are not directly additive, but must be combined by adding the VARIANCES (the square of the standard deviation) and taking the square root of the sum.

Factors which greatly affect σ_o, but are not shown in the figure, are called ASSIGNABLE CAUSES. These are actual errors of omission or commission, such as intentional departure from specified proportions or methods, or malfunction of equipment. Assignable causes usually produce much larger variations than random causes, so they can be detected and eliminated by thorough inspection. Assuming no assignable causes are operating, the principal sources of variance are as follows:

$\sigma^2{}_a$ is the true INHERENT VARIANCE that is due to RANDOM DISTRIBUTION of such things as different-sized particles in a mass of aggregate, or microflaws in hardened concrete. Inasmuch as $\sigma^2{}_a$ is caused by this local nonhomogeneity within the volume of material actually tested, it can be reduced only by using a test portion of sufficient size to average out the random effects.

$\sigma^2{}_t$ is the within-increment between-test portion variance due to the lack of REPEATABILITY of the test procedure, which includes effects of reducing increments to test portion size, or other preparatory work. These factors, in turn, are affected by differences among items of equipment and differences among operators. In situations where $\sigma^2{}_t$ is large, and cannot be reduced by using more precise test equipment or improved operator technique, it is necessary to average the results of nearly identical test portions to reduce experimental error.

TABLE 1

RANDOM NUMBERS

.967	.696	.749	.291	.892	.948	.220	.659	.193	.493
.271	.870	.864	.466	.554	.627	.425	.994	.296	.456
.581	.869	.656	.924	.427	.720	.665	.666	.106	.031
.986	.782	.667	.850	.069	.071	.155	.102	.629	.663
.502	.574	.315	.431	.225	.163	.928	.404	.648	.685
.836	.206	.882	.227	.358	.260	.139	.026	.490	.834
.428	.942	.919	.875	.502	.296	.066	.170	.833	.652
.150	.457	.448	.215	.612	.522	.794	.850	.195	.887
.945	.364	.897	.877	.917	.887	.331	.606	.918	.403
.743	.241	.729	.016	.865	.333	.136	.811	.629	.269
.909	.019	.009	.420	.109	.843	.523	.665	.360	.193
.914	.574	.253	.761	.116	.120	.901	.342	.334	.921
.601	.553	.599	.966	.316	.077	.788	.101	.470	.765
.552	.077	.415	.527	.858	.025	.579	.787	.432	.391
.630	.673	.919	.146	.994	.307	.804	.112	.455	.583
.998	.239	.874	.420	.777	.351	.169	.582	.890	.062
.892	.696	.137	.155	.689	.972	.760	.914	.566	.815
.550	.885	.356	.375	.530	.125	.396	.025	.285	.542
.454	.731	.704	.873	.481	.791	.549	.953	.087	.551
.165	.996	.335	.212	.654	.979	.614	.486	.358	.595
.669	.726	.698	.683	.470	.682	.017	.510	.425	.284
.729	.448	.410	.144	.751	.947	.732	.633	.348	.743
.081	.277	.841	.977	.619	.007	.801	.943	.464	.658
.428	.117	.501	.402	.890	.317	.800	.875	.564	.772
.508	.146	.959	.424	.631	.301	.587	.908	.942	.985
.503	.566	.543	.476	.497	.543	.751	.608	.820	.372
.601	.326	.068	.242	.817	.472	.251	.884	.448	.838
.205	.446	.190	.696	.209	.862	.716	.265	.477	.535
.164	.838	.470	.040	.815	.592	.371	.059	.242	.794
.104	.755	.903	.594	.636	.195	.522	.235	.235	.840
.062	.990	.667	.356	.732	.721	.035	.039	.375	.636
.150	.962	.773	.433	.244	.692	.892	.957	.870	.390
.925	.355	.398	.222	.441	.649	.570	.306	.866	.690
.096	.336	.196	.847	.123	.086	.440	.722	.081	.854
.576	.417	.810	.159	.270	.612	.212	.242	.021	.894

$\sigma^2{}_a + \sigma^2{}_t$ is the variance among results on test portions taken from the same increment. It is often called experimental error, because it is not usually possible to separate $\sigma^2{}_a$ and $\sigma^2{}_t$ except by indirect methods.

$\sigma^2{}_s$ is the error due to nonhomogeneity within the segment or batch. If increments are taken from different places in the same square yard of pavement or the same filling of a weigh hopper with aggregate, there will be differences among the increments due to local segregation. In the case of pavement, it may be feasible to reduce this segregation by improved construction techniques. This type of segregation within batches of concrete or aggregates may not affect quality of construction, because it may be removed by the following process steps. It may, however, result in misleading test results unless increments are taken by collecting material from different parts of the batch.

$\sigma^2{}_b (= \sigma^2{}_a + \sigma^2{}_t + \sigma^2{}_s)$ is the total variance among test portions taken from the same segment or batch. The chief effect of $\sigma^2{}_b$ is to create uncertainty as to the reasons for the size of overall variance $\sigma^2{}_o$, except in cases where nonhomogeneity within the segment affects construction quality.

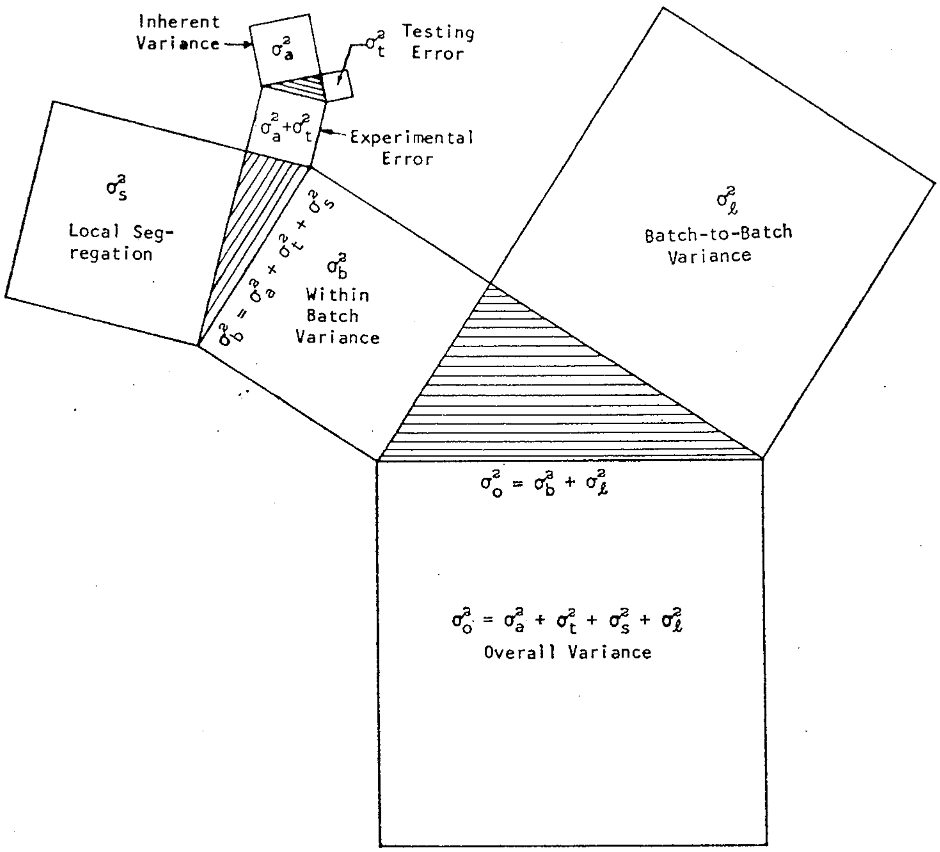


Figure 12. Sources of variance.

As pointed out in the preceding analysis, a large reduction in the size of $\sigma^2{}_b$ usually can be accomplished only by reducing $\sigma^2{}_s$.

$\sigma^2{}_l$ is the variance among segments, or batches, and is the most significant contributor to $\sigma^2{}_o$, the overall variance. In the case of aggregates this variation is usually caused by improper stockpiling and handling techniques. In products such as portland cement or bituminous concrete a large value of $\sigma^2{}_l$ is usually an indication of faulty proportioning. In the case of pavement courses, large variations in the measurements of characteristics are usually due to insufficient processing or inefficiency of equipment, or both.

$\sigma^2{}_o(= \sigma^2{}_a + \sigma^2{}_t + \sigma^2{}_s + \sigma^2{}_l)$ is the total overall variance of test portions taken from a lot. This is the variance that directly affects the writing of practical specifications, because realistic specification limits, or tolerances, must usually be wide enough to accomodate a RANGE of at least $\pm 2.5\sigma_O$. Unless it is feasible to reduce the size of the components of $\sigma^2{}_o$, restrictive limits will lead to a large percentage of test results outside of the limits, or to a condition of "tight specifications loosely enforced," where actual variations are concealed by the application of field tolerances, or by other methods.

Investigation as to the relative sizes of the sources of variance will point out where efforts should be made to reduce factors affecting the uniformity of test results, and will indicate how test portions should be distributed within the lot. Figure 12 is scaled to show roughly the relative sizes of variances associated with stockpiling of coarse aggregates. In other situations, the relative sizes may be quite different, as in the case of the variance of the indicated asphalt content of bituminous concrete, where $\sigma^2{}_a$ and $\sigma^2{}_t$ have a large effect on $\sigma^2{}_o$.

Treatment of Outliers

Whether or not to include values from a collection of measurements that vary greatly from the average, $\bar{X}$, in computations is often a perplexing problem. If these outliers stem from errors of technique or prior computation, there is no question but that they should be excluded. When there are no such known assignable (findable) causes, it is questionable whether any values not obviously impossible should be discarded without further investigation. However, when one or more very large or very small values appear in a small collection of measurements made for acceptance sampling purposes, it is not practical to determine the cause by a lengthy investigation.

The decision as to whether or not to exclude outliers must usually be based on the data that contain them. The problem is to decide whether the outliers stem from an assignable cause, or really belong in another set of data; that is, happen to belong to another lot and were included by mistake or are the result of improper sampling, preparation, or testing, or whether they would be expected to occur if a large number of measurements were made.

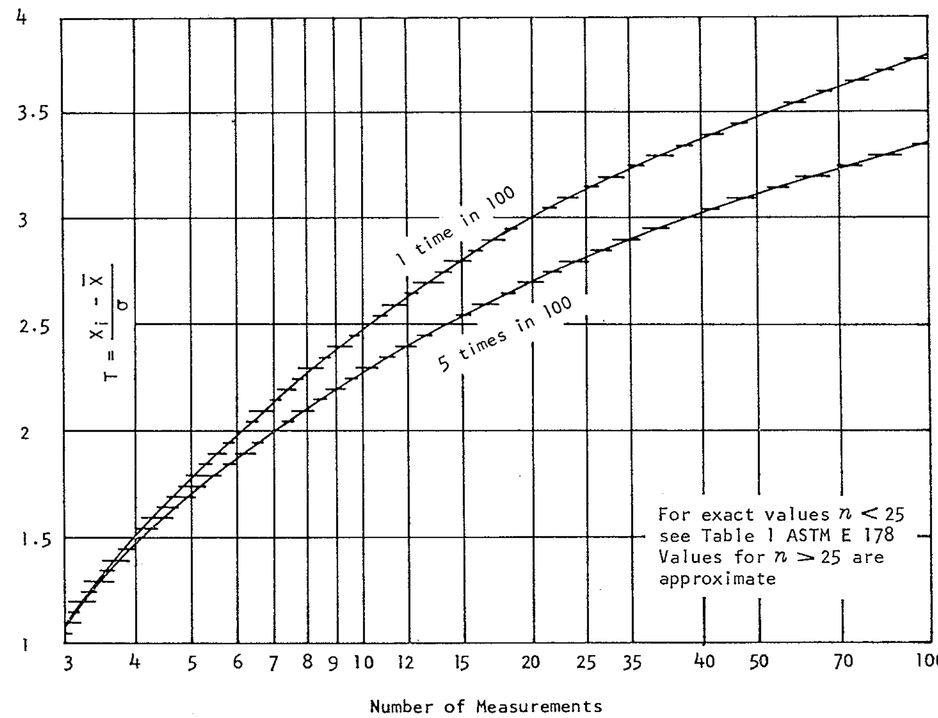


Figure 13. Test for outliers; values of T *which may be exceeded by chance.*

For example, a sample of five bricks is tested in compression. The compressive strengths are, respectively, 2,900, 2,600, 4,400, 2,500, and 2,600 psi, and the average is 3,000 psi. If the measurement on specimen 3 is included in the average, the brick will meet the requirements for AASHO Grade SW, which is acceptable. If this measurement is excluded, the brick must be classed as Grade MW, which is not acceptable. Assuming no other specimens are available, the decision as to retaining the measurement must be based on the data.

There are various ways of dealing with this problem. A generally accepted philosophy is that the valid measurements belong to a lot described by some type of distribution. Therefore, outliers may have a position far enough behind the "tails" of this distribution to make it obvious that they should not be included. Accordingly, the first step is to find how many standard deviation (σ) units the largest value is away from the sample average. First, the value of σ is computed from the square of the deviations from the average, or

$X_i - \bar{X}$		Deviation/100	Square of Deviation
3000 — 2900	=	1	1
3000 — 2600	=	4	16
4400 — 3000	=	14	196
3000 — 2500	=	5	25
3000 — 2600	=	4	16
			254

$$\sigma = \sqrt{\frac{\Sigma(X_i - \bar{X})^2}{n-1}} = \sqrt{\frac{254}{4}} \cong \sqrt{64} = 8 \times 100 = 800$$

To find the distance, T, of the outlier in estimated standard deviation units from the average, the difference between the outlier, X_i, and the average, $\bar{X}$, is divided by the standard deviation, σ, estimated from the data. Thus, $T = (X_i - \bar{X})/\sigma = (4{,}400 - 3{,}000)/800 = 1{,}400/800 = 1.75$.

Assuming the valid measurements belong to a lot described by a normal distribution, the decision as to whether or not this value should be expected depends on the number of measurements in the collection. The concept is that if there are a few persons in a room the chance that one of them is 6 in. taller than the average is very small. However, in a large group of people, such as the spectators at a baseball game, it is quite probable that there will be an exceptionally tall person in the crowd. From Figure 13, which is based on this principle, it is seen that 1.75 is between the critical values of 1.71 for 5 percent significance and 1.76 for 1 percent significance. This means that a value as large as 4,000 psi could occur by chance about 2 times in 100. Because it is not very probable that this value came from the same lot as the others (the brick may have been accidentally taken from a batch burned in another kiln) there would be justification for discarding it and classifying the brick represented by the sample as Grade MW and unacceptable.

Inasmuch as the presence of a very high or a very low value in the group of measurements made on a lot can have an important influence on the acceptance decision, any such value not meeting the criteria previously given should be investigated. Unless it can be established that the measurement is valid it is probably best to take another complete set of measurements. If this is not practical, another measurement obtained on the same basis as the rest of the group must be substituted for the measurement which does not meet the outlier criteria.

This method of screening data provides a scientific basis, independent of personal judgment, for deciding whether or not a suspected "fluke" should de discarded when making an acceptance decision.

Use of Statistical Methods

A TYPICAL EXAMPLE

To illustrate how statistical methods are used to establish specification limits and acceptance criteria, a realistic specification for thickness of a crushed aggregate base course and the method of applying acceptance criteria are presented, followed by a discussion and explanation of the statistical procedures involved.

SPECIFICATION

BASE COURSE—CRUSHED STONE

Thickness

Crushed stone base course shall have a nominal compacted thickness of eight (8) inches. Each day's construction shall be tested for acceptance or rejection immediately after final compaction. When tested in accordance with Acceptance Plan No. 1 an indicated eighty (80) percent of the base course shall be within a tolerance of minus three-quarters (¾) inch and plus one (1) inch, of the nominal thickness. At no point shall the thickness of the base be less than six and three-quarters (6¾) inch. Over-thick base extending above Plan grade shall be regraded to conform to Par. ___ "Smoothness." Areas having less than the specified minimum thickness of 6¾ inches shall be removed and replaced. The Contractor shall furnish labor and materials for digging and repairing seven (7) test holes at locations designated by the Engineer. If seven (7) tests indicate by Acceptance Plan No. 1 that less than 80% of the base will fall within the specified tolerances, the thickness of the bituminous pavement shall be increased by one-half (½) inch over the entire area represented by the tests. All work in connection with test holes and all corrective measures shall be at the Contractor's expense.

ACCEPTANCE PLAN NO. 1

Locate the designated number of samples by use of a table of random numbers and make the specified measurements at these locations. Compute the average of these measurements, $\bar{X}$, and the difference, R, between the largest and the smallest measurement.

If an upper specification limit, U, is given, subtract $\bar{X}$ from this value and divide the result by R. Enter Table 5 or the chart which forms a part of the acceptance plan (similar to Fig. 14) with the result of this computation and read and record the percentage of material or construction which falls within the upper limit.

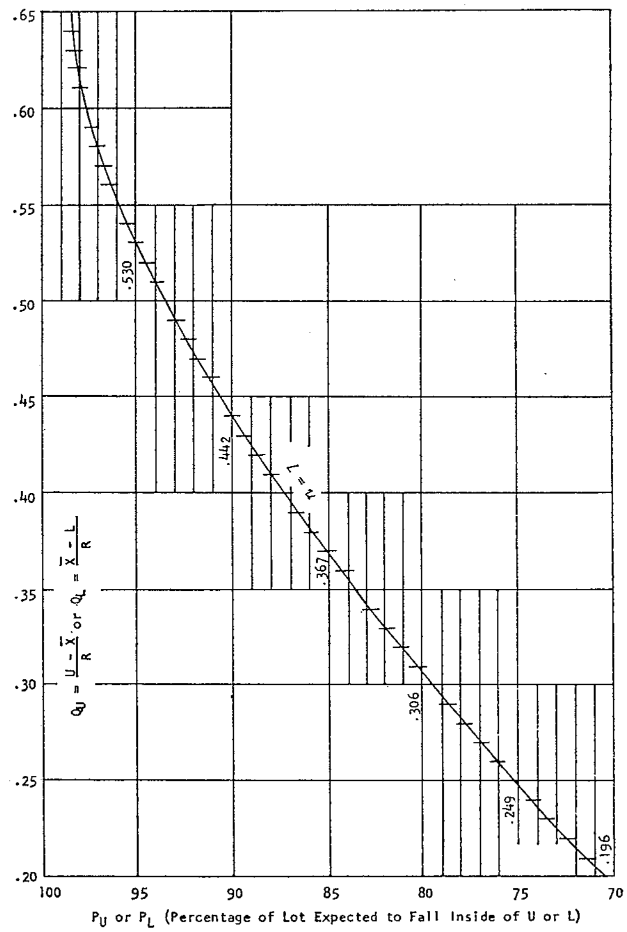


Figure 14. Lot acceptance plan range method, mean and variance unknown.

If a lower specification limit, L, is given, subtract this value from $\bar{X}$ and divide the result by R. Enter Table 5 or the chart which forms a part of the acceptance plan with the result of this computation and read and record the percentage of material or construction which falls within the lower limit.

USING THE ACCEPTANCE PLAN

Assume that a lot, in this case the day's construction of 1,500 ft of base, has been compacted and is ready for test. The engineer must make a decision as to whether or not the base meets specification requirements. As a first step, sampling locations are preselected by use of a table of random numbers. Then, test holes about 2 ft in diameter are dug at these locations and the thickness of the base is measured by placing a straightedge across each hole and measuring the distance to the subbase at the third-points of two diameters at right angles to each other. The four results for each test hole are averaged and recorded as follows:

STATION	OFFSET FROM LEFT (FT)	AVERAGE THICKNESS (IN.)
162 + 70	21	8.2
163 + 08	8	7.6
166 + 40	2	7.0 (X_1)
167 + 60	10	8.6 (X_7)
169 + 20	5	7.0
170 + 00	16	8.5
172 + 10	14	7.7
		Av. 7.8

In this case the upper specification limit is 9.0 in. Following the directions of the acceptance plan gives $\overline{X} = 7.8$, $U = 9.0$, $R = (X_7 - X_1) = (8.6 - 7.0) = 1.6$, $(U - \overline{X})/R = (9.0 - 7.8)/1.6 = 0.75$, and the chart (Fig. 14) indicates that more than 99 percent of the base will measure less than the upper limit of 9.0 in.

Similarly, with respect to the lower specification limit of 7.25 in., $\overline{X} = 7.8$, $L = 7.25$, $R = 1.6$, $(\overline{X} - L)/R = (7.8 - 7.25)/1.6 = 0.344$, and the chart (Fig. 14) indicates that more than 83 percent of the base will measure more than the lower limit of 7.25 in.

Inasmuch as the computations indicate that at least 83 percent of all measurements $[100 - (17 + 0)]$ will fall within the specified tolerances and no single measurement was less than 6.75 in., the acceptance plan indicates that the lot (1,500 ft of stone base) should be accepted.

DISCUSSION OF EXAMPLE

This example contains most of the features common to all advanced-type specifications and statistical acceptance plans, as follows:

1. The desired value of the characteristic (thickness) is stated, but it is qualified by the word "nominal" to make it clear that it is realized that there will be variations from this value.

2. A definite quantity of material or construction is specified for acceptance or rejection. This quantity is called a lot and this type of plan is called a lot acceptance plan. The lot is defined as a day's construction. The reason for this is that a lot is supposed to be a quantity of material or construction that is produced by essentially the same process. During the course of a day it is probable that the same materials and equipment will be used, so it is probable that the lot will be more alike from point to point than if it were made up of material processed on different days.

Some other kinds of lots might be a stockpile of aggregate, or the entire continuous production of one size of concrete pipe. The advantages of a lot acceptance plan are that the contractor knows where he stands from day to day and can take any necessary corrective action while equipment is at hand, and is alerted to the necessity of preventing defects in future work. Also, the engineer is protected from the possibility that a large quantity of defective work will be produced, and that the exigencies of the situation will make adequate correction impractical.

3. Realistic tolerances are stated. In this case, the tolerances would be realistic if they were based on a large number (600) of random measurements of *acceptable* base constructed under routine conditions. These measurements might reveal that the actual thickness varied from 1 in. under to 2 in. over at a very few points, but that computations based on *all* the measurements indicated that more than 80 percent could be expected to fall within the specified tolerances. Protection against extreme deviations that would affect performance is provided by definite statements as to maximum permissible deviations.

The contractor can have no complaint that tolerances so derived are too restrictive and are impossible to meet. On the other hand, the specification writer can be confident that these tolerances do completely describe acceptable construction and that they will not require unusual methods or equipment that would increase the cost value without increasing the use value. This cost-benefit relationship is discussed in another section of this report.

4. A definite number of measurements is specified. The principal reason for this is that the number of measurements is related to the risks of accepting poor material or rejecting good material. However, there is the additional advantage that standardizing the number of measurements makes for uniformity of specification enforcement from one job to another.

5. The acceptance plan specifies that the location of the measurements be determined by the use of a table of random numbers. This is absolutely essential if statistical methods are to be used. This method of location relieves the engineer or inspector of the responsibility of deciding what a "representative" sample is, and of charges of unfairness or favoritism to the contractor. Again, uniformity of specification enforcement is greatly improved.

6. The specification definitely requires the contractor to furnish labor, materials and equipment required to make the inspection possible. This relieves technically qualified personnel from manual labor and makes possible more efficient use of their special skills.

7. The acceptance plan requires that each recorded measurement be the average of four measurements made at each location. This not only averages out small deviations in thickness, but also fits the data better to the statistical method. Wherever multiple measurements are cheaply and easily obtained, it is advisable to use this method of averaging.

8. The specification states that a definite percentage of the *material or construction* be within the specified tolerances, not that a percentage of the measurements be in compliance. This is an important distinction, because in the statistical approach individual measurements are not considered significant—it is the information gained from the measurements as to the characteristics of the lot that is important. However, in some cases unusually large or unusually small measurements will appear in a group of measurements. Inasmuch as one such measurement can greatly affect the result of applying the acceptance criteria, a decision must be made as to whether to use such a measurement or to discard it. (Preferably, another measurement similarly obtained should be substituted.) In a previous

section ("Treatment of Outliers") a rule was given as to how to make this decision.

9. The acceptance plan includes detailed instructions as to how the required simple computations are to be made. Only a knowledge of arithmetic is required to design and apply any of the selected plans in this report.

10. To make possible the description of mathematical operations (such as adding, subtracting, and dividing) in the form of equations, certain symbols have been used in the acceptance plan. These are merely a kind of "shorthand" used to describe these operations clearly and compactly. Certain of these symbols and terms will be unfamiliar to some engineers, but their meanings are clearly defined. However, some statisticians may disagree with the definitions. Unfortunately, there is not good agreement on this matter, so symbols and terms that appear to be most appropriate for the particular purposes of this report have been selected and are used consistently.

11. As in all other acceptance plans, the final decision as to whether to accept or reject is made by comparing the number resulting from the computations with a standard. In this case the standard is a chart; in others it may be a table of numbers or a numerical value stated in the specifications. Some of the computations required to arrive at these standards involve complex and highly specialized mathematical procedures. However, this work has already been done and, as previously stated, the design and application of the selected plans presented in this report require only ordinary arithmetic and reference to easily available tables.

DESIGN OF SPECIFICATION ACCEPTANCE SAMPLING PLANS FOR HIGHWAY CONSTRUCTION

General Requirements

To be both realistic and practical any acceptance plan must satisfy certain prerequisites, which also involve some additional facets of the overall problem. The most important prerequisites are as follows:

1. There must be direct correlation between the criticality of the specification requirement as defined by the engineer and the "measurement" or "estimating" risk.

2. The buyer's risk and the seller's risk must be selected so that both the engineer and the contractor will be willing to accept the risk associated with the acceptance plan which corresponds to the criticality of the particular specification requirement.

3. The size of the sample (number of increments) required must be practical. Obviously, a plan which would require 20 or more increments from each lot would be too costly and time-consuming to be practical as the basis for accepting or rejecting most of the lots encountered in highway construction.

4. The tolerance limits must be reasonable and acceptable to the engineer. It is expected that some of the actual variations, both in materials of construction and in the sampling and testing procedures, will shock some engineers. Nevertheless, the tolerance limits established for any realistic and practical acceptance plan must reasonably reflect successful past construction experience.

5. The statistical procedures and the mathematical calculations must be simple and straightforward, so that the method can be understood and used by highway personnel without excessive training or specialized instruction.

6. A particular specification requirement must be explicit and subject to one, and only one, interpretation by the lawyer, the accountant, and the special investigator, as well as by the engineer, the materials supplier, and the contractor.

7. The plan must be suitable for use by the highway industry. It must be so designed as to be applicable to the various types of materials and construction on both big jobs and small ones.

Types of Acceptance Plans

This report presents and exemplifies two general types of acceptance plans—those for inspection by VARIABLES and those for inspection by ATTRIBUTES.

SAMPLING PLANS FOR INSPECTIONS BY VARIABLES

Sampling plans for inspection by variables apply to all cases where a characteristic is measured, such as the tensile strength of reinforcing steel. There are two cases—one where the standard deviation is known, the other where it is not. Actually, in most applications of statistical methods to highway construction specifications, the true standard deviation, σ', is not known. However, it may be assumed to be known if it is estimated from a large number of measurements of the value of a characteristic, and the process that produced the material or construction can be assumed to be stable and free from assignable causes of variation. If the true standard deviation is known, both the buyer's and the seller's risks can be set at any desired value, slightly fewer tests are necessary upon which to base an acceptance decision, and the acceptance rule can be more simply stated.

When the true standard deviation, σ', is not known, it must be estimated from the measurements on a sample or from values typical of similar conditions. One of the plans presented in this report makes use of the range estimate, R, of σ'. When the standard deviation is not known, only one risk, either the buyer's or the seller's, can be controlled. The other will depend on the true value of the standard deviation. In this report the approach has been to fix the buyer's risk. The plan then places a premium on uniformity, because material or construction which has an acceptable average quality, and has a uniform value of the measured characteristic, is less likely to be rejected than if the value varies widely. Inasmuch as a uniform, as well as an acceptable average, level of quality is usually highly desirable in highway construction, a plan using this approach appears to be generally appropriate.

Other advantages are that, if it is not assumed that the standard deviation is known, plans can be designed that will be appropriate for similar materials that are produced by different processes, and for similar items of construction that are produced by different methods, using different types of materials. An estimate of σ' obtained from typical values, such as those derived from similar construction, if available from a SIGMA BANK, is necessary if the seller's risk is to be estimated.

With any type of variable acceptance plan, specification limits may take three forms. There may be an upper limit, a lower limit, or both an upper and lower limit for the measured characteristic. The plan may be designed in one of two ways. It may specify a minimum percentage of material or construction having a value of the measured characteristic within the limit(s), or a maximum or minimum value of a characteristic may be specified.

ATTRIBUTES PLANS

Attributes acceptance plans are those that must be used when it is not practical to measure a characteristic, and each item inspected must be classed as either suitable or defective. Many types of such plans are available; however, in this report only one type, called a "single sampling plan," is discussed and exemplified. This type of acceptance plan can be used in connection with specifications such as those limiting the number of chipped bells in a lot of concrete pipe, or the number of out-of-tolerance deviations from a straightedge in a lot consisting of a day's construction of a pavement course.

To use an attributes plan the specifications must state the percentage of DEFECTIVES that will be allowed in an acceptable lot. The acceptance sampling procedure that will accept a lot of this quality most of the time consists of drawing a sample of n items from the lot and inspecting them for defects, or by making n observations as to whether a tolerance has been exceeded. The number of defectives found among n items is then compared with a tabular value. If the number of defectives in the sample is greater than the tabular value the lot is rejected. Tabular values for various values of AQL (ACCEPTABLE QUALITY LEVEL) and n are given in Table 3.

Extensive tables are available in MIL-STD-105D, *Military Standard for Sampling Procedures and Tables for Inspection by Attributes.*

Engineering Criteria and Risks

FACTORS AFFECTING CRITICALITY

From the engineering viewpoint each specification limit and its associated acceptance plan should be based on the CRITICALITY of the measured property as it affects safety, performance, or durability. The word "criticality" has been selected for use in this report to express the overall concept of relative importance of various factors, because it is more descriptive and shorter than the expression "degree of criticalness." The factors to be considered in determining criticality are:

1. *Safety*—danger to human life.
2. *Serviceability*—inconvenience and other consequences, including military, of disruption of service or use of the road or bridge.
3. *Cost*—for construction, control, and maintenance or replacement.

TABLE 2
PROBABILITY OF REJECTION RELATED TO CRITICALITY

CLASSIFICATION OF REQUIREMENT	P_g	P_p
Critical	0.050	0.995
Major	0.010	0.950
Minor	0.005	0.900
Contractual	0.001	0.800

CRITICALITY RATINGS

For classification purposes, the following ratings of criticality are suggested:

Critical—when the requirement is essential to preservation of life.
Major—when the requirement is necessary for the prevention of substantial economic loss.
Minor—when the requirement does not materially affect performance.
Contractual—when the requirement is established to control uniformity and/or provide a standard basis for bidding.

GUIDELINES FOR CHOOSING RISKS ACCORDING TO CRITICALITY OF REQUIREMENT

As discussed earlier, there is a buyer's risk and a seller's risk involved each time a decision is made to accept or reject a lot of material or construction. The limits to be placed on these risks, and the way they are to be divided between buyer and seller, depend largely on the criticality rating of the requirement. For example, if the requirement were really critical, such as the tensile strength of the steel reinforcing strands in precast concrete bridge members, the specifications should be written to reduce to an absolute minimum the risk of accepting lots of reinforcement of unacceptable quality. On the other hand, if the requirement were purely contractual in purpose, such as the 5-ft length of tie-bars for longitudinal joints in concrete pavement, the risk of rejecting acceptable lots should be kept to a minimum because rejected lots would eventually lead to an increase in cost.

Suggested values of probabilities associated with criticality are given in Table 2. For convenience in using these values in equations and when referring to tables, the risks are stated in terms of:

P_g = The approximate probability of rejecting acceptable material or construction having the desired mean value, $\bar{X}'_g$, of the measured characteristic.

P_p = The probability of rejecting unacceptable material or construction having a mean value, $\bar{X}'_p$, of the measured characteristic which denotes the material or construction as poor or undesirable.

In general, high probability of rejection gives increased assurance that only high-quality material will be accepted, but it also eventually results in increased costs because additional material will be rejected unless the actual average is maintained at an unrealistically high level. Acceptance plans operate in such a way that if the standard deviation, σ, of the actual construction or the material is less than the desired value, the probability of rejecting good material is decreased. The reverse is also true. When this is understood by the contractor or producer it creates a strong incentive to supply construction or material of uniformly high quality.

GUIDELINES FOR DEVELOPING ACCEPTANCE LIMITS FOR SPECIFICATIONS

Preliminary Considerations

OBJECTIVES

The objectives of including numerical limits in a specification are to insure adequate performance at minimum cost. Inasmuch as increased quality usually means increased cost, in the form of higher bid price and additional engineering time and expense, use value and aesthetic value must be carefully balanced against cost value. The exact quality that the buyer is willing to pay for should be specified in terms of realistic and enforceable numerical limits of significant characteristics.

DEFINING QUALITY

A significant characteristic is one that directly affects the performance or appearance of a material or an item of construction. As such, it is the measure of quality. To insure quality, it is necessary to place upper, or lower, or both upper and lower limits on some characterizing factor of one or more significant characteristics of a material or item of construction. In the area of highway construction this is sometimes difficult to accomplish. Sometimes the significant characteristic is not known; more often it cannot be measured directly; and, in most cases, the exact relationship between the numerical value of a measured significant characteristic and functional performance or cost is not well defined. For example, one significant characteristic of a steel bolt is its diameter. If the diameter is too large, the bolt will not enter the hole prepared for it. If the diameter is too small, the bolt will not have its full strength and the loose fit may allow misalignment of the parts that it joins. The diameter of a bolt may be specified to almost any desired degree of accuracy (it is easily measured) and the expense of attaining the desired quality may be estimated from known machining and inspection costs. However, in the case of asphalt cement, which is a widely-used construction material, there is no general agreement as to the significant characteristic that affects the durability of the pavement in which the asphalt is used. As a result, the desired quality of asphalt cement is currently defined in terms of measurable properties such as penetration, ductility, viscosity, and spot test, which are mostly methods of identification rather than a means of evaluating quality.

In the case of portland cement concrete, the significant characteristic that chiefly determines the compressive strength of this material is the cement/voids ratio, which in turn is a function of the water/cement ratio and the percentage of entrained air. Because it usually is not practical to measure the cement/voids ratio of plastic concrete directly under construction conditions, the desired quality is often defined in terms of measured properties such as cement content, slump, and percent entrained air.

Resistance to plastic flow is a significant characteristic of asphaltic concrete; it is evident that below some critical value of resistance the pavement would be deformed by traffic and become unserviceable. However, when resistance to plastic flow is estimated from some measurable property, such as Marshall stability, the critical value is not well defined, because asphaltic concrete mixtures having a Marshall stability ranging from 300 to more than 2,500 lb have given satisfactory performance.

A practical specification should define the desired quality in terms of realistic levels of significant characteristics. Where this is not entirely possible the requirements must be stated in terms of measurable properties, but it should be kept in mind that more exacting requirements for a measurable property will probably increase cost value but will not necessarily increase use value.

PURPOSE OF LIMITS

The purpose of prescribing numerical limits for a measurable property may be to insure that some critical value that would affect performance is not exceeded, or to insure uniformity. For example, the job-mix formula for asphaltic concrete specifies a size of sieve through which all of the aggregate must pass and a range within which the percentages passing smaller sieves must be maintained.

One purpose of limiting the maximum size of the aggregate particles is to avoid difficulties in placement and rolling, and one purpose of placing limits on the percentages passing the other sieves is to insure uniformity of aggregate voidage. This is necessary, because a significant characteristic of asphaltic concrete which greatly affects performance is the ratio of asphalt by volume, S_b, to the aggregate voids, V_a, usually called the percent voids filled with asphalt. Unless this ratio is maintained at about the value given by

$$S_b = 0.833 \text{ VMA} - 1.4 \qquad (3)$$

the asphaltic pavement will be either overplastic or less durable. From Eq. 3 it is evident that the aggregate voidage must be controlled at a constant value or the asphalt content would have to be adjusted whenever a change occurred. Because when other factors are constant aggregate voidage is a function of gradation, it is necessary to control the gradation so that changes in the percentage of aggregate voids do not result in a surplus or deficiency of asphalt.

BASIS FOR ESTABLISHING VALUES OF NUMERICAL LIMITS

In the foregoing example the significant characteristic was the percentage of voids filled with asphalt, but the measured property was the aggregate gradation. Although current specifications place arbitrary job-mix formula limits on the gradation, it is apparent that to establish a realistic basis for these limits would require that the permissible range of the percentage of voids filled with asphalt be determined, and that the allowable variations in gradation of an aggregate for a particular asphaltic concrete mixture be determined with respect to this range. Although it is possible to derive the required values by means of a theoretical or an experimental approach, a more practical method is to measure the properties of acceptable construction. By means of PROBABILITY SAMPLING the level and normal variation of the measured property can be directly determined.

PRACTICAL PROCEDURE FOR ESTABLISHING REALISTIC LIMITS

1. Determine the significant characteristics which are known or are believed to control the performance of the material or construction.
2. If a significant characteristic cannot be measured directly, determine the properties which are known or are believed to be correlated with the significant characteristic and which are practical to measure.
3. Select the method of test by which it is most practical to find the value of the measured property. This involves consideration of (a) the suitability of the method as a control test that will provide a quick indication of a deficiency at a time when remedial action is possible, (b) equipment and manpower costs, and (c) the accuracy of determination. A method with a large associated EXPERIMENTAL ERROR may be preferable to a more PRECISE method if a large number of test results can be obtained in a short time, because a large standard deviation of the test method can be reduced if a sufficient number of measurements is available.
4. Using the selected test method, which will be used for acceptance purposes, make a sufficient number of measurements to provide acceptable estimates of the mean and the standard deviation of the measured property, by means of probability sampling.
5. Repeat Step 4 a sufficient number of times at different locations to determine if the standard deviation of the measured property (a) varies widely due to different construction conditions, equipment, or materials and the average value of the characteristic also has a wide variation; (b) varies widely, but the average value of the property remains near the target value; or (c) is practically constant under usual construction conditions.
6. On the basis of analysis of results obtained by Step 5, choose the appropriate acceptance plan from the "Guidelines for Selection of Type of Acceptance Plan," given later in this chapter.

OTHER METHODS OF ESTABLISHING NUMERICAL LIMITS

Limits may be assigned values based on engineering requirements or on those in standard specifications. However, care must be taken to make sure that these limits are actually realistic when applied to local materials and performance requirements. The test method specified for acceptance must be the same as that used when the limits were derived. For example, when applying Marshall voids criteria use of bulk specific gravity of aggregates instead of apparent specific gravity would lead to erroneous decisions.

Statistical limits based on existing specifications or from the analysis of historical data may not necessarily be realistic, because statistical limits are designed to include the normal variations of the measured property on probability samples. Current specification limits and many historical data are often based on representative samples and, in some cases, the results of resampling.

Guidelines for Selection of Type of Acceptance Plan

CASE 1—PLAN TO ESTIMATE PERCENT WITHIN TOLERANCE; MEAN AND STANDARD DEVIATION UNKNOWN

When there is no information as to the mean or standard deviation of a measured property, or if it is known that these parameters vary over a wide range, the criterion for the acceptance plan may be the percentage of measurements on a lot that may be expected to fall within a given limit or limits. Such a limit may be an arbitrary or assigned value, but to be realistic the value and the expected percentage of within-tolerance material or construction should be derived from measurements on probability samples taken from acceptable materials or construction.

The use of this type of acceptance plan has been described in the section on "Use of Statistical Methods," under "Application of Statistical Methods." Although easy to design and use, this plan has the disadvantage that in some cases it is difficult to estimate the risks of making a Type I or Type II error, and these risks cannot be fixed.

CASE 2—PLAN TO PROVIDE FIXED PROTECTION AGAINST ACCEPTING POOR MATERIAL; STANDARD DEVIATION UNKNOWN.

This is a most efficient plan because it makes maximum use of all available information pertinent to the acceptance situation. Unlike the usual plans used in industry, this plan is designed to provide a fixed probability of rejecting poor lots and places on the seller (contractor or producer) the responsibility of supplying construction or material of uniform acceptable quality. Increased variation in quality or a decrease in level of quality greatly increases the seller's risk of rejection.

To make a decision as to whether to accept or reject a lot, it is only necessary to make four or more measurements, compute their average ($\bar{X}$) and range, and divide the difference between the average of the measurements and the mean value of poor (unacceptable) material by a value computed from the range of the sample measurements. If the result is smaller or larger than the appropriate lower or upper specification limit the lot is rejected.

This is probably the plan most suitable for general use in all cases where *unacceptable* material or construction can be defined in terms of the mean value of some significant characteristic or measurable property. No further information is needed to fix the buyer's risk. To estimate the seller's risk a reasonably good estimate of the standard deviation must be available or must be derived. An estimate may be obtained from measurements on probability samples taken from similar materials or construction, such as those on file in a sigma bank.

If such an estimate is not available, a reasonably reliable value of σ may be derived by first estimating the

TABLE 3

SINGLE SAMPLING PLANS FOR NORMAL INSPECTION

LOT OR BATCH SIZE	SAMPLE SIZE (NO.)	ACCEPTABLE QUALITY LEVELS[a] (NORMAL INSPECTION)																									
		0.010	0.015	0.025	0.040	0.065	0.10	0.15	0.25	0 40	0.65	1.0	1.5	2.5	4.0	6.5	10	15	25	40	65	100	150	250	400	650	1000
		AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE
2 to 8	2															0 1		▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	30 31
9 to 15	3													▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	30 31	44 45
16 to 25	5												▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	30 31	44 45	▲
26 to 50	8											▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	30 31	44 45	▲	
51 to 90	13										▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	30 31	44 45	▲		
91 to 150	20									▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	▲	▲	▲			
151 to 280	32								▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	▲						
281 to 500	50							▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	▲							
501 to 1200	80						▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	▲								
1201 to 3200	125					▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	▲									
3201 to 10000	200				▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	▲										
10001 to 35000	315			▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	▲											
35001 to 150000	500		▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	▲												
150001 to 500000	800	▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	▲													
500001 and over	1250	0 1	▲		1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	▲														

[a] ▼ = Use first sampling plan below arrow. If sample size equals or exceeds lot or batch size, do 100 percent inspection. ▲ = Use first sampling plan above arrow.

Aç = Acceptance number. Re = Rejection number.

range within which 95 percent of the values of the measurement can be expected to fall and dividing this difference by four; that is,

$$\sigma = \frac{R_{95}}{4} \tag{4}$$

The chief disadvantage is that although the seller's risk, or probability of rejecting acceptable material or construction, can be estimated for a particular situation, this is not a fixed value but will increase as the actual variability of the measured property increases.

CASE 3—PLAN TO PROVIDE FIXED PROTECTION AGAINST ACCEPTING POOR MATERIAL OR REJECTING GOOD MATERIAL; STANDARD DEVIATION KNOWN

This plan is suitable for use when either acceptable or unacceptable material or construction can be defined in terms of the mean value of some significant characteristic or measurable property and the standard deviation is known.

The advantages of this type of plan are that both the buyer's and the seller's risk can be fixed and a somewhat lesser number of measurements is required on which to base an acceptance decision.

CASE 4—PLAN TO PROVIDE PROTECTION AGAINST ACCEPTING LOTS CONTAINING AN EXCESSIVE PERCENTAGE OF DEFECTIVE ITEMS

This type of plan must be used when the significant characteristic cannot be measured and is not associated with a measurable property. In such a situation, the acceptance decision is based on the number of defectives in the lot. Examples are the number of chipped bells in the quantity of 24-in. concrete pipe set aside for shipment to a project, or the number of deviations from straightedge tolerance in a day's construction of pavement.

The recommended plans have seller's risk, or probability of rejecting good material or construction, of from 11 percent to 1 percent, depending on the size of the lot, and provide a choice of values for the buyer's risk. To use the plan, a definite number of observations is made by probability sampling. The number of observations which indicate out-of-tolerance conditions, or defectives, is then compared with a tabular value (see Table 3). If this value is exceeded the lot is rejected. (Although this type of plan is easy to design and use, it is not as efficient as plans using measurements as a basis for the acceptance decision. In other words, more observations than measurements are required for the same risk of making a Type I or Type II error.)

Guidelines for Design of Specification Acceptance Plans

CASE 1—PLAN TO ESTIMATE PERCENT WITHIN TOLERANCE; MEAN AND STANDARD DEVIATION UNKNOWN

Step 1—State the desired nominal value of the recorded measurement.

Step 2—State the number of increments in the sample or the number of random locations at which acceptance measurements are to be made. Suggested numbers, based on the criticality of the significant characteristic to which the plan applies, are given in Table 4.

TABLE 4

NUMBER OF MEASUREMENTS IN RELATION TO CRITICALITY

CLASSIFICATION OF CHARACTERISTIC	NUMBER OF MEASUREMENTS
Critical	9
Major	7
Minor	5
Contractual	4

Step 3—State the tolerance on this measurement (or the upper and lower tolerances in the case of a double specification limit), and the percentage of the material or construction that must fall within the tolerance(s).

The tolerance(s) and the expected percent within tolerance must be realistic and should be based on the values of the measurement found in acceptable construction.

Step 4—State the action to be taken if the percentage of within-tolerance material or construction is less than that specified.

Step 5—State the extreme limit(s) of the measurement for acceptable material or construction and the action to be taken if this requirement is not met.

Step 6—Supply directions for applying the acceptance plan, using standard symbols as defined in the glossary.

(a) Average all measurements to find $\bar{X}$; that is,

$$\bar{X} = \frac{\Sigma X_i}{n} \tag{5}$$

(b) In cases where sample size is < 10 find R by subtracting the smallest value from the largest value in the group of measurements.

(c) In cases where sample size ≥ 10 arrange measurements in the order of their taking and divide into subgroups of 5 each. Find R for each subgroup, add these values, and divide by the number of subgroups to find $\bar{R}$.

(d) Find the quality index, Q_U, from

$$Q_U = \frac{(U - \bar{X})}{R \text{ (or } \bar{R})} \tag{6}$$

(e) Find the quality index, Q_L, from

$$Q_L = \frac{(\bar{X} - L)}{R \text{ (or } \bar{R})} \tag{7}$$

(f) Estimate the percentage of the lot within the upper tolerance limit by entering Table 5 with Q_U, using the column appropriate to the total number, n, of measurements.

(g) Estimate the percentage of the lot within the lower tolerance by entering Table 5 with Q_L, using the column appropriate to the total number, n, of measurements. (The tabular values may be placed in graph form when a fixed number of measurements is to be used in connection with a particular acceptance plan.)

(h) In cases where both upper and lower tolerance

TABLE 5

TABLE FOR ESTIMATING PERCENT OF LOT WITHIN TOLERANCE (RANGE METHOD)

PERCENT WITHIN TOLERANCE	Q_U OR Q_L										
	$n=4$	$n=5$	$n=7$	$n=10$*	$n=15$*	$n=25$*	$n=30$*	$n=35$*	$n=40$*	$n=50$*	$n=60$*
99	0.66	0.66	0.65	0.82	0.88	0.93	0.94	0.95	0.95	0.97	0.97
98	0.64	0.65	0.61	0.76	0.80	0.83	0.84	0.85	0.85	0.86	0.86
97	0.63	0.62	0.58	0.71	0.74	0.77	0.78	0.78	0.78	0.79	0.79
96	0.62	0.60	0.55	0.68	0.68	0.72	0.73	0.73	0.73	0.74	0.74
95	0.60	0.58	0.53	0.64	0.66	0.68	0.68	0.69	0.69	0.70	0.70
94	0.59	0.57	0.51	0.62	0.63	0.64	0.65	0.65	0.66	0.66	0.66
93	0.58	0.55	0.49	0.59	0.61	0.61	0.62	0.62	0.62	0.62	0.62
92	0.56	0.53	0.47	0.57	0.58	0.59	0.59	0.59	0.59	0.60	0.60
91	0.55	0.51	0.46	0.54	0.55	0.56	0.57	0.57	0.57	0.57	0.57
90	0.54	0.50	0.44	0.52	0.53	0.54	0.54	0.54	0.54	0.55	0.55
89	0.52	0.48	0.43	0.50	0.51	0.52	0.52	0.52	0.52	0.52	0.52
88	0.51	0.46	0.41	0.48	0.49	0.50	0.50	0.50	0.50	0.50	0.50
87	0.50	0.45	0.40	0.47	0.47	0.47	0.48	0.48	0.48	0.48	0.48
86	0.48	0.44	0.38	0.45	0.45	0.46	0.46	0.46	0.46	0.46	0.46
85	0.47	0.42	0.37	0.43	0.44	0.44	0.44	0.44	0.44	0.44	0.44
84	0.46	0.41	0.36	0.42	0.42	0.42	0.43	0.43	0.43	0.42	0.42
83	0.44	0.40	0.34	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.41
82	0.43	0.38	0.33	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39
81	0.42	0.37	0.32	0.37	0.37	0.37	0.37	0.37	0.38	0.38	0.38
80	0.40	0.36	0.31	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36
79	0.39	0.34	0.29	0.34	0.34	0.34	0.34	0.34	0.35	0.35	0.35
78	0.38	0.33	0.28	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
77	0.36	0.32	0.27	0.32	0.32	0.31	0.31	0.32	0.32	0.32	0.32
76	0.35	0.30	0.26	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
75	0.34	0.29	0.25	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
74	0.32	0.28	0.24	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
73	0.31	0.27	0.23	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.27
72	0.30	0.25	0.22	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
71	0.28	0.24	0.20	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
70	0.27	0.23	0.19	0.22	0.23	0.22	0.23	0.23	0.23	0.23	0.23
69	0.26	0.22	0.18	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
68	0.24	0.21	0.17	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
67	0.23	0.19	0.16	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
66	0.21	0.18	0.15	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
65	0.20	0.17	0.14	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
64	0.19	0.16	0.13	0.15	0.16	0.15	0.15	0.15	0.15	0.15	0.15
63	0.17	0.15	0.12	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
62	0.16	0.14	0.11	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
61	0.15	0.13	0.10	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
60	0.13	0.11	0.09	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11

* When $n \geqq 10$, the samples are arranged consecutively in subgroups of five, the range, R, of each subgroup is determined, and the average range, $\bar{R}$, of all subgroups is computed for use in finding Q_U or Q_L.

TABLE 6

SUGGESTED BALANCE OF ACCEPTANCE SPECIFICATION FACTORS; STANDARD DEVIATION UNKNOWN

CRITICALITY OF REQUIREMENT	PROBABILITY [a] OF REJECTION OF GOOD MATERIAL, P_g	PROBABILITY OF REJECTION OF POOR MATERIAL, P_p	t	NUMBER OF MEASUREMENTS, n	DIFFERENCE BETWEEN MEANS, T_a [b]	ACCEPTANCE LIMITS [c]
Critical	0.0640	0.995	3.355	9	$\pm 1.75\sigma$	$\bar{X}'_p \pm 0.376R$
Major	0.0085	0.95	1.943	7	$\pm 1.75\sigma$	$\bar{X}'_p \pm 0.271R$
Minor	0.0043	0.90	1.533	5	$\pm 2.00\sigma$	$\bar{X}'_p \pm 0.295R$
Contractual	0.0005	0.80	0.978	4	$\pm 2.25\sigma$	$X'_p \pm 0.237R$

[a] Probabilities for single limit specification. When specification has both an upper and a lower limit, the probability of rejecting acceptable material may theoretically be doubled.

[b] Difference between means is approximately equal to the estimated value of σ multiplied by the tabulated factors.

[c] $\bar{X}'_p \pm T_s$.

limits are involved, find the percentage of the lot within the tolerances from

$$P_{U,L} = (P_U + P_L) - 100 \qquad (8)$$

This is the acceptance plan illustrated with the thickness of crushed stone base example previously discussed.

CASE 2—PLAN TO PROVIDE FIXED PROTECTION AGAINST ACCEPTING POOR MATERIAL; STANDARD DEVIATION UNKNOWN.

Definition of Symbols—In describing a plan diagrammatically, it is necessary to use certain symbols, which are defined as follows:

$\bar{X}'_g$ = the mean value of a lot which is acceptable and should have a small probability of rejection, P_g;

$\bar{X}'_p$ = the mean value of a lot which is of borderline quality or unacceptable and should have a high probability of rejection, P_p;

P_g = (see $\bar{X}'_g$);

P_p = (see $\bar{X}'_p$);

$K_p = \dfrac{\bar{X}'_g - \bar{X}'_p}{\sigma}$ = the number of standard deviation units between the average value of the measured characteristic in acceptable and unacceptable construction or material;

T_a = the distance between means ($\bar{X}'_g - \bar{X}'_p$), in measurement units;

R = the range of the measurements of the characteristic made on the sample, or the difference between the largest and smallest test values;

M = a factor used to convert the sample standard deviation, s, to the range, R, or $s = M\,R$. Needed values of M are 0.486, 0.430, 0.370, and 0.337, respectively, for n = 4, 5, 7, and 9;

t = the number of standard deviation units which define a given area under the t distribution curve;

s = an estimate of the standard deviation, σ, in this plan computed from the range, R;

n = the number of increments to be measured and on which the acceptance decision is to be based. Note that this is a fixed number of measurements and not a minimum. In general, other factors remaining constant, increasing the number of measurements will decrease the risk of accepting unacceptable material or of rejecting acceptable material.

General Considerations—To design this type of plan, with a fixed probability, P_p, of rejection of poor material, for a particular specification, it is necessary to specify the value of $\bar{X}'_p$ for lots of *unacceptable* material. As previously discussed, this value should be based on reasonable engineering requirements or on the characteristics of acceptable materials or construction. As nearly as possible, the exact quality or use value required should be specified inasmuch as the necessary safety factors or tolerances are built into the acceptance plan and the use of a higher value can only result in increased cost, or enforcement difficulties. The probability P_p should be chosen on the basis of the criticality of the characteristic. The probability P_g of rejecting acceptable material will be as given in Table 6 when the actual value of the standard deviation is equal to the estimated or derived value.

For convenience, suggested values of P_g and P_p are given in Table 6 for different classifications of the criticality of the significant characteristic or measured property, as discussed previously. If this classification of criticality and the associated pairs of P_g and P_p are accepted, all the information necessary to set specification limits by use of this plan is given in Table 6.

When using this particular sampling plan, unacceptable material means material drawn from a lot with mean $\bar{X}'_p$; P_g is the probability of rejecting this material. For example, if the specification has only a lower, or an upper limit, and if 1,000 lots of critical material of unacceptable quality were offered for test and were accepted or rejected according to this plan, 99.5 percent, or about 995 lots, would be rejected.

If the specification has only a lower, or an upper limit, and the actual value of the lot standard deviation, σ, is equal to the assumed or derived value so that the distance between the means, T_a, of acceptable and unacceptable material is approximately equal to $K_p\sigma$, the probability of rejecting acceptable lots of critical material is 6.4 percent. For example, if 1,000 lots of critical material were offered for test and were accepted or rejected according to this plan, about 64 lots would be rejected.

If the specification has both an upper and a lower limit, the probability of rejecting good material is doubled and P_g becomes 12.8 percent, so that about 128 acceptable lots would be rejected.

There are three possible cases: (2-a) the specification states a lower limit of acceptability; (2-b) the specification states an upper limit of acceptability; and (2-c) the specification states both an upper and a lower limit. These cases are illustrated by the following practical examples of the method of incorporating this acceptance plan into specifications.

CASE (2-a)—LOWER LIMIT ONLY

A specification is to be prepared for a granular subbase. The source of this material will be local deposits of sand which vary widely in maximum size. One of the objectives of the specification is to provide a stable working platform which will not be rutted or displaced by the equipment used to construct the base course. Because it is not practical to specify gradation bands which will be suitable for all the possible sources, and which will insure the stability of the subbase, it is decided to specify a minimum value for the UNIFORMITY COEFFICIENT, C_u, in addition to other quality requirements. The uniformity coefficient is defined as the ratio of the diameter of the 60 percent finer point to that at the 10 percent finer point on the gradation curve.

It is known that local sands having a value of C_u less than 3.5 are of borderline stability, so $C_u = 3.5$ is selected as the average value of unacceptable material ($\bar{X}'_p$). Because remedial measures are easily applied if the subbase does not meet the specification requirement and proves to be unstable, the requirement is classified as minor, so the

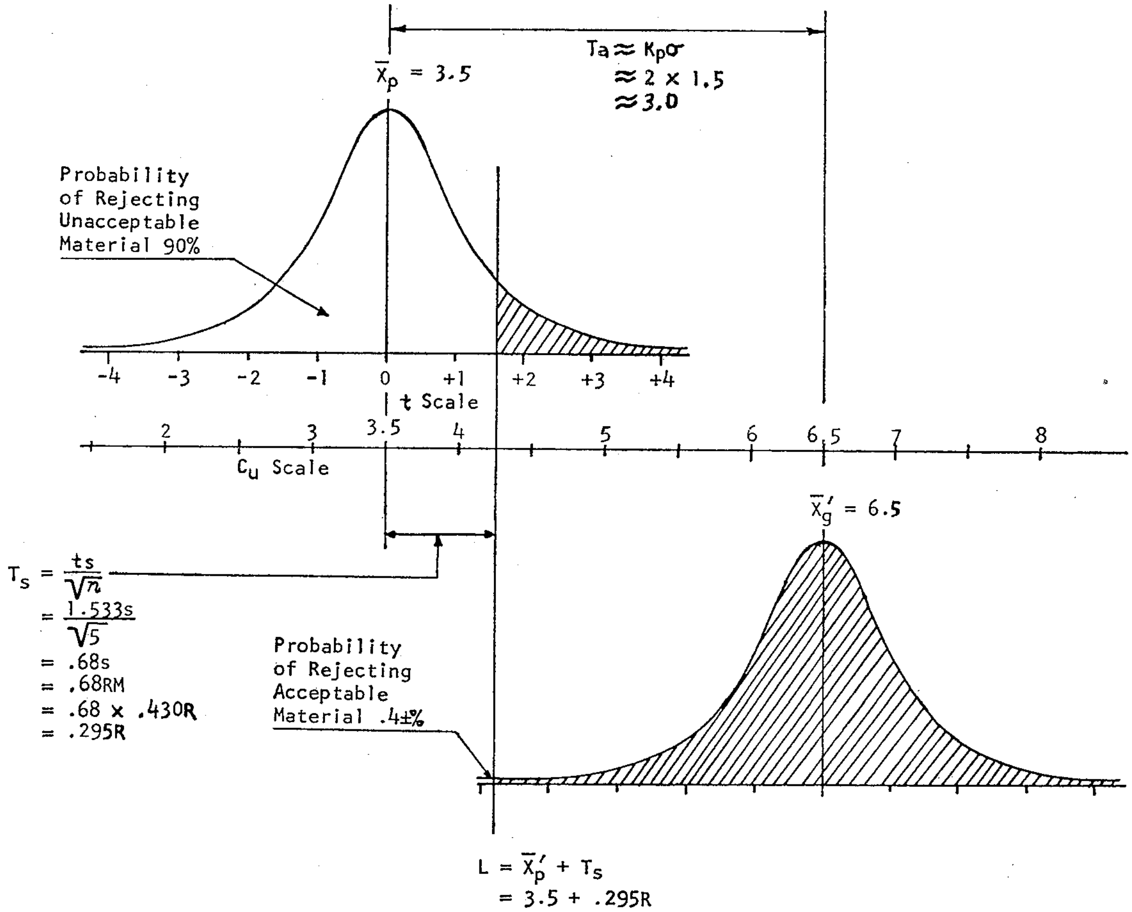


Figure 15. Probabilities P_p *and* P_g *of rejecting lots when* $\overline{X}'_g - \overline{X}'_p = 3.0\ C_u$.

lower acceptance limit (from Table 6) is $L = \overline{X}'_p +$ $0.295\ R = 3.5 + 0.295\ R$.

The acceptance rule will be: If the average ($\overline{X}$) of the measurements on five samples is less than L, reject the lot; if the average ($\overline{X}$) is equal to or greater than L, accept the lot.

The specification for the subbase material would read, in part, as follows:

GRADATION

Granular subbase material shall be taken from pits approved by the Engineer and shall all pass a three (3) inch sieve. The material shall have a nominal minimum Uniformity Coefficient (C_u) of 6.5. Labor and equipment shall be furnished for the taking of samples from the completed subbase at locations designated by the Engineer. Five (5) samples shall be taken for each 1,500 feet, or less, of subbase constructed with material from a single source. If the results of the gradation tests on the five samples have an average value of C_u less than 3.5 plus 0.295 times the difference between the largest and smallest value, the material composing the 1,500 feet, or less, of the subbase represented by the samples shall be removed and replaced, or brought to a stable condition by an approved method.

Any material having a C_u value of less than 3.5 shall be removed and replaced with material meeting specification requirements.

If it is estimated that the standard deviation of C_u will be about 1.5, the situation may be visualized as shown by Figure 15. These sketches are similar to those of the normal distribution, appropriate if the standard deviation is known; but since the standard deviation is not known, a NON-CENTRAL t DISTRIBUTION is being used and the distribution curves shown are not to scale.

In Figure 15, the value of L, in the units of the characteristic C_u, is not fixed, but depends on s, which is the measure of variability of the lot. As the material becomes more variable, the value of L is increased so that the probability of rejecting a lot having an average value of $C_u = 3.5$ remains at 90 percent. It is doubtful that a natural material, taken from various pits, would have a constant standard deviation, but this is automatically taken care of by the acceptance plan so that there is never more than a 10 percent risk of making a Type II error and accepting borderline material.

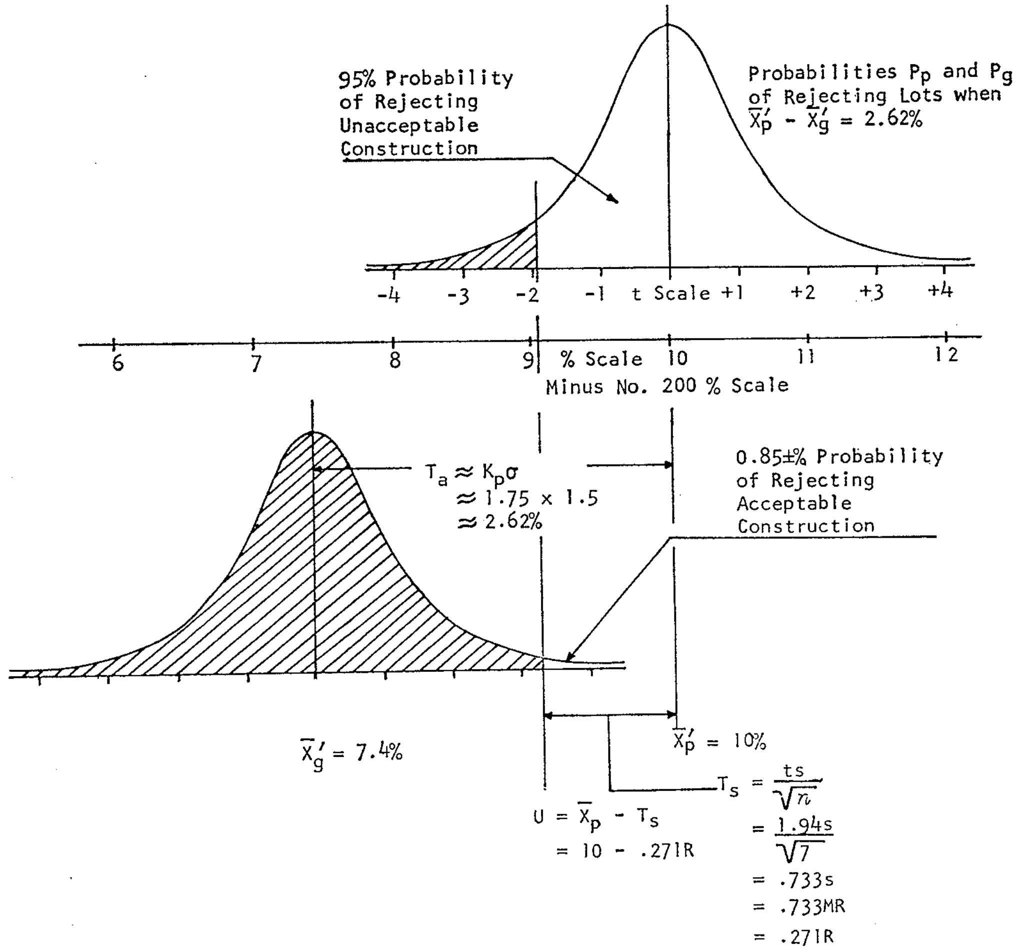


Figure 16. Probabilities P_p *and* P_g *of rejecting lots when* $\overline{X}'_p - \overline{X}'_g = 2.62\%$.

On the other hand, it is to the contractor's advantage not only to supply a subbase material with a high C_u value, but also to maintain as uniform a value as possible, because high variability could lead to rejection of material having a satisfactory average value.

CASE (2-b)—UPPER LIMIT ONLY

A specification is to be prepared for a base course composed of 1½-in. maximum size, graded crushed stone. It is known that a very critical significant characteristic, with respect to performance, is the percentage by weight of the material in place that will pass the No. 200 sieve. The optimum percentage for 1½-in. maximum size, well-graded stone is about 9 percent and a quantity of minus No. 200 in excess of 12 percent will lower the load-carrying capacity of the base and make it frost susceptible. On a judgment basis, lots of unacceptable material are defined as those containing a mean value of 10 percent or more of minus No. 200 material. Because this is an essential quality requirement the buyer is willing to pay the cost of (a) necessary processing (such as washing the aggregate) and (b) using rubber-tired compaction equipment to minimize degradation, in order to obtain maximum use value. To make sure that the buyer gets the quality paid for, it is necessary to design an acceptance plan that will provide a high probability of rejecting unacceptable base construction containing as much as 10 percent minus No. 200 material. To do this, the characteristic is classed as major and the number of samples, n, and acceptance limit, U, are taken from Table 6. The upper acceptance limit, U, is then $X'_p - 0.271\ R = 10 - 0.271\ R$. The specification would read, in part, as follows:

> The nominal percentage of material passing the No. 200 sieve in the compacted base shall be nine (9) percent. The Contractor shall furnish labor and equipment for removing seven (7) samples from each day's base construction at locations designated by the Engineer. The space resulting from sampling shall be refilled and compacted in accordance with specification requirements. When tested in accordance with AASHO T-11 the quantity of material passing the No. 200 sieve, as indicated by the average of the seven (7) tests, shall not be greater than 10% minus 0.271 times the difference between the largest and smallest percentages indicated by the seven (7) tests. Base course not meeting this requirement shall be removed and replaced with acceptable construc-

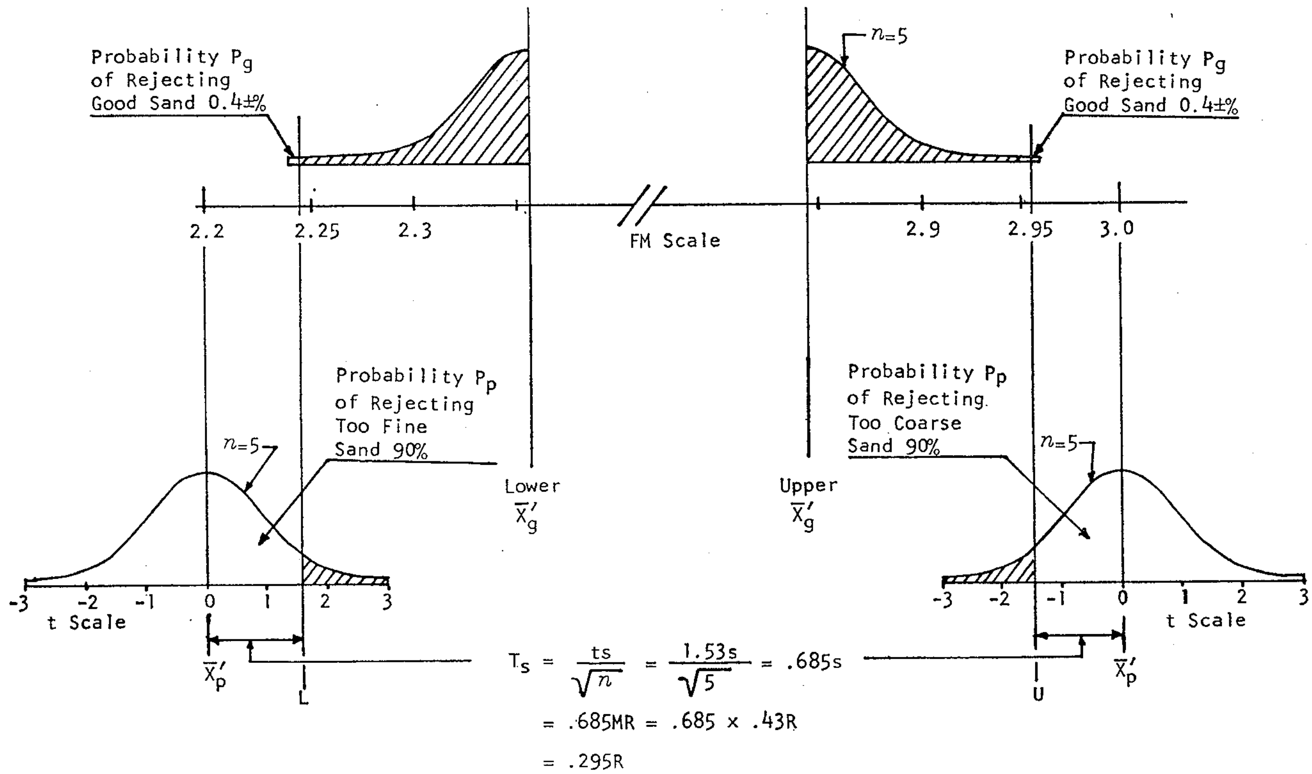


Figure 17. Probability P_p of rejecting lots when FM = 2.2 or 3.0.

tion, meeting all specification requirements, at no expense to the Commission.

This plan allows a tolerance of 1 percent minus No. 200 material above the optimum and provides a fixed 95 percent probability of rejecting construction in which the percentage of fines exceeds this tolerance. In this case, it is difficult to estimate the contractor's risk of having construction containing less than 10 percent fines rejected on the basis of the seven tests. The probability of rejecting acceptable construction will depend on the average percentage of fines actually in the construction and also on the variation in this quantity. This variation, in terms of standard deviation, will depend on the contractor's choice of equipment and methods used to process, place, and compact the material. A horseback guess may be that, about 95 percent of the time, the actual percentage of minus No. 200 at any sampling point in the base will be between 6 and 12 percent. A rough estimate of the standard deviation, σ, may be obtained by dividing this range by 4 (that is, $\sigma = (12 - 6)/4 = 6/4 = 1.5$ percent.

Using this derived value of the standard deviation the situation may be visualized as shown by Figure 16. Similar to the previous case, the location of U will depend on the sample standard deviation and buyer's risk will depend on the actual value of the lot standard deviation.

TABLE 7

SUGGESTED BALANCE OF ACCEPTANCE SPECIFICATION FACTORS; STANDARD DEVIATION KNOWN

CRITICALITY OF REQUIREMENT	PROBABILITY [a] OF REJECTION OF GOOD MATERIAL, P_g	PROBABILITY OF REJECTION OF POOR MATERIAL, P_p	NUMBER OF MEASUREMENTS, n	DIFFERENCE BETWEEN MEANS, T_a	ACCEPTANCE LIMITS [b]
Critical	0.050	0.995	6	$\pm 1.72\sigma'$	$\bar{X}'_p \pm 1.051\sigma'$
Major	0.010	0.950	5	$\pm 1.78\sigma'$	$\bar{X}'_p \pm 0.736\sigma'$
Minor	0.005	0.900	4	$\pm 1.93\sigma'$	$\bar{X}'_p \pm 0.642\sigma'$
Contractual	0.001	0.800	3	$\pm 2.27\sigma'$	$\bar{X}'_p \pm 0.486\sigma'$

[a] Probability for single limit specification; when specification has both an upper and a lower limit, the probability of rejecting acceptable material may theoretically be doubled.

[b] $\bar{X}'_p \pm T_s$.

CASE (2-c)—BOTH UPPER AND LOWER LIMITS

It is necessary to prepare an acceptance plan for concrete sand, which may come from any one of several sources. The material is to be inspected at the source and the lot may be a stockpile or a barge load. In addition to the requirements of AASHO M-6, it is necessary to further define the gradation in order to insure that the concrete will have satisfactory workability, strength, and durability. It is known that sand from different sources has different gradations, and that a narrow gradation band would exclude some sources.

The significant characteristic in this case is the fineness modulus (FM), which describes the gradation by use of a single number. Inspection of results of record tests shows that a sand having FM $= 2.2$ is undesirably fine, whereas a sand having FM $= 3.0$ is undesirably coarse, and that the standard deviation is about 0.07. Acceptance limits can be taken from Table 6, using the minor classification. In this case, the acceptance limits would be $\bar{X}'_{p1} + 0.295\ R = 2.2 + 0.295\ R$ and $\bar{X}'_{p2} - 0.295\ R = 3.0 - 0.295\ R$ and the acceptance clause would be:

> In addition to the requirements of AASHO M-6, concrete sand shall have a nominal Fineness Modulus of not less than 2.2 or greater than 3.0. The Producer shall furnish labor and equipment for taking five (5) samples from each stockpile or barge, at locations designated by the Engineer. When tested in accordance with AASHO T-27 the average FM of the five (5) test results shall not be less than 2.20 plus 0.295 times the difference between the largest and smallest test result or greater than 3.00 less 0.295 times the difference between the largest and smallest test result.

Using the estimated standard deviation of 0.07 FM units, the situation may be visualized as shown in Figure 17. The conditions are much the same as in the two previous cases, except that the probability of rejecting lots of good material is theoretically doubled, due to the double limit. However, lots of sand having an average FM near the

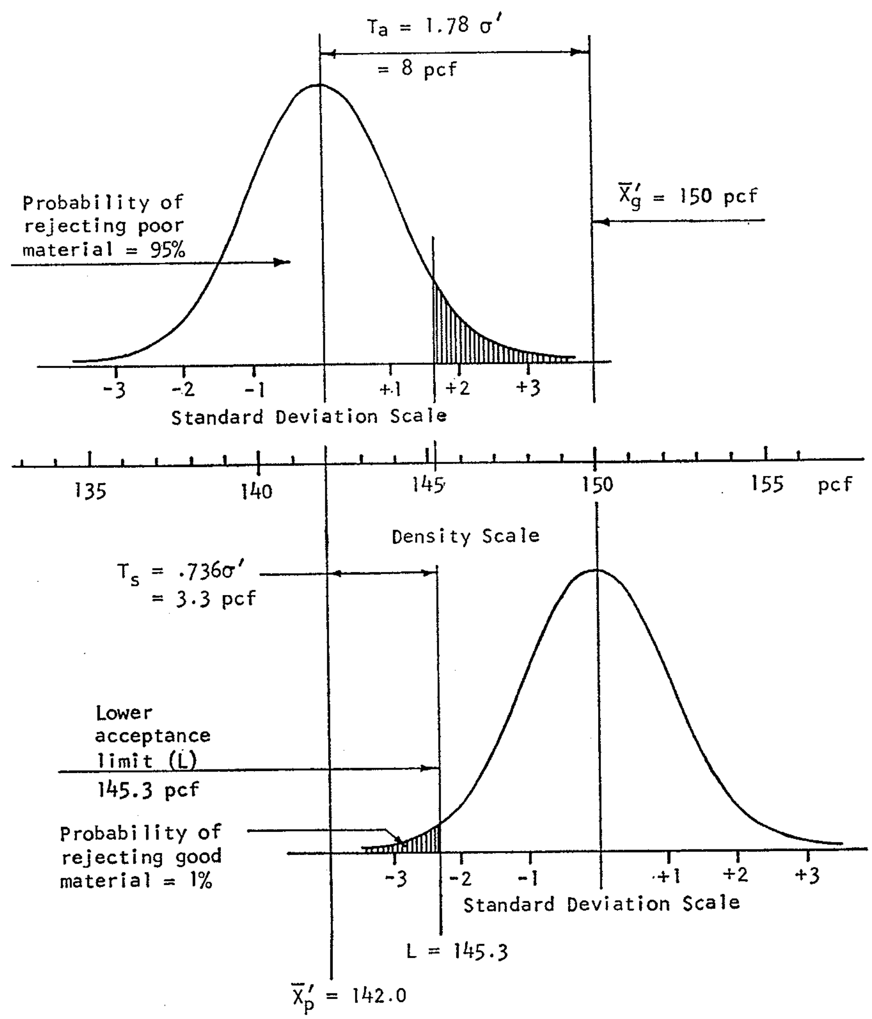


Figure 18. Operating characteristics, lower acceptance limit (Case 3-a).

center of the allowable range have practically no risk of rejection.

This plan would insure against accepting sand outside of the specification limits more than one time out of 10, or of rejecting sand that was within the specifications more than about one time in 100 if the standard deviation is equal to the estimated value.

CASE 3—PLAN TO PROVIDE FIXED PROTECTION AGAINST ACCEPTING POOR MATERIAL OR REJECTING GOOD MATERIAL; STANDARD DEVIATION KNOWN

This plan is very similar to that used for Case 2. The principal difference is that the true value of the standard deviation, σ', of the characteristic is believed to be known and unchanging. As before, P_g refers to the probability of rejecting good material or construction, and P_p refers to the probability of rejecting borderline material or construction.

As in Case 2, suggested values of probabilities for characteristics of different degrees of criticality have been selected and are presented, with the related acceptance given in Table 7, which contains all the information necessary to prepare an acceptance plan for the given probabilities.

As in Case 2, there are three possible cases: (3-a), lower limit only; (3-b), upper limit only; and (3-c), with both an upper and a lower limit. These three cases are discussed in the following examples.

CASE (3-a)—LOWER LIMIT ONLY

A crushed-stone base of the specified type and of borderline quality has an average density of 142 pcf and a standard deviation of 4.5 pcf. The density of the base is considered a major requirement. Values of n, T_a, P_g, and P_p are taken from Table 7. Thus $n = 5$ and the lower acceptance limit would be $L = \bar{X}'_p + 0.736\ \sigma' = 142 + (0.736 \times 4.5) = 145.3$ pcf. The acceptance clause of the specifications would be stated like this:

> Crushed-stone base shall be compacted to a nominal density of 150 pounds per cubic foot. Acceptable crushed-stone base construction shall have an average density of not less than 145.3 pounds per cubic foot based on the results of five (5) density tests, made in accordance with AASHO Designation T-181 at locations designated by the Engineer.

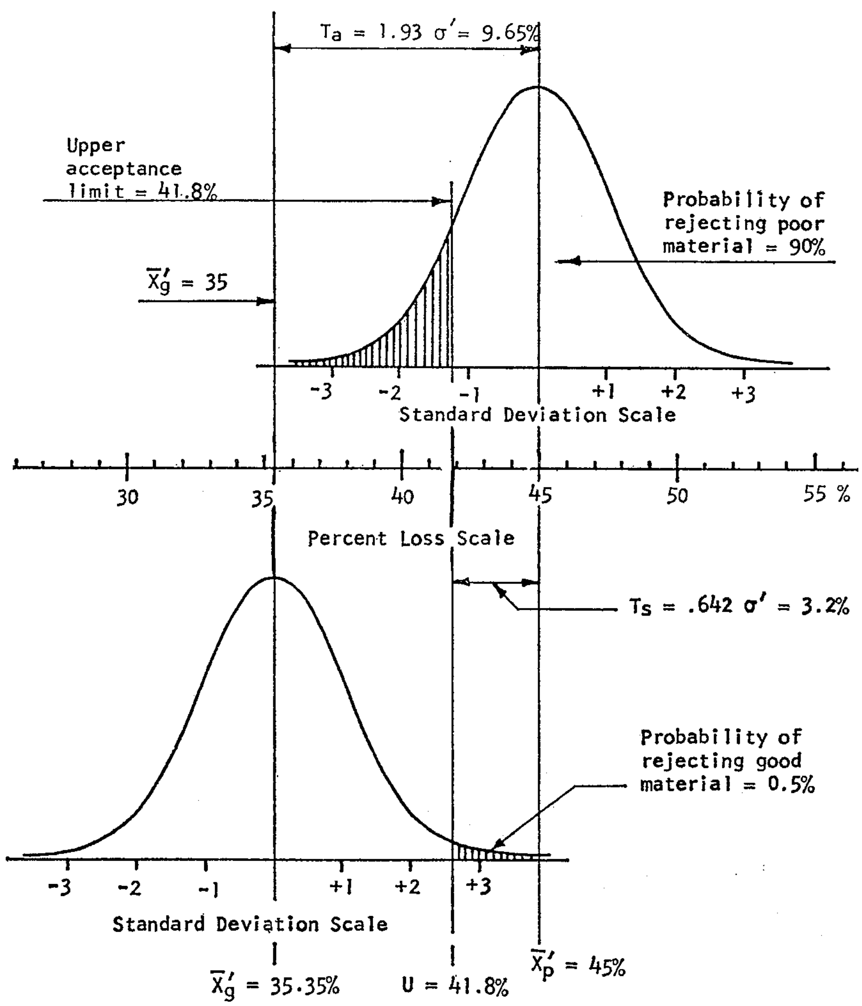


Figure 19. Operating characteristics, upper acceptance limit (Case 3-b).

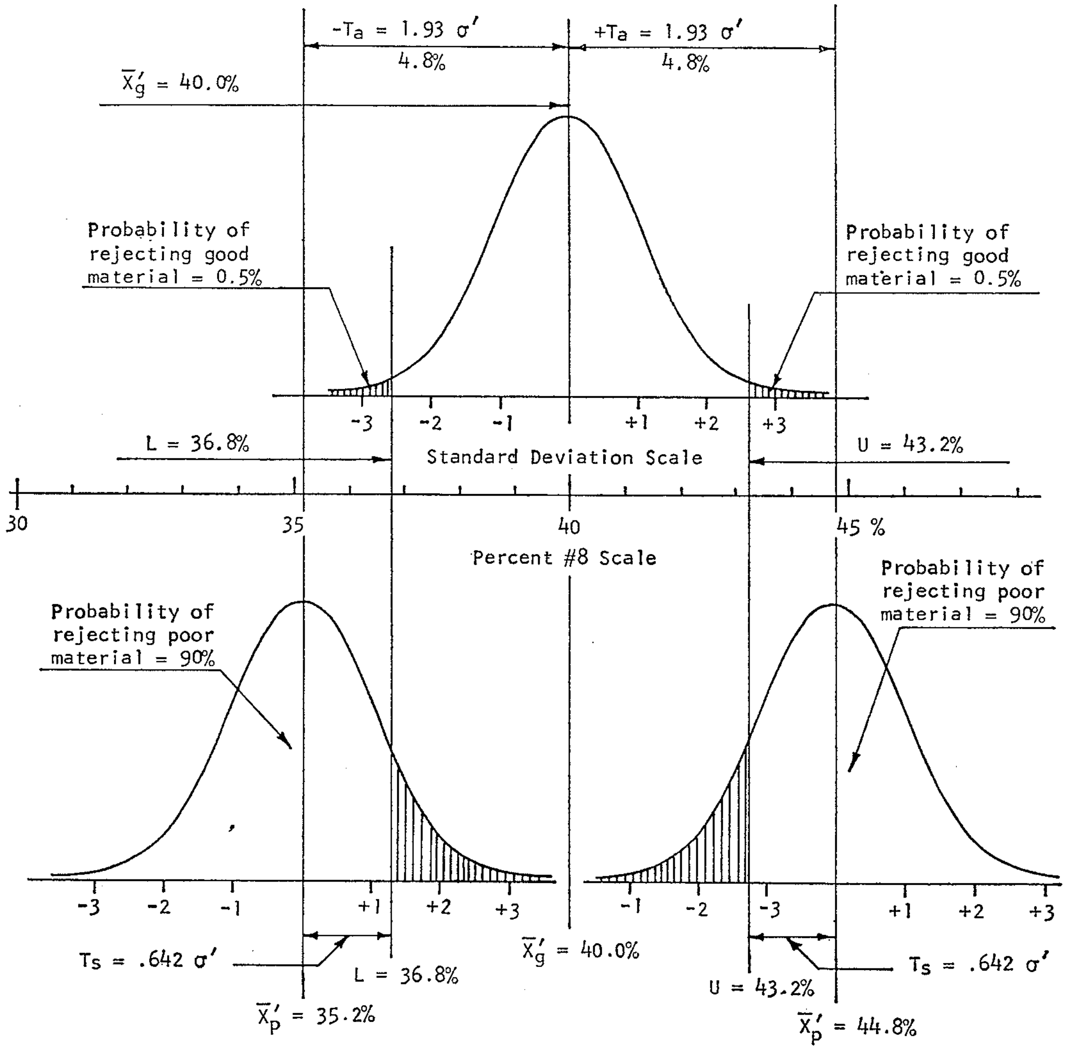


Figure 20. Operating characteristics, upper and lower acceptance limits (Case 3-c).

The situation is shown in graph form by its OPERATING CHARACTERISTICS (Fig. 18).

CASE (3-b)—UPPER LIMIT ONLY

Many available data indicate that coarse aggregate available in an area has a poor record of satisfactory service as a component of bituminous concrete when the average Los Angeles abrasion loss is 45 percent, and that the standard deviation is about 5 percent. In this application the loss on abrasion is classified as a minor requirement.

The computations for this case are quite similar to those for Case (3-a). However, T_s is subtracted from $\bar{X}'_p$ instead of being added to it. Inasmuch as the requirement for Case (3-a) was a major criticality classification, the values taken from Table 7 are slightly different; thus $n = 4$ and $U = \bar{X}'_p - 0.642\ \sigma' = 45.0 - 3.2 = 41.8\%$. The acceptance clause of the specification would read:

> The nominal maximum average percentage of wear of aggregate shall be 35 percent. Acceptable aggregate shall have an average percent of wear of not more than 41.8 percent based on the results of four (4) tests made in accordance with AASHO T-96 on random samples taken from the prepared and stockpiled aggregate.

The situation, in graph form, is shown by the operating characteristics (Fig. 19).

CASE (3-c)—BOTH UPPER AND LOWER LIMITS

A study of a bituminous-concrete surface mixture indicates that the best performance is obtained when the portion of the total aggregate passing the No. 8 sieve is maintained at 40 percent ($\bar{X}'_g$). Tests made on samples taken from batches in the truck indicate that the standard deviation is about 2.5 percent at most plants. The requirement is classified as minor.

This case appears more complicated, because there are two limits. However, the computations and those for Case (3-b) are almost identical, because the requirement has the same criticality classification. The calculations for Case (3-c) are as follows:

$$\bar{X}'_p = \bar{X}'_g \pm 1.93\ \sigma' = 40 \pm 1.93 \times 2.5 = 44.83 \text{ or } 35.17$$
$$L = 35.17 + 0.642\ \sigma' = 35.17 + 0.642 \times 2.5 = 36.8$$
$$U = 44.83 - 0.642\ \sigma' = 44.83 - 0.642 \times 2.5 = 43.2$$

The acceptance clause of the specifications would be as follows:

> The desired average value for the percent of total aggregate passing the No. 8 sieve is 40 percent. Acceptable mixtures shall have an average percent passing of not less than 36.8 percent and not more than 43.2 percent based on the results of four (4) mechanical analyses made in accordance with AASHO T-30.
>
> Samples on which the tests are made shall be taken from the batch immediately after discharge of the mixer, by use of the sampling method directed by the Engineer.

The situation, in graph form, is shown by the operating characteristics (Fig. 20).

CASE 4—PLAN TO PROVIDE PROTECTION AGAINST ACCEPTING LOTS CONTAINING AN EXCESSIVE NUMBER OF DEFECTIVE ITEMS

It is desired to write a specification defining asphaltic concrete pavement having a surface smoothness satisfactory with respect to rideability. Available data indicate that a satisfactory ride will be obtained if each 100-ft section has no more than one ¼-in. deviation from a 10-ft straightedge, or three ¼-in. deviations from a 16-ft straightedge, with no deviations of ⅛-in. in less than a 30-in. span. Each day's construction is to be considered a lot, and the total number of units in the lot, on any line parallel to the centerline, is the length in the lot divided by 100. The specification would read, in part:

> Pavement of acceptable smoothness shall have not more than one (1) deviation of ¼ inch from a 10-foot straightedge or more than three (3) deviations of ¼ inch from a 16-foot straightedge and no deviations of ⅛ inch or greater in a 30-inch span, in 100 feet. Pavement having more than the allowable number of defects in one hundred (100) feet shall be removed and replaced, or brought to within the allowable tolerances by a method approved by the Engineer.

The acceptance plan will be applied by first dividing the length of the day's construction by 100. This gives the total number of units in the lot. Table 3 is now entered with this number and the number of randomly located 100-ft units to be tested is found in the second column. By use of a table of random numbers the location of each of these 100-ft units is predetermined and is marked on the pavement. Each of these units is tested with straightedges. The number of 100-ft units classed as defective is then compared with the appropriate number in Table 3 and the day's construction of pavement is classed as acceptable or nonacceptable.

For example, if 17,850 ft of pavement are finished in one day, the number of 100-ft units in the lot is 17,850/100 = 178. From Table 3, the appropriate sample size is 32 100-ft units.

The location of these measurements is found by the use of a table of random numbers and each 100-ft unit is measured and classed as defective or nondefective. Three defective 100-ft units are found. If an allowance of 4.0 percent of total units out of tolerance is considered appropriate, the 4.0 percent column of Table 3 indicates that for a sample size of 32 the lot should be accepted if the number of defectives is not greater than 3 and rejected if the number of defectives is 4 or more.

Inasmuch as the number of defective units was 3, the test indicates that the pavement should be accepted.

CHAPTER FOUR

SOME POLICY AND COST CONSIDERATIONS

The economic aspects of highway construction provide the principal criteria for most guidelines for writing practical and realistic specifications. Although due consideration should be given to aesthetic values, most highway specifications are governed by overall cost, including construction plus maintenance costs. It is beyond the scope of this project to even attempt a detailed cost analysis of all the various specification items governing the construction of a modern highway. Nevertheless, certain general guidelines which are common to the economic justification for most specifications are presented herein.

LIFE EXPECTANCY

It has been customary to think in terms of 20 years as the life of a road for both design and maintenance cost projections. Just how realistic this guideline is may be subject to question. Although there are, of course, many very old roads in the sense of general location, most highways undergo varying degrees of modification in less than 20 years. Realignment, widening, resurfacing and, less frequently, total rebuilding of both secondary and primary roads is taking place at an ever-increasing rate. It would be interesting to know the average life of the various classes of highways in various sections of the country. In any case, there is nothing magic about the 20-year period. Although admittedly based on opinion rather than any factual analysis, it is tentatively suggested that 10 to 15 years would be a more realistic guideline for most roadway materials and construction specifications. Major structures and certain major beltlines and expressways should probably continue to be designed and built to 20-year or longer standards. All farm-to-market roads and most state secondary roads, however, could probably be constructed and maintained at a lower overall cost if built on the assumption that they would be subject to some major modification within 10 years. For state primary roads a 12- to 15-year life expectancy is suggested, depending on location and anticipated use considerations.

SAFETY FACTORS

Design safety factors have an obvious influence on costs. Although these are not directly part of the construction specifications, they greatly influence the level of the specification requirements. Safety factors have also been called "ignorance" factors and it is axiomatic that as research and technological advance decrease the engineering ignorance level, more economic safety factors can and should be used. Overdesign is obviously costly, whether it be in thickness or in specifying a higher quality of either materials or construction than is necessary.

It is probably also true that engineers are influenced in their selection of safety factors by lack of knowledge of the actual variability associated with both materials and construction and with their testing and inspection. As the variations associated with all elements of road building are better defined, not only do more realistic tolerances become possible from the specifications viewpoint but lower safety factors and more economical construction also will be feasible from the design viewpoint. It is recommended, therefore, as a general policy guide that safety factors be periodically reviewed and reflected in specification requirements in light of variance studies and the better definition of realistic tolerances.

ECONOMIC IMPLICATIONS OF THE STATISTICAL APPROACH

Uniformity Incentives

Probably the largest and most significant economic consideration to be realized from the statistical approach to practical and realistic construction specifications lies in the direct dollar motivation provided to the contractors, materials suppliers and producers. The producers or manufacturers of most proprietary materials (such as steel, paint, asbestos cement pipe) have long been aware of the importance of statistical quality control. Most such manufacturers have learned by competitive necessity to control the uniformity of their products and to minimize their seller's risk. It is surprising that these same techniques have not earlier found their way into the equally competitive highway construction field. The answer probably lies in poorly defined and usually split responsibility for quality control shared in a rather hodge-podge manner by the buyer (engineer) and the seller (contractor) under traditional highway specifications.

Process Control vs Acceptance Testing

The distinction between process control and acceptance testing is important. Acceptance testing is based on the principle of estimating the parameters of a characteristic of the lot by limited sampling. Normally these parameters consist of the average quality level and a measure of variability or dispersion. As previously cited, if the true mean, $\bar{X}'$, and the true standard deviation, σ', are known, there is no problem in comparing against the standard requirements as basis for an engineering decision to either accept or reject the lot. The four types of acceptance plans presented in Chapter Three provide the engineer with means of estimating the characteristics of the lot and of calculating the probabilities associated with making a wrong decision. Further, he can do this with a known degree of assurance which can be adjusted to fit the criticality of the situation. It is the engineer's responsibility to accept or reject the lot on behalf of the owner, whether that lot be a poured footing, a barge of sand, or a day's run of paving.

It is contrary to the normal training of most highway engineers to think in terms of average quality and variation as the basis of acceptance or rejection, rather than the quality of the individual increments in the lot under question. Nevertheless, he has been "estimating" the acceptability of the material or work all along, whether he realized it or not. The fact that he has based his judgment on samples taken from one point rather than another has probably merely increased the chance of his making a biased judgment without the benefit, and without the knowledge, of the risks associated with his decision. It is just not practical or economically feasible to test or inspect every increment, but the size of the lot can be adjusted to best fit the particular situation. In fact, one of the big economic advantages to this philosophy of acceptance testing is that the amount (and cost) of inspection can be adjusted to most economically give the protection needed. However, in any case, the engineer accepts or rejects a lot whether it be a truckload, 1,000 feet, or a day's run of pavement.

Process control, on the other hand, is the means of providing adequate checks during production (or construction) to minimize the contractor's or producer's risk (seller's risk) of having the lot rejected. A process is said to be in control when all economically removable variations have been eliminated. In fact, a primary purpose of process control is to eliminate assignable causes of variance so that the overall variability of the finished lot will approximate the standard deviation that was used to design the sampling plan for acceptance of the lot. It may be said that process control endeavors to maintain a given level of production with respect to both the average value and the degree of uniformity, whereas acceptance testing is a check on the finished product to see to what degree these goals have been attained.

Process control should be the responsibility of the contractor or producer. In many instances in highway construction, the engineer (or his representative, the inspector) and the producer have shared this responsibility. At a hot-mix plant, for instance, the inspector periodically runs bin gradations and/or extractions to guide the quality control of bituminous concrete. Even though the specifications may state in one form or another that this service does not relieve the contractor of his responsibility to provide an acceptable product, the inspector, in fact, has assumed a stake in process control. The engineer thus assumes at least a moral responsibility for the success of the completed product or construction or for its failure to meet requirements. This split responsibility sometimes makes difficult the strict enforcement of the specifications and too often leads to embarrassing or compromising situations.

A recommended basic policy guideline, therefore, is that as rapidly as possible the full responsibility for process control be placed squarely where it belongs on the contractor or producer. Steps have already been taken in this direction in some states. In North Carolina, for example, the State Highway Commission and the appropriate trade associations have cooperated in the training, testing, and qualifying of ready-mix concrete plant technicians. Virginia has done the same for both portland cement and asphaltic concrete, and there well may be others. West Virginia is instituting a program for transferring this responsibility for process control more directly to the contractors. Included in this program is the examination and qualifying of contractor's personnel. Of course, many contractors have voluntarily included competent materials engineers in their organizations. This trend and these programs should be encouraged by all.

No matter how the responsibility for construction control is shared, however, that control must be effective. Otherwise, there will be either an uneconomical risk of rejection or an awkward situation if a large amount of completed work is found to be unsatisfactory when tested for acceptance. In highway construction it is not always practical to tear out and replace defective work, and ineffective construction or process controls may lead to problems that have no satisfactory solution. This report deals primarily with the development of guidelines for realistic acceptance limits and tolerances as a separate and distinct problem from that of process control. However, if these acceptance limits are to be met, both the level and variability of important characteristics must be controlled during production or construction.

Dollar Incentives for Contractor

The principles and the acceptance plans given in Chapter Three provide great motivation in the form of direct dollar incentive to the contractor or producer to maintain effective process control and to improve the uniformity of his product. This incentive takes two forms, as follows:

1. Greater uniformity (lower standard deviation, σ) means a lower seller's risk regardless of the acceptance plan used. The probability or risk of having acceptable material rejected can be greatly reduced, in most cases, by even a relatively small improvement in uniformity.
2. With some acceptance plans—Plan No. 2 notably—the average quality level that will be accepted is a function of the indicated sample standard deviation. The lower the variability (range) the closer the contractor may operate to the limiting specification value.

Thus, the contractor can save money through improved uniformity of operation by not only decreasing his chance of rejection, but also by actually being able to operate to a lower average quality level. For instance, this could make the difference in having to wash base course aggregate for control of minus 200; or it could mean meeting compressive strength requirements with less portland cement in the mixture; or of a lower cost local sand being acceptable for use in an asphalt mix.

The guideline recommendation is that this powerful incentive be publicized so that all segments of the highway industry will be motivated not only to make the direct savings potentially available but also to embrace rather than resist these basic concepts. The philosophy of specification acceptance plans based on statistical principles, regardless of how sound they may be, is a difficult one at best. Anything that can be done to let the contractors, materials suppliers, and producers know that they have a real dollar stake to be gained is all to the good. It is suggested that it is not too early even now to carry this message by appropriate committee action to the several highway contractor and trade associations. Continued publications on the application of statistical concepts before technical and professional engineering groups would also help to further prepare the way for adoption of these principles.

Cost Incentives for Owner

Not only does the contractor have a real cost incentive to improve uniformity under these specifications, but the engineer and the owner also benefit. Improved uniformity means fewer highs and fewer lows, which in turn mean fewer weak spots in the construction, thereby reducing maintenance costs. These acceptance plans offer greater assurance that the product or construction will perform as intended. As previously noted, greater assurance in construction should ultimately mean more realistic design safety factors. Further, this assurance is tied to the criticality of the requirement characteristics, thereby permitting wiser spending of the testing and inspection dollar. These acceptance plans and the resulting improved uniformity they encourage should also result in lower inspection costs because fewer samples and fewer inspectors will ultimately be needed for the same degree of protection for the state. Equally important is the fact that now the engineer and the contractor will have a common goal and incentive in helping each other attain optimum uniformity throughout.

AUTOMATION

Use of mechanical aids and electronic control will continue to offer an effective and appropriate means for improved uniformity. The motivations resulting from adoption of realistic specifications based on statistical concepts should constitute quite an inducement for greater use of automation. It is anticipated that as the contractors begin to realize the direct benefits of improved uniformity they will turn to automation as a logical means for further improvement. By the same token, of course, these things go hand in hand in that automation becomes a factor in encouraging the adoption of the new specifications by providing an important means for realizing the benefits therefrom.

The general guideline recommended is to encourage automation, particularly where improved uniformity of a finished product can be demonstrated. Like everything else, this becomes a cost balance, and excesses should be watched for and avoided. It is the responsibility of the instrument manufacturers and the equipment suppliers to "iron out the bugs" as completely as possible before bringing new automation equipment onto the market. In any case, specifications must allow for periods of manual operation for maintenance and repair of the automatic features and controls.

The question arises as to whether the states should require automation or whether it would be better in the long run to write and enforce the specifications in such a manner as to induce or lead the contractors and equipment manufacturers in this direction. For instance, there is much current interest in the automation of hot-mix asphalt plants. Michigan and New York will (in 1965) require full automation with over and under cutoffs. North Dakota, South Dakota and Washington require automation of proportioning and mixing; California and Texas may cover this by a special provision.

The danger in having state highway departments take the lead in requiring plant automation is that they may prematurely force the industry into uneconomical expenditures that might otherwise be avoided. The same inconsistencies arise here as in attempts to specify other equipment. The highway industry is advancing just too rapidly for specification writers to consistently stay up with the advancements in automation and equipment technology. New gadgets are coming out faster than the engineering family can possibly evaluate and properly reflect in the specifications. In any case, the proving ground for proprietary products in the free enterprise system has traditionally been, and should remain, the marketplace.

Recommended guidelines with respect to automation are:

1. Full advantage should be taken of the economic inducements toward automation by placing a dollar premium on uniformity, as recommended elsewhere in this report. Automation specifications themselves should be relatively simple and limited to the minimum required to bring along the laggards to conform with statewide quality and uniform practice levels.

As nearly as possible "end use" type requirements should be specified with reasonable tolerance limits given where appropriate. Free latitude should be given for the exercise of full competitive incentives. The contractor or producer should have free choice of selection on the open market and there should be no restrictions as to method, technique, or specific equipment items that may or may not be used.

2. Provision should be made to permit operation using manual controls if a breakdown of the automatic features occurs. The contractor or producer should be required to demonstrate reasonable diligence in repairing or alleviating the breakdown. Guidelines for defining a reasonable time allowance will vary, of course, with the process, the automation equipment, and the proximity to repair facilities. Except in very remote areas three working days would seem to be a reasonable allowance for the repair of the automatic controls on a hot-mix plant or on a ready-mix concrete plant.

3. The transition to automation should be a cooperative venture with the contractors and producers. The state and the appropriate trade associations should work out the ground rules and the timing together to best fit their local conditions.

4. Some provision should be made to recognize and provide for special situations wherein it would not be good business economically to completely convert all of the plants in the state at the same time. Some of the smaller, older plants may be doing a good and needed job of producing most economically for a given local area. Volume of business in that area may make it difficult to capitalize complete automation over a reasonable period of time. The recommended guideline for these special situations is to allow operation under a grandfather clause until such time as other major modifications or a change in location is required, or until the business situation changes sufficiently to place that plant in a different category. The category definitions, timing, and other considerations can be spelled out as part of the local ground rules.

5. Whatever ground rules are agreed upon for the state should apply fairly and equally to all plants within a given category. In some states, the commission or department owns and operates its own plants. These are purportedly for maintenance use primarily, but frequently reach into sizeable new construction or resurfacing projects. The same rules and regulations and controls that apply to contractors' or producers' plants should also be enforced in an equal manner on the state-owned plants.

STANDARDIZATION AND RESTRICTIVE REQUIREMENT POLICIES

Although the optimum quality level to be specified for the various construction components would seem to be largely the straightforward balancing of engineering requirements against overall costs, there are certain policy questions associated with the availability and relative cost (cost value) of some materials and products to be considered. Policy with respect to adaptation of the AASHO specifications by the individual state highway departments and the attitude of the Bureau of Public Roads with respect to both standardization and to so-called restrictive requirements can and does have a marked influence on the guidelines for realistic specifications. In this discussion there is no criticism intended, implied or otherwise, of either

AASHO or the Bureau of Public Roads. The ensuing discussion is merely an attempt to define and analyze objectively those aspects which influence specification guidelines.

AASHO Guide Specifications

On the one hand it is desirable that highway specifications be standardized as much as possible to facilitate shipment of materials across state borders, and for the more economical manufacture of products and equipment for use in different parts of the country. On the other hand, there are certain local conditions (climate and traffic), precedents, and availability of materials which make it mandatory to use different specification requirements for some materials and products. The AASHO Guide Specifications are a noteworthy milestone toward standardization, but they are not necessarily the best engineering nor the most economic specifications for some states. In fact, the very nature of the compromises necessary to establish guides for the country as a whole would in itself mitigate against optimum use of local materials and products. In general, the quality levels in the AASHO Specifications are by necessity geared to accommodate that state having the *lowest* level economically available for that particular item.

An obviously desirable guideline is to encourage standardization of such things as test methods or requirements for those materials, products, or items of construction wherein the same quality level and the same tolerances can logically be applied equally in all states at approximately the same cost. Even under these circumstances, however, care should be taken in the setting up of such standards to properly and adequately define the governing conditions under which both the items specified and the use requirements are in fact equal. For instance, even though a standard product is available at essentially the same cost in all states, it may be good engineering to specify a different quality level or to place more emphasis on the testing and control of certain product characteristics because of differences in local use requirements. Such things as variation in freeze-thaw resistance, load requirements, traffic count, and life expectancy are obvious, but there are other, subtler differences. The personnel (both contractor and highway department) in some states are most versed through experience in the use of some methods of construction, some materials, or some proprietary products. In other cases, the efficiency of a given technique or product may depend upon its compatibility with other materials. Thus, even in some of the seemingly obvious situations favoring standardization there may be good reason for some modification to best fit local materials, practices, and people. Nevertheless, it is recommended that objective appraisals be made of the reasons underlying the "special" features of state specifications which make them differ from AASHO recommended standard practice to assure that each area of nonuniformity is really a bona fide reflection of experience found to best fit local conditions or materials, and that the "special" need still exists.

Guidelines for Standardization Appraisal

Guidelines for making such appraisals should include consideration of two basic conditions—(1) where the quality level is independent of cost within the limits under consideration; and (2) when the cost of specifying a higher quality level must be offset by some corresponding benefit.

HIGHER QUALITY AVAILABLE AT SAME COST

Some localities are endowed by nature with more suitable and higher quality road building materials than others. Vermont, for instance, has more than enough of good hard stone, whereas Louisiana, for one, has trouble finding suitable aggregate big enough to crush and relatively soft aggregates are all that are available in other areas. It would be pointless for Vermont to allow a 50 L.A. abrasion specification merely to conform with a national standard. By the same token it is pointless for the quality level of asphalt cement to be geared to the minimum level economically available in some other parts of the country. North Carolina, for instance, is endowed with five major asphalt suppliers who routinely maintain quality levels for the AASHO T 179-60 Thin Film Oven Test well above 60 percent retained penetration and 100 ductility on the residue for the AP3 (85/100) grade. The corresponding level suggested by the AASHO guide is 50 percent retained penetration and 75 minimum ductility.

What should be the guidelines under these circumstances? On the one hand, it is agreed that any restrictive specification that would result in restraint of trade or inhibit competition should be avoided as being economically unsound in the long run. On the other hand, where there is an adequate supply available at the same competitive cost, it is neither logical nor economically good business to specify and use a lower quality level material or product. It is not only illogical to permit lower quality at the same cost, but it can have other less obvious adverse effects. One is to remove the motivation for research and improvement of highway materials. If highway specifications do not keep abreast of technological advances in either equipment or materials, the dollar incentive for further improvement is endangered. Another disadvantage is to unnecessarily and uneconomically invite the use of distress materials, with possible resulting discouragement of capital investment for the installation of optimum facilities for the best long-range use of local materials.

Thus, a basic guideline for those situations in which an adequate supply of a given material or product is available is to specify the highest quality level that can safely be met without increasing the cost. Safe operating levels might be defined in cooperation with the local suppliers or trade association and then checked by trial and error. Such quality improvement can be reflected stepwise as warranted and/or explored on a trial basis for reasonable periods before final adoption.

HIGHER QUALITY AT INCREASED COST

The problem of defining just how much a higher quality level is worth is considerably more difficult. For many highway materials, products, and items of construction the desired quality direction is known and test methods are available for measuring relative differences. The problem, however, lies in quantitatively relating that particular test to the serviceability of the road. Some limiting values have been established by experience and others can be calculated or estimated by one means or another on the basis of sound engineering judgment. In general, however, it is extremely difficult to define the significant quality attributes and then to quantify the relative value of a given change in some measurable characteristic.

There are two basic approaches to obtaining better answers—one is designed test road experiments, and the other is analysis of existing roads. Test roads are notoriously expensive and time consuming. It is surely not economical to attempt to quantitatively justify all of the many specification requirements in common use. On the other hand, designed experiments related to satellite studies of the AASHO Test Road in Ottawa, Ill., should yield valuable information on materials performance as well as on design criteria. The second method is more practical from the viewpoint of both time and cost. Some studies are now under way and more should be instigated to measure both quality level and the variability associated with the characteristics of existing pavements. In some cases the further analysis of performance records and of maintenance costs might yield valuable information. Unfortunately, in many cases lack of proper documentation or of sufficient reliable data militates against their use.

A more thorough discussion of guidelines for surface smoothness, thickness, and some aspects of aggregate gradation requirements is contained elsewhere in this report. A further general point, however, has to do with the economic impact of lowering the quality level of some materials. It should not be generally assumed that a relaxing of quality level will necessarily be reflected in a significant decrease in product cost. In fact, it is conceivable that over the long run a given relaxation could actually result in a higher unit cost. Assume, for instance, that a quarry operation has been set up on the basis that the operating overhead can be distributed over a given volume of production, which volume in turn was based largely on the anticipated requirements of the highway department operating at a given specification level—i.e., L. A. abrasion of 35. Now, if the specifications are relaxed to let in marginal material of say an L.A. of 40, the producers of the marginal material will have no motivation to cut their price below that necessary to get the business, which will probably be only slightly lower than the higher quality product. The first producer, however, must now amortize his plant and distribute his operating overhead over a lower volume production, thereby increasing his unit cost. Although this type of situation surely does not exist with all materials nor under all circumstances, the point is that there is potentially more than meets the eye to the economic aspects of changing specification levels. Thus, the recommended guideline when change in cost value is a factor is that the *overall* potential economic effects be explored in cooperation with the trade associations involved and the long-range influences carefully considered in analyzing the desirability of either raising or lowering specification levels.

COST-TOLERANCE CONSIDERATIONS

An attempt was made in this study to appraise various methods or approaches to defining the cost-tolerance relationship as well as the cost-quality level relationship. The benefit to be derived from making a specification more (or less) restrictive, or from changing the quality level, can be calculated in some cases and in others it can be estimated on the basis of sound engineering judgment. The corresponding increase (or potential savings) in construction costs, however, is not so easily defined. In fact, there is essentially no quantitative information in the literature, and few numerical data were unearthed in this study.

One frequently hears the lament "it will cost a fortune to control it that closely," or "we can't afford to go that high (or low)." When pinned down, however, the lamenters are generally unable to make a reasonable estimate as to just how much it will cost or at what point a given change will have a significant influence on costs. It is obvious that there must be some practical limit in many highway specifications beyond which closer control or a higher quality level becomes impractical because the cost value is excessive with respect to the use value (it costs more to accomplish than the resulting benefit is worth). In order to arrive at the optimum for practical and realistic construction specifications, both the justification and the corresponding cost to all segments of the industry must be defined.

As part of this study interviews were held with various contractors, materials suppliers, and equipment manufacturers, as well as with other highway engineers and trade association executives. A check list used during these interviews was intended not so much to find specific answers but rather to explore potential sources of pertinent factual information.

In addition to this check list a special cost-tolerance questionnaire prepared by the research agency was distributed by the National Limestone Institute. The same questionnaire was also provided to the Highway Director of the Associated General Contractors for distribution to two AGC committees.

Some of the questions were specific in that they sought definite opinions or data relative to smoothness and thickness tolerances for the principal courses of both rigid and flexible pavements. The questions concerning commercial aggregates also were written in such a way as to invite quantitative answers. Certain other questions were geared to obtain some readings on those areas in either the specifications themselves or in their administration which have a significant influence on cost. In all cases the person being interviewed was encouraged to discuss any aspect of the overall cost-specification, cost-tolerance, or cost-administration relationship he wanted to. The interview was purposely designed to make it easy for him to "sound off" on his favorite gripe.

Again, it should be emphasized that the primary objective of trying these various approaches has been to explore means of getting the information rather than to attempt wide coverage of the full industry at this time. Once these samplings have been evaluated and the optimum sources for different types of cost-tolerance information established, more comprehensive data gathering may be warranted as part of some future project.

A summary of findings and impressions is given in the following by class or type of information source.

State Highway Engineers

Interviews included a chief bituminous engineer, chief materials and construction engineers, specification writers, an assistant chief design engineer, and various field personnel. As might be expected, these state highway engineers were unable to quantify any significant portion of the cost-tolerance questions. As a group they are just not in a position to know, or need to know, the details of construction costs to this degree.

Both a Pennsylvania project engineer and a North Carolina bituminous engineer stressed delay as being an important cost consideration—delays due to acceptance testing and reporting of crushed aggregate base course were specifically mentioned. Tolerances or limitations which cause delays or which necessitate hand labor are most costly. One engineer also stressed the desirability of fair and fast estimates to minimize interest costs.

Bureau of Public Roads

Although no concerted effort was made to interview Bureau of Public Roads engineers, the possibility of obtaining some worthwhile facts pertinent to these cost considerations from the production study data accumulated by the Bureau for a number of years under the direction of Mr. Morgan Kilpatrick, was explored. This would seem to be a good possible source, particularly with respect to the influence of both tolerances and quality level on production rates. Although beyond the scope of this project, it is recommended that the Bureau data be reviewed and further analyzed with these cost considerations in mind.

Contractors

Fifteen contractors were interviewed, largely in Maryland and North Carolina. The sampling included both large and small operators. In general, those interviewed were not able to quantify their answers, but there were some positive opinions and pertinent comments expressed.

In an interview with the cost engineer of a large contracting organization the following opinions were obtained:

1. A surface tolerance of ½ in. in 10 ft longitudinally for crushed stone base is fair and costs little more to produce than would a ¾-in. tolerance, but a ¼-in. tolerance would be impractical. To reduce costs, the tolerance would have to be widened to the point that no fine grading was required.

2. A specification containing an extreme or "no payment" limit of ½-in. deficiency in base thickness, combined with a requirement that in any continuous 200 ft of finished surface the algebraic difference of any two points on the finished surface from their respective plan elevations must not exceed ½ in., proved to be impractical. Placement of about 7 percent additional hot-mix base material was necessary to insure against deficient thickness, and if the base was ½ in. too thick the surface course grade tolerance was reduced to zero.

Equipment Manufacturers

Ten highway equipment manufacturers were contacted to determine which tolerances they considered critical in various equipment units and what effect tightened tolerances would have on production costs of these units. In only one instance did a manufacturer give a direct answer. In this case it was stated that the operating tolerance of an asphalt metering device was ± 0.25 percent; to increase the accuracy to ± 0.1 percent would mean approximately a fourfold increase in production cost.

Other responses were less specific and only a generalization can be drawn that as tolerances are made tighter, production costs increase in some type of geometric progression.

Materials Suppliers

The materials suppliers interviewed included one asphalt supplier and three local aggregate producers. The best reading was obtained by the questionnaires distributed through the good offices of the National Limestone Institute.

None of the materials suppliers interviewed was able to quantify the effect of closer tolerances on the cost of his products. All have learned to live with existing specifications and have geared their process controls accordingly. As cited elsewhere in this report, there is evidence that the specification limits for certain quality attributes of asphalt cements could be raised to the advantage of both the suppliers and the users. Many of the specification requirements for asphalt, and for certain other proprietary products used in highway construction, are for definition of grade, or for other identification purposes totally unrelated to serviceability, durability, or other significant quality characteristics. Some of these requirements are obsolete and the tolerance limits have become meaningless. In general, however, the limited interviews conducted in this area failed to reveal any quantitative information concerning the influence on cost of either tightening or opening current specification tolerances.

Some 25 replies were received from members of the National Limestone Institute. Practically all of these replies indicated that reduction in costs was attainable if gradation tolerances or other requirements were more realistic. The questions that elicited the greatest response are summarized in the following:

Question: What sections of highway specifications do you think need improvement and what are your suggestions?

Most of the replies to this question were concerned with the need for uniform gradation specifications and the adoption of simplified practice recommended gradations. One producer reported that he had to meet specifications for three different state highway departments plus the Corps of Engineers and the Bureau of Reclamation, although there were no significant differences in field performance. No cost figures were obtained on this item, but one producer reported that he had to maintain stockpiles of 28 different sizes of aggregates, which increased the inventory to the point that personal property taxes were increased.

Question: What particular tolerances are most troublesome with respect to your operational costs?

Various replies to this question were received. Some concerned impractical ± 5 percent (in one case ± 2½ percent) tolerances on the percent passing the No. 4 sieve, with an estimated cost reduction of about $0.10 per ton if the tolerance could be relaxed to include a reasonable range. Another mentioned a requirement that only 10 percent of a ½-in. maximum size aggregate be retained on the ⅜-in. sieve. A reduction in cost of $0.10 to $0.20 per ton was estimated if the specification was changed to 60 to 90 percent passing the ⅜-in. sieve. Probably the specification limits and tolerances have the greatest effect on the cost of crushed stone, because a tight limit or tolerance, if enforced, would require washing the stone. One producer reported that he was unable to meet an "impossible" requirement of master range 3 to 6 percent passing the No. 200 with a 1½ percent tolerance on the job-mix formula, without washing the stone and adding back the minus No. 200 material. He estimated a saving of $1.00 per ton if the master range was opened to 3 to 12 percent with a 2 percent tolerance on the job-mix formula.

Question: In what way does the administration of specifications affect your cost?

Most of the replies to this question concerned delays in acceptance testing and reporting, unqualified personnel taking samples in the field, and delays associated with ticket issuance and record keeping by state employees. No cost figures were given. In response to this question one producer noted that current specifications resulted in the waste of No. 4 to No. 100 material, with a consequent increase in cost of $0.15 per ton in portland cement concrete aggregate and $0.20 per ton in bituminous concrete aggregate.

Trade Associations

Eight trade associations were contacted to varying degrees in connection with this study. In general, it is believed that the permanent staffs, particularly the technical directors, of the trade associations (proprietary products, materials, equipment manufacturers, and contractors groups) are in a position to make valuable contributions toward improved highway specifications. They represent a source of worthwhile practical information which should be utilized by the highway specification writer. Full cooperation beween the technical staffs of the state highway commission and the trade associations should be encouraged. An important general recommended guideline is that the specification writer give the appropriate trade association full opportunity to review and comment on any anticipated change, revision, or modification to be made in any specification pertinent to its interests.

Some trade association executives are in a position to know or to estimate a few of the factors related to the cost-benefit, cost-level, or cost-tolerance question. In general, however, the amount of firsthand quantitative information available was found to be relatively scanty. It is believed, however, that the trade associations are a logical avenue for obtaining the necessary data through their members, given sufficient time and guidance as to the specific information needed. In all cases they were cooperative, interested, and in agreement that it is highly desirable to quantify those factors necessary to attain practical and realistic specifications for their segment of the industry.

Discussion with one of the larger trade associations is presented in greater detail. To obtain the point of view of the National Crushed Stone Association, its headquarters staff was interviewed with two basic objectives in mind: (1) To determine what long-range improvements in aggregate specifications were of most interest to the membership; and (2) to explore the availability of cost-tolerance relationships. Information obtained in reply to queries pertaining to these objectives was as follows:

With respect to the needs for improved crushed stone specifications:

1. The greatest need lies in improved methods of sampling. Particularly needed is the determination of the sampling errors or the variability in test results as a function of both sampling technique and the inherent variation due to random distribution of the different sized aggregate particles.

2. Next in importance has to do with test requirements with no established correlation with the quality or serviceability of the finished product. Research work by the Missouri Highway Department on the relationship between shale content and quality was cited as a good example of the type of information needed to limit the amount of deleterious material on a sound economical basis. The scratch test was cited as an example of poor engineering because of lack of established relationship with a meaningful quality attribute. Another area needing better definition is the amount and nature of minus 200 material. Dusty stone should not be permitted for certain applications, such as bituminous surface treatment, but it is needless to require washing for some other end uses unless the nature of the dust itself is bad.

3. With respect to tolerances the existing limits are considered to be fair and reasonable, with the exception of those on the minus 200 wherein better definition with relation to end use is needed.

4. Lack of standard specifications for crushed stone properties or gradation is not serious as far as the state highway departments are concerned; but it is serious among other agencies, such as the Army Corps of Engineers and the New York Port Authority. In other words, there is apparently little existing problem for those quarries producing for shipment to more than one state for normal highway use. There is considerable problem, however, due to lack of standardization among other than state highway department agencies.

TABLE 8

RAILROAD BALLAST PRODUCTION (SEVERINGHAUS)

SPECIFICATION	PERCENT PASSING 2 IN.	1½ IN.	1 IN.	¾ IN.	½ IN.	OUTPUT (TONS/HR)
AREA	100	90–100	20–55	9–15	0–5	—
Exact	100	100	30–40	4–6	0–1	65
Medium special	100	88–93	35–45	10–12	0–1	130
Coarse special	97–100	86–92	20–30	8–10	0–1	165
Fine special	100	90–95	50–60	10–18	1–3	165
Std. quant. prod.	98–100	85–90	40–55	0–15	0–2	200

With respect to the administration of crushed stone specifications:

1. Delays due to acceptance testing and reporting have given trouble in isolated areas.

2. The matter of confusion caused by improper sampling and the lack of definition of sampling error has been discussed previously.

With respect to the relationship between specification limits and costs of commercial aggregates:

1. In general, it does not necessarily follow that a lowering of quality level or the opening of allowable tolerance will result in an appreciably lower price to the consumer. Often the change merely lets in new competition from marginal producers with but little effect on the price structure. In fact, it can have a serious adverse effect in those situations wherein a large volume throughput is needed to protect the rather substantial capital investments in machinery and handling equipment associated with some crushed-stone operations. In such a case the unit price actually may have to be increased to maintain a profitable operation, or the facility may have to be shut down, resulting in curtailment or loss to the state of the higher quality aggregate production.

2. With respect to gradation tolerances, one must consider screening efficiency as a function of production rate. The qualitative interrelationships are known, although sometimes poorly understood, but the quantitative analyses soon break down because of lack of factual data. Some data were obtained showing the effect on the output of railroad ballast in tons per hour as a function of specification tolerances. These data (Table 8) show that a normal production rate of 200 tons per hour was reduced to 65 tons per hour as the specifications were changed.

3. The point at which a given specification limit for commercial aggregates will influence cost will vary widely from area to area. Two examples were cited:

(a) Where there is plenty of cheap water, washing aggregate is not as economically significant as it is in some western states where the availability of water is limited. The particular aggregate source is also a factor—serpentine is generally bad, silica dust is normally already controlled because of health hazard, granite is no problem generally, but western limestone is most serious because of water availability.

(b) L.A. abrasion limits should be set on an area basis. Where there is no hard stone it is obviously uneconomical to specify a low maximum L.A. Conversely, it would be poor engineering to allow the use of soft aggregates in Vermont, for instance. Thus, the economics of the specification limits must be governed by available supply.

4. With respect to sodium sulfate soundness, specification limits are too low in many cases. The relationship to quality is questionable, particularly in the lower levels. Additional research on the stone itself is needed.

5. With respect to flat and elongated particles, there is apparently a good bit of current interest in ASTM on this subject. It is believed that 10 percent on a 5:1 basis is acceptable, but anything less would hurt economically. In portland cement concrete it costs more to get workability with a higher percentage of flat and elongated particles, but the relationships have not been quantified.

CHAPTER FIVE

ADMINISTRATIVE AND GENERAL ENGINEERING GUIDELINES

FEDERAL CONTROL PROCEDURES

No discussion of specification level or specification tolerances can be really complete without recognizing the influences of the controls associated with highway construction involving federal funds. Whether such controls are right or wrong, or whether the administration is properly handled, is neither here nor there for purposes of this report. However, the fact that the record sampling procedures are in existence, and that some degree of federal checking will probably continue, is germane.

Adoption of the guidelines contained in this report for practical and realistic construction specifications should greatly help to solve some of the communications problems that plague practically all levels of road building. Many of the problems that arise are due to lack of understanding or of differences in interpretation of the specifications, not only between contractors and engineers, but also between lawyers and engineers or accountants and engineers in both state and federal government. Different practices and interpretations of the same regulations are applied in different states. Also, within some states and within some offices of the Bureau of Public Roads there is still evidence of lack of uniform thinking regarding some aspects of federal controls of highway funds and construction. Much progress is being made through the fine cooperative efforts of AASHO, the Bureau of Public Roads, HRB, ARBA, AGC and other trade and technical associations. However, a continuing policy guideline should be to foster a better understanding of the basic philosophy and reasons for construction specifications from the engineer's viewpoint; and a better understanding of the philosophy and need for practical and realistic control of both quality and dollars throughout all segments of the highway industry. The need for better understanding of basic philosophies will become even more important as the new statistical concepts are adopted.

The acceptance testing plans and the procedures presented in Chapter Three will also assist in obtaining a better correlation between Bureau record sampling results and the state routine control test results. Also, as the new methods of incorporating realistic construction tolerances into the specifications are adopted there should be fewer discrepancies which are the fault of neither the contractor nor the state but which arise from poorly worded requirements which fail to take into account the normal variability associated with most highway materials.

In the meantime, however, there is need to recognize a potential danger arising from current federal control policies. Simply stated, the danger is that there may be too much emphasis placed on finding means of satisfying the letter rather than the intent of the law to the detriment of proper specifications for control of highway construction to obtain the most economical and serviceable roads over the long pull. More specifically, the danger consists of relaxing specification tolerances and adjusting the quality levels so that there will be essentially no negative test results that have to be "explained." If the engineers at both state and federal levels are encouraged to relax specification tolerances prematurely and unwisely, there is an obvious danger to both serviceability and overall cost. Further, if engineers refrain from or postpone the upgrading of their specifications where indicated to take advantage of improved materials or construction techniques, the danger is also obvious. The degree to which either of these have really hurt construction to date cannot be defined, but specific cases in both categories are known. Full cognizance of the situation should be taken to avoid being stampeded into unwise tolerances now and to avoid jeopardizing the acceptance of realistic tolerances as they are defined and become available later on.

This problem is largely a matter of timing and two guidelines are recommended, as follows:

1. That the work necessary for definition of realistic tolerances and adoption of statistical concepts in both the writing of improved specifications and the acceptance testing for compliance be expedited.
2. In the meantime, that the influences of pressures all up and down the line be re-examined in light of the improvements, both those under way and those made to date, in highway construction controls. This should apply to the Legislative Investigation Committee, the General Accounting Office, the Bureau of Public Roads, and the state highway departments at all levels. This does not mean curtailment of any worthwhile functions or relaxing of the responsibilities associated with these important areas of public domain. It does mean recognizing and weighing the consequences of relaxing specification tolerances simply to avoid negative results on a test report.

UNIFORM INTERPRETATION AND ENFORCEMENT

The best of specifications cannot fully accomplish their mission unless they are uniformly interpreted and enforced. This statement may seem a bit trite and obvious at first, but failure on the part of the engineers to enforce the specifications can and does have far-reaching effects on the whole highway industry. If the guidelines and principles recommended in this report are followed, there should be considerably less chance for ambiguity and misinterpretation on the part of contractors and engineers or lawyers and accountants. Much of this advantage will be lost, however, if in spite of greater clarity there is a lack of uniform enforcement.

It is the engineer's responsibility and his duty, not only to the owner but also to the rest of the industry, including the contractor, to enforce the ground rules. This does not have to be rigid and arbitrary adherence applied in a police-state atmosphere. The specifications can and should be applied in a just and fair manner with the contractor and the engineer (inspector) working together.

Most contractors state that they want to do a good job—that they want to upgrade the quality standards of road construction and will wholeheartedly back and support sound and realistically applied quality controls. However, there is no practical way in which the contractors can really police themselves. They can summarily dismiss the "fly-by-night" from their associations, but they have neither the means nor the authority for controlling the quality of the other fellow's work. This is the responsibility of the engineers in public domain, and if they do not do a proper, uniform job of quality control, they are letting down the legitimate contractor who is trying to build a better road. He wants and should have uniform interpretation and enforcement of the specifications to protect his competitive position as well as the quality of the roads. Forcing him to compete—and compete he must—with shoddy workmanship or substandard materials is obviously unfair and detrimental to everyone and to all levels of the highway industry. The contractors have a responsibility and must do their part, but the engineers set both the ground rules and the level of attainment.

Consider, however, the effects of nonuniformity in any sense, either interpretation or enforcement of the specifications or of the policy ground rules. Under these circumstances the contractor has two recourses. One, he can raise his bid to allow for strict enforcement or adverse (to him) interpretation; or two, he can take a chance on getting by or of finding some other means of "coming out" on the job. In either case, he is in an untenable position which the taxpayers must ultimately pay for in one way or another.

There should be some reasonable leeway for the exercise of engineering judgment in the field to handle extenuating circumstances cooperatively in a straightforward and businesslike manner. With uniform interpretations and with uniform administrative policies such reasonable latitudes should be, and are, practical and of benefit to all concerned.

What then, is the guideline that can be included in the specification that will provide assurance to the engineer that his decisions with respect to interpretation and enforcement of requirements will not be unduly criticized? Can this same guideline give assurance to the contractor that the requirements will be uniformly enforced? Possibly the gist of such a guideline may be found in the doctrine of "substantial conformance" as stated by Sherwood K. Booth, Deputy General Counsel, Bureau of Public Roads, in a panel discussion presented before the AASHO Committee on Legal Affairs, Detroit, Mich., December 2, 1960:

> Where a contractor in good faith has made substantial performance of the terms of the contract but there are slight omissions and defects which can be readily remedied so that an allowance therefor out of the contract price will give the other party in substance what he has bargained for, the contractor may recover the contract price, less the damages on account of the omissions. On the other hand, if the defect is substantial, goes to the essence, and cannot be corrected without replacement of the work, the contractor would be required to bear the replacement cost.

EDUCATIONAL CONSIDERATIONS

Acceptance of the statistical approach can do much to promote uniformity of interpretation of specifications. The engineer who is aware of the statistical risks involved in making an acceptance decision knows how much evidence is necessary to defend that decision, if necessity should arise. The contractor who understands the workings of an acceptance plan can proceed with confidence when he must meet the requirements of such a plan, knowing that it is based on practical limits, and that this plan will be applied uniformly to the work of his competitors as well as to his own. The technician who has been briefed on the rudiments of statistics will not flinch from the test result that is "a little outside the specification" and will realize that he is doing his employer a disservice if he does not report it, instead of deciding to "take another sample."

Currently, many engineers appear to be under the impression that adopting statistically derived specification limits means controls will be relaxed and that inferior quality will be accepted. For this reason, the bottleneck to the acceptance of the statistical approach is at the top, and the higher echelon must be convinced that the purpose of statistical limits is to recognize that there are considerable variations in the level of any characteristic of any material or of any type of construction. Some of these people may be hard to convince, because data acquired by current research programs indicate that the normal range of variation of some characteristics is much larger than indicated by control tests based on "representative" samples.

Concurrently, these top people must be brought to realize that only after the actual variation existing in current construction is known can the causes of this variation be analyzed, and the quality level and uniformity increased by removal of assignable causes of variation, when such increase would result in greater use value.

It is believed that the program currently being implemented by the Bureau of Public Roads will do much to convince those engineers who have an opportunity to examine data derived from probability sampling that wide variations do exist in acceptable construction. The next question is: What to do about it? How are top engineers to interpret these data so as to gain a personal understanding of its significance and implications? How are these data to be analyzed and utilized? How are specifications to be written that will properly allow for normal variation, but will distinguish acceptable material or construction from that which is unacceptable, under different conditions of criticality? How are technicians to be trained in the important details of acquiring and processing data? Some guidelines for handling these problems have been presented in this report, but a full treatment of all pertinent details is far beyond its scope.

It is evident that a highway engineering statistical manual should be available and some of the requirements for such a manual are even now apparent. This manual should not assume that the user had any prior knowledge of statistical methods and should:

1. Be confined to theory and method pertinent to highway engineering problems.
2. Be written, as far as is possible, in simple engineering language, with full explanation of all statistical terms.
3. Be written in "programmed learning" format so as to be suitable for either training course or self-study use.
4. Contain worked out examples of typical applications of statistical methods to highway construction.

Such a manual would accomplish many purposes. One that may not be obvious would be to standardize the mathematical and statistical symbols used by highway engineers. Unless such symbols and their precise definitions have common usage, considerable confusion and misunderstanding can be expected in connection with the interpretation of future technical papers and reports dealing with highway construction statistics.

VALUE ENGINEERING

Definition of Terms

Everyone wants more road for the money, but any experienced highway engineer knows that it is false economy to jeopardize quality. To reduce quality below some critical point means heavy maintenance costs, an increasingly serious problem as highway mileage is extended. To obtain optimum mileage with available funds, without obligating large amounts of future funds for maintenance, requires that allocated resources be expended with maximum efficiency, and herein lies the potential contribution of value engineering.

Value engineering must be carefully defined and clearly understood if it is to provide significant economies in highway construction. This requires, first, an understanding of what constitutes value in highway construction and an explanation of what value engineering is, and what it is not.

The value of a canteen of water to a thirsty man varies with the man's distance from a source of supply. The value of a ship's compass to its navigator is vastly different from its value to a housewife. The obvious logic of these statements illustrates that value is a variable.

Value, although it is a broad term, has been categorized so that it can be defined meaningfully. Three such categories of principal importance with respect to highway construction are:

1. *Use value*—The obtained characteristics and qualities of a material, product, or item of construction, associated with accomplishment of functional performance.

The main performance characteristics of a pavement are safety, smoothness, longevity, and the ability to support wheel loads without permanent deformation.

2. *Cost value*—The price of a collection of units of material or an item of construction, having specified characteristics, in terms of money, proportion of available manpower, or depletion of natural resources.

Here, natural resources refer to local materials having some particular characteristic, which are in short supply, or will be exhausted in the foreseeable future. Manpower refers particularly to qualified engineering or technician personnel available within the budget of a highway department.

3. *Aesthetic value*—The worth of an item of construction in terms of pleasing appearance or gratifying performance.

Appearance, as used here, refers to minor details of construction, such as special finishes on concrete surfaces.

Obviously, any specification requirement has some cost value associated with it. To be justified it must have some equivalent use value or some worthwhile combination of use value and aesthetic value. The relationships, as applied to highway construction, are the province of value engineering, which can be defined as follows:

Value engineering—An organized effort directed at analyzing the function of highway components with the purpose of achieving the required function at the lowest total cost.

The definition of highway components seems obvious; such things as embankment, base, surface course, structures, and drainage are easily listed. But value engineering can include the means of achieving the function of a component such as the administrative and engineering costs of operating a highway department. In addition to the direct cost of a square yard of base there is an associated cost of inspection and testing of materials, field and laboratory testing, paperwork, and the processing of claims. These secondary costs, although relatively small, are related to the number and nature of specification requirements.

As used in the preceding definition of value engineering, function means the same as performance or use value. Required means that neither more nor less than what is actually needed and wanted is to be attained. By organized effort is meant a definite set of procedures which will achieve the desired result.

Procedures

With respect to highway construction, procedures should include:

1. Component selection.—Components selected for function analysis should represent a substantial part of the overall cost of the construction of a highway so that any possible reduction in unit cost will achieve significant savings. There should also be an apparent potential for cost reduction. One criterion is to compare the current unit cost with that for similar items, fulfilling the same purpose, constructed in other areas.
2. Determination of function.—The function(s) that must be performed by each component must be analyzed. The function of a component may vary according to anticipated traffic demands or because of climatic conditions.
3. Information gathering.—This means the collection of all pertinent facts concerning the component. These include the present cost, projected availability of materials, essential performance characteristics, actual level and variability of measurable properties of current acceptable

material or construction, and historical background of present requirements.

4. Development of alternatives.—The creation of ideas for the use of other materials, or different methods of construction, that appear to have sufficient potentials for performing the required function at a reduced cost to warrant testing, or use on a trial basis.

5. Cost analysis of alternatives.—The development of estimates of the cost of alternatives and the selection of one or more that will effect economies.

6. Testing of alternatives.—Laboratory tests, trial sections, or other proof that the use of the selected alternatives will not jeopardize the functional requirements of the component.

7. Preparation of specification.—The specification should include only those requirements essential to functional performance. At this point application of unjustified safety factors or incorporation of arbitrary or redundant requirements can wipe out the cost savings originally anticipated.

Objective of Value Engineering

At this point the difference between cost-cutting and value engineering should be clear. Cost-cutting is attacking things as they are to reduce their cost. Value engineering, on the other hand, takes nothing for granted and attacks everything about a component that will not change the essential performance characteristics or use value below the required level. In short, value engineering is a reappraisal of highway component requirements, from both a function and a cost standpoint, done to assure maximum value using more recent knowledge of relative material and equipment costs on the one hand, and a better understanding of the technical and engineering requirements related to performance on the other.

The basic objective of many current specification requirements, at the time they were written, was to achieve a standard by some means or other. The objective of value engineering is to provide a component having the required functional performance at a reduced cost value.

GENERAL ENGINEERING GUIDELINES

There are but few general engineering guidelines to cover the technical aspects of construction specifications. Each material, product, or item of construction has its own problems, its own reasons for being, its own primary and secondary control factors or properties. It is obviously beyond the scope of this limited study to even attempt the establishment of guidelines for each individual material or item of construction. Nevertheless, a few general guidelines or principles are given, following which the three items specifically mentioned in the project statement—aggregates, thickness, and smoothness—are covered in greater detail.

General guidelines recommended for the engineering or technical aspects of highway construction specifications are:

1. Each material, product, or item of construction should be classified as to its relative importance. The metal used in highway signs, for instance, is not as important as the steel girders in a bridge. Each has its function, and each exerts its influence on overall serviceability and costs. However, the consequences of accepting a faulty bridge girder could be extremely serious, whereas a faulty lot of signs can be more readily replaced.

The criteria or guidelines for judging the relative importance of the various materials, products, or items of construction themselves are the same as those given for criticality. It should be noted, however, that the criticality ratings apply to the specification requirement and include considerations other than the relative importance of the item itself.

2. The specification requirements for a given material, product, or item of construction should also be classified. There are certain primary characteristics which are critical to satisfactory performance, whereas other requirements are of secondary nature having contractual or identification significance only. For instance, the tensile strength and elongation characteristics of steel cables used in prestressed concrete beams would have a significant bearing on the structural integrity of a concrete structure and therefore should be classed as a critical requirement. Sudden failure of the structure could result in loss of life and every precaution should be taken to avoid this possibility. On the other hand, actual diameters of individual wires in the cables are not so important. It is obviously uneconomical and poor engineering to spend as much time and money on the testing of secondary specification requirements as is spent on the primary characteristics. Just because a material or item of construction is in itself an important part of the construction does not necessarily mean that each specification requirement is important. In fact, the serviceability of most highway construction items is a function of, or can be described by, a relatively few primary characteristics. It is recommended that emphasis be placed on pinpointing those primary characteristics which really are meaningful, thereby enabling spending of the testing dollar to better advantage.

3. The buyer's and seller's risks should be established at practical and realistic levels to reflect the criticality of the specification requirements, as defined in Chapter Three. It should be noted that criticality is a function of both the relative importance of the material, product, or item of construction itself and the significance of the characteristic or requirement specified.

4. Quite independent of the relative significance of some specification requirements (i.e., primary versus secondary characteristics) is the matter of relative significance as a function of historical experience in a given local area (state or region). The ASTM and AASHO specifications for many construction materials (such as portland cement, asphalt cement) contain a number of secondary requirements which are only significant, or the quality levels of which are only significant, in certain parts of the country. Some state specifications are so far behind current quality levels that the significance of some of their specification requirements have lost meaning. For instance, the ductility

at 77°F requirement of 100 + cm is pointless in most parts of the country, not because ductility per se is unimportant, but because most modern asphalts never fail the test. It is pointless to repeatedly run the ductility on every lot of asphalt cement to be approved by a state highway department, at least on the east coast, when a spot check from each refinery or supplier once or twice a year would suffice.

Thus, it is recommended that the engineering or technical significance of the secondary requirements of proprietary materials in particular be examined periodically from the viewpoint of the number of failures historically encountered. This evidence should then be used to either upgrade the quality level requirement or to adjust the frequency of testing to most economically obtain the protection deemed necessary.

5. A further general engineering guideline is to attempt to define specified characteristics or requirements as a single factor that can be expressed numerically. It is recognized that the interrelationships existing among the specification requirements for some materials or items of construction are important. Nevertheless, for the sake of clarity and to facilitate the use of statistical methods, it is highly desirable to reduce these relationships to measurements that can be expressed as a single factor or coefficient whenever possible. Examples include use of fineness modulus or the Hudson $\overline{A}$ instead of aggregate gradation on various sieves; VTS index rather than viscosity at two or three different temperatures to define the viscosity-temperature relationship of asphalt cement; or the uniformity coefficient, C_u, for relative particle size control. Illustrations of the use of this principle are scattered throughout this report. Whenever possible, coefficients or factors derived from rational analyses of fundamental properties should be used. However, empirical relationships or factors can and do serve a useful function in highway specifications when properly used as interim expediencies pending further definition of fundamental properties.

6. The point has already been made that the relatively few primary characteristics governing quality should be pinpointed and emphasized in the specification. A corollary to this is the recommendation that critical and objective engineering analyses of the specification requirements be made periodically in an attempt to find new and better relationships with service performance. Just because "we have always done it that way" does not constitute a good criterion for a practical and realistic construction specification.

Bases for improved specifications for construction, as well as for design, are potentially available from the AASHO Road Test. Two examples of use of this information in writing more realistic thickness and smoothness specifications are given in Chapters Seven and Eight. But this is only a start. The engineering family should be alert to the other applications, not only from the AASHO Road Test but also from the multimillion-dollar annual research program made mandatory by the Congressional Highway Act. The results of research conducted (a) by the states themselves or under the 1½ percent HPR program, (b) within the Bureau of Public Roads, and (c) under these National Cooperative Highway Research Program studies should be reflected, where appropriate, in the specifications if optimum value is to be derived from these expenditures. This effort is in addition to an already impressive advance in highway construction technology from the stepped-up research sponsored by the materials suppliers, equipment manufacturers, contractors, trade associations, and other free enterprise segments of the industry. Thus, a basic guideline recommendation is that each state highway department establish a suitable means for taking a good close look at the engineering and technical aspects of its specifications *each year* to assure keeping abreast. Reflection in the specification requirements is one of the most important and significant ways in which technological advances and the fruits of modern research can be reduced to practice.

SCOPE OF SPECIFIC ENGINEERING GUIDELINES

The three items—aggregate gradation, thickness of bases and pavements, surface smoothness—as suggested in the project statement, have been selected to illustrate these general guidelines. These are reported separately in Chapters Six, Seven, and Eight. An attempt has been made to find some new approach to define and relate a significant specification characteristic to serviceability. Current practice, as reflected by the specification requirements of a sampling of 15 state highway departments and 2 federal agencies, is included. In some cases it has been possible to provide a reasonably current tabulation of specific requirements for all 50 state highway departments. In reading these chapters it should be understood that:

1. No attempt has been made to cover all the literature pertaining to these broad subjects, only that pertinent to specification writing.

2. The specification requirements for the 17 agencies are current, but in those cases where tabulations are presented covering all 50 state highway departments the latest available published data were used as a source of information.

3. An attempt has purposely been made to find something novel or new to illustrate various points. These ideas are admittedly not time proven and, although believed to be technically sound on the basis of current information, they are undoubtedly subject to challenge, at least in part.

4. No attempt has been made to write a textbook covering all of the technical aspects of aggregates, thickness, or smoothness. Rather, the objective has been to select those aspects illustrative of certain guidelines germane to the writing of practical and realistic construction specifications.

CHAPTER SIX

AGGREGATE GRADATIONS

In this and the following two chapters no attempt has been made to write a textbook. Instead, the objectives are to present illustrative guidelines and new approaches to methods of analyzing relationships between specification requirements and performance.

PURPOSE OF CONTROLLING GRADATION OF AGGREGATES

It is generally agreed that of the various controllable characteristics of aggregates, gradation is of primary interest. However, there is not unanimity of opinion as to the importance of controlling gradation or what variations should be allowed under various conditions. Economic considerations and availability of local materials have led to a diversity of requirements for gradation of aggregates used for similar purposes in different geographic areas. This is exemplified by the requirements for gradation of base course aggregates in various states shown in Table 11. Several surveys have shown that this diversity is characteristic of requirements for other applications.

The basic reasons for specifying gradation are as follows:

1. To limit maximum size because of restricting dimensional considerations.
2. To limit the quantity of fines (minus No. 200 material) because of plasticity or capillarity and frost action considerations.
3. To control the quantity and size of aggregate voids.
4. To limit the surface area.
5. To produce adequate shear strength.
6. To obtain adequate workability.
7. To control the texture of exposed surfaces.

RELATIONSHIP OF GRADATION TO VOIDS

Requirements as to maximum size and quantity of FINES depend on the particular use to be made of the aggregate. The proportion of particles of different sizes within this maximum and minimum range, for most applications, is related to certain mathematical relationships. Workability, density, and shear strength are more or less interrelated and are maximized when the proportion of one size group to another is in the ratio, R, of 1 to 1.35.

As shown in Figure 21, when aggregates are separated into size groups by the use of STANDARD SIEVES absolute minimum voidage is obtained when the percentage passing each sieve is approximately 1.35 times the percentage passing the next smaller sieve.

This may or may not be a desirable condition. In asphaltic concrete, for example, it is necessary to provide sufficient aggregate voidage to accommodate the quantity of asphalt required to coat the aggregate particles with durable films of asphalt. The relative size of the voids is also of importance, because small voids tend to reduce permeability whereas large voids reduce capillarity and provide space for frost expansion. Working from this concept of the effect of the ratio of one size group to another, aggregate gradations can be tailored for specific applications. For example, Table 9 gives three theoretical gradations having the same maximum size but with widely different voidage characteristics.

Gradations A and C have approximately the same excess of voids over gradation B, but the voids differ greatly in average size. The quantity of voids as affected by gradation is relative, inasmuch as particle shape and surface texture of the particles will determine absolute voidage in any particular gradation.

The ratio of 1 to 1.35 for successive size groups agrees well with the maximum density log-log slope of 0.45 verified by the Bureau of Public Roads and with Fuller's parabolic maximum density curve, which has influenced many gradation specifications. However, as previously stated, maximum density may not produce optimum voidage for some applications, and any theoretical curve used as a basis for a gradation band should be investigated with respect to its suitability for use under actual construction conditions. For example, the relationship between percent asphalt by volume required for durability of asphaltic concrete, and the aggregate voidage resulting from the aggregate gradation is such that the aggregate voidage should exceed 15 to 17 percent, rather than be forced to a minimum value. As can be seen by inspection of current specifications, it is common practice to grade binder courses so as to produce large voids ($R > 1.35$) and wearing courses so as to produce small voids ($R < 1.35$).

TABLE 9

EFFECT OF GRADATION RATIO ON VOID SIZE

SIEVE SIZE	PERCENT PASSING		
	GRADATION A, HIGH PERCENTAGE OF SMALL VOIDS	GRADATION B, MINIMUM VOIDS	GRADATION C, HIGH PERCENTAGE OF LARGE VOIDS
1½ in.	100	100	100
¾ in.	83.3	74.1	62.5
⅜ in.	69.4	54.9	39.1
No. 4	57.8	40.7	24.4
No. 8	48.2	30.1	15.3
No. 16	40.2	22.3	9.6
No. 30	33.5	16.5	6.0
No. 50	27.9	12.2	3.8
No. 100	23.3	9.0	2.4
No. 200	19.4	6.7	1.5
	$R = 1.2$	$R = 1.35$	$R = 1.6$

AGGREGATE GRADATION SPECIFICATIONS

Asphaltic Concrete

BASIS OF CURRENT SPECIFICATIONS

A review of current specifications for asphaltic concrete aggregates has shown that there is an extreme diversity in gradation requirements, even for paving mixtures used for similar purposes. This lack of uniformity of requirements is illustrated by the typical gradings specified by the agencies included in Table 10. In the broad area of paving mixtures, some aggregates are WELL GRADED, some SKIP GRADED, some OPEN GRADED, and some DENSE GRADED. Inasmuch as all of these mixtures are presumably giving satisfactory service in some application, there is little evidence that gradation is intrinsically related to performance. Although, in general, dense-graded aggregates having a relatively large maximum size show a high resistance to deformation in laboratory tests, this is not necessarily an indication of superior use value, because POORLY-GRADED sand aggregate has given satisfactory performance in some applications. On the other hand, gradations based on theoretical curves have not performed satisfactorily in some pavements. In other words, there does not appear to be any basis in current practice for a "best" type of gradation for universal application. However, there are certain general considerations that may be considered to be guidelines for judging the practicality of any gradation specified for use in an asphaltic paving mixture.

MAXIMUM SIZE OF AGGREGATE

In general, the size of the sieve through which all or practically all of the graded aggregate must pass is limited to about ½ to ⅔ the thickness of the paving course. Also, as maximum size increases, the stability, or resistance to deformation, increases and the proportion of asphalt required to produce a durable mixture decreases. For this reason, gradations starting with a large maximum size of aggregate up to 1½ or 2 in. are both suitable and economical for black base construction in areas where crushed stone is available locally. In overlay work, black base using a large maximum size of aggregate has been found to reduce or defer reflection cracking. For construction of

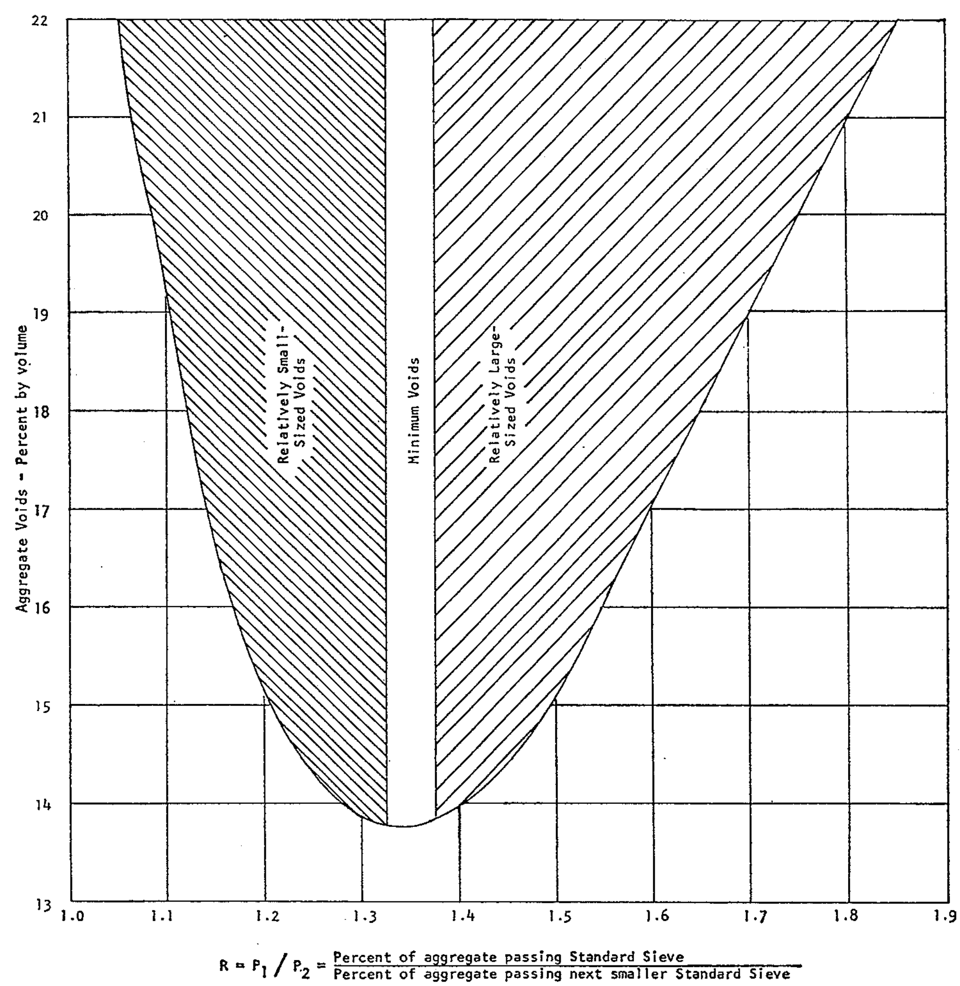


Figure 21. Relationship of P_1/P_2 ratio to aggregate voidage.

TABLE 10

GRADATION OF AGGREGATES FOR BITUMINOUS MIXTURE (HOT-PLANT MIX)

		TOTAL PASSING SIEVE SIZE (%)															
AGENCY	MIXTURE	2 IN.	1½ IN.	1 IN.	¾ IN.	½ IN.	⅜ IN.	¼ IN.	NO. 4	NO. 8	NO. 10	NO. 30	NO. 40	NO. 50	NO. 80	NO. 200	BITUMEN
A	Base, 1-in. max. coarse[a]			95–100	80–95		50–65		35–50			12–25				2–7	—[b, c]
	Surface, ¾-in. max. coarse			100	90–100		60–75		40–55	27–40		12–22				3–6	—[b, c]
	Surface, ¾-in. max. medium			100	95–100		65–80		45–60	30–45		12–25				3–7	—[b, c]
	Surface, ¾-in. max. fine			100	95–100		70–85		50–65	37–52		18–30				4–10	—[b, c]
	Surface, ½-in. max. coarse				100	95–100	70–90		50–67	35–50		15–30				4–7	—[b, c]
	Surface, ½-in. max. medium				100	95–100	80–95		55–72	38–55		18–33				4–8	—[b, c]
	Surface, ½-in. max. fine				100	95–100	80–95		58–75	43–60		20–35				6–12	—[b, c]
	Surface, ⅜-in. max.					100	95–100		60–85	50–70		28–40				7–14	—[b, c]
	Surface, No. 4 max.						100		95–100	70–80		35–50				7–16	—[b, c]
B	Base[d]	90–100		70–95		48–62			28–40	23–33		17–25			6–14	1–4	4.0–5.5[c]
	Leveling[a]			90–100		60–80			32–43	26–36		19–27			7–15	1–5	4.5–5.5[c]
	Surface, Type A			100	90–100	70–85			40–52	30–40		18–28			8–16	4–8[e]	5.0–6.5[c]
	Surface, Type B				100	95–100			50–60	40–50		25–35			10–20	6–10[bbb]	5.0–8.0[c]
E	Binder, A[t]			95–100[f]		10–30[g]			5–15[h]		7–22[i]		5–18[j]		3–10[k]	3–7	3.5–7.0
	Binder, special, B[u]				95–100[l]	20–40[g]			5–15[h]		7–22[i]		5–18[j]		3–10[k]	3–7	3.5–7.0
	Surface[v]					95–100[m]			10–30[h]		7–22[i]		5–18[j]		3–10[k]	3–7	4–7
F	Binder			100[n]							14–36						4–8
	Leveling					100[o]					14–36						4–8
	Surface, 25A					100[p]					25–40[k]					4.5–8	4.5–8.0
	Surface, 31A						100[h]				30–50[k]					5–7	5.0–9.0
G	Base, Type C				100	95–100[q]			40–60		20–40					0–5	3.5–4.5[c]
	Base, Type D				100	85–100[q]	40–70		15–30		5–15					0–5	4.2–5.0[c]
	Surface, Type A				100	98–100[q]	70–85		50–65		35–50		15–30		8–16	4–8	5.2–6.2[c]
	Surface, Type B					95–100[r]			52–68		35–50		18–32		8–16	4–8	5.2–6.2[c]
H	Base, S.A.				100						70–100		15–90		5–45	2–15	5.5–9.5
	Base, D.G.			100	95–100	65–90					30–55		35–90[s]		15–45[s]	1–15[s]	4.0–7.0
	Surface, S.A.								100		90–100		35–75		15–45	7–15	7.5–12.0
	Surface, S.A.				100	90–100	70–90				45–80		35–90[s]		15–45[s]	7–20[s]	5.0–10.0
	Surface, S.A.					100	75–100				60–90		35–90[s]		15–45[s]	7–20[s]	6.0–11.0
	Surface, D.G.						100				75–95		35–90[s]		15–45[s]	1–15[s]	6.0–10.0
I	Surface				100				40–70		25–55					2–10	3.5–7.0[c]
J[ccc]	Mix I[bb]		0–35[w]	25–70[x]		0–20[y]		0–15[h]			1–11[z]	2–15[aa]		2–14[j]	2–13[k]	0–5	4–6
	Mix II[cc]		0–25[w]	20–45[x]		10–25[y]		5–15[h]			2–14[z]	5–18[aa]		4–18[j]	3–16[k]	4–8	5–7
	Mix III[cc]			8–25[x]		20–45[y]		5–25[h]			2–14[z]	5–18[aa]		4–18[j]	3–16[k]	4–8	5–8
	Mix IV[dd]			0–10[x]		12–40[y]		8–30[h]			2–17[z]	4–24[aa]		6–22[j]	3–20[k]	4–8	5.5–9
	Mix V[ee]			0–5[x]		20–35[y]		15–30[h]			8–22[z]	4–15[aa]		3–15[j]	4–9[k]	4–8	5–8
	Mix VI[ff]					0–10[y]		8–25[h]			3–25[z]	8–30[aa]		10–28[j]	6–25[k]	4–10	8–11
	Mix VII[gg]							0–5[h]			4–25[z]	10–35[aa]		12–33[j]	8–28[k]	10–15	9–11.5
K	Class A			100	70–100	55–85	45–70		30–55		20–45		10–25		7–15	4–8	—
	Class B				100	70–100	55–85		40–65		30–50		15–30		8–20	4–9	—
	Class C					100	70–100		50–75		35–55		15–33		10–23	4–10	—
	Class D					100	75–100		35–55		20–35		10–18		6–13	2–8	—
L	Binder		100	90–100		35–65		10–35		5–20[hh]							4.0–5.5
	Base	100		60–75		20–50		5–20		0–5[hh]							2.5–4.0
	Surface, 1A			100		95–100		65–85		32–65[hh]		15–39[ii]	7–25		3–12	2–6	5.8–7.0
	Surface, 1AC					100		95–100		45–70[hh]		8–40[ii]			3–15	2–8	6.0–8.0
	Surface, 2A					100		90–100		65–80[hh]			35–70		17–40	5–12	7.5–8.5
	Surface, 2B					100		88–93		58–72[hh]			35–54		14–32	6–12	7.0–8.0
	Surface, 3A			100		95–100		60–80		25–55[hh]		5–20[ii]			2–10	1–4	5.8–7.0
M	Base[nn]	10–35[w]		10–45[x]		5–40[g]			0–5[ll]	10–40[mm]				2–17[k]		0–5	4–8
	Surface, Type A[oo]			0–5[jj]	7–30[x]	7–30[kk]	10–35[g]		0–10[ll]	20–45[mm]				3–15[k]		0–8	4.0–9.5
	Surface, Type B[pp]				0–6[x]	10–35[kk]	10–35[g]		0–10[ll]	20–45[mm]				3–15[k]		0–8	4.5–9.5
	Surface, Type C[qq]					0–7[kk]	25–50[g]		0–15[ll]	20–45[mm]				3–15[k]		0–8	4.5–9.5
N	Base, binder, Type A	100	80–100			60–80			40–55		30–45		15–30		8–20	2–8	4.0–6.5[c]
	Binder, surf., Type B				100	80–100	70–90		50–70		35–50		15–30		10–20	3–9	5.0–7.5[c]
	Level, surf., Type C					100	80–100		55–75		40–55		18–33		10–22	4–10	5.0–7.5[c]
O	Binder			100	90–100		38–68		15–44	10–30	7–24[rr]	4–19		1–14	0–10[ss]	0–5	4.0–7.5
	Surface, Nat. S.									100	88–100[rr]	70–92		50–80	20–40[ss]	9–15	9.0–12.5
	Surface, Gr. S.						100		90–100	85–100	65–82[rr]	45–64		26–42	14–24[ss]	9–15	7.5–11.0
	Surface, Sn. S.						100		90–100	85–100	70–90[rr]	65–85		50–70	20–35[ss]	10–15	8.0–11.0
P[ddd]	Base, Type A[yy]	100	95–100[tt]		15–40[kk]		10–25[g]		5–20[h]		0–20[i]		3–15[j]		2–15[k]	0–8	3–6
	Base, lev., Type B[zz]			100	95–100[uu]		10–40[g]		5–25[h]		0–30[i]		4–20[j]		3–20[k]	0–8	3.5–7
	Surface, Type C[aaa]				100	95–100[vv]	10–35[g]		10–30[h]		0–30[i]		4–25[j]		3–25[k]	0–8	3.5–7
	Surface, Type D[aaa]					100	95–100[ww]		10–30[h]		0–30[i]		4–25[j]		3–25[k]	0–8	4.0–8.0
	Surface, Type E								100[xx]		15–40[i]		20–45[j]		12–32[k]	7–20	7.5–12
Q	Base, binder		100	95–100		65–90			40–65	25–50				7–20		3–12	3.5–6.0
	Surface, No. 3			100		95–100	75–100		45–85	30–60				10–25		5–12	5.0–7.0
	Surface, No. 4					100	95–100		70–85	50–70				10–25		5–10	5.0–7.0

[a] 100 percent passing 1¼ in. [b] No maximum bitumen content specified; for Types A, B, and C minimum percentages of bitumen set at 4.8, 4.4, and 3.8 percent, respectively. [c] Percent bitumen not included. [d] 100 percent passing 2½ in. [e] 3–5 percent filler included. [f] 20–40 percent retained on ½ in. [g] Retained on No. 4. [h] 40–60 percent retained on No. 10. [i] Retained on No. 40. [j] Retained on No. 80. [k] Retained on No. 200. [l] 15–30 percent retained on ½ in. [m] 25–50 percent retained on No. 4. [n] Passing 1¼ in., 60–80 percent retained on No. 10. [o] Passing ⅝ in., 60–80 percent retained on No. 10. [p] Passing ⅝ in., 50–65 percent retained on No. 10. [q] Passing ⅝ in. [r] 100 percent passing ⅝ in. [s] Passing No. 10 considered separately. [t] 20–40 percent passing ½ in. and retained on No. 10; 20–35 percent passing No. 10 and retained on No. 200. [u] 33–48 percent passing ½ in. and retained on No. 10; 20–40 percent passing No. 10 and retained on No. 200. [v] 45–65 percent passing ½ in. and retained on No. 10; 25–40 percent passing No. 10 and retained on No. 200. [w] Retained on 1 in. [x] Retained on ½ in. [y] Retained on ¼ in. [z] Retained on No. 30. [aa] Retained on No. 50. [bb] Total retained on No. 10, 55–85 percent. [cc] Total retained on No. 10, 45–65 percent. [dd] Total retained on No. 10, 30–60 percent. [ee] Total retained on No. 10, 40–55 percent. [ff] Total retained on No. 10, 15–30 percent. [gg] Total retained on No. 10, 0–5 percent. [hh] Passing ⅛ in. [ii] Passing No. 20. [jj] Retained on ¾ in. [kk] Retained on ⅜ in. [ll] Retained on No. 6. [mm] Passing No. 6, retained on No. 50. [nn] Total retained on No. 6, 60–75 percent. [oo] Total retained on No. 6, 45–75 percent. [pp] Total retained on No. 6, 45–70 percent. [qq] Total retained on No. 6, 40–65 percent. [rr] Passing No. 16. [ss] Passing No. 100. [tt] Passing 1¾ in., 15–40 percent retained on ⅞ in. [uu] Passing ⅞ in., 20–50 percent retained on ⅜ in. [vv] Passing ⅝ in., 15–40 percent retained on ⅜ in. [ww] 20–50 percent retained on No. 4. [xx] 0–5 percent retained on No. 10. [yy] Total retained on No. 10, 60–80 percent. [zz] Total retained on No. 10, 55–70 percent. [aaa] Total retained on No. 10, 50–70 percent. [bbb] 4–6 percent filler included. [ccc] 1½ in., 1 in., ½ in., and ¼ in. are round opening sieves. [ddd] Types A and C = coarse-graded; Types B and D = fine-graded; Type E = sheet asphalt.

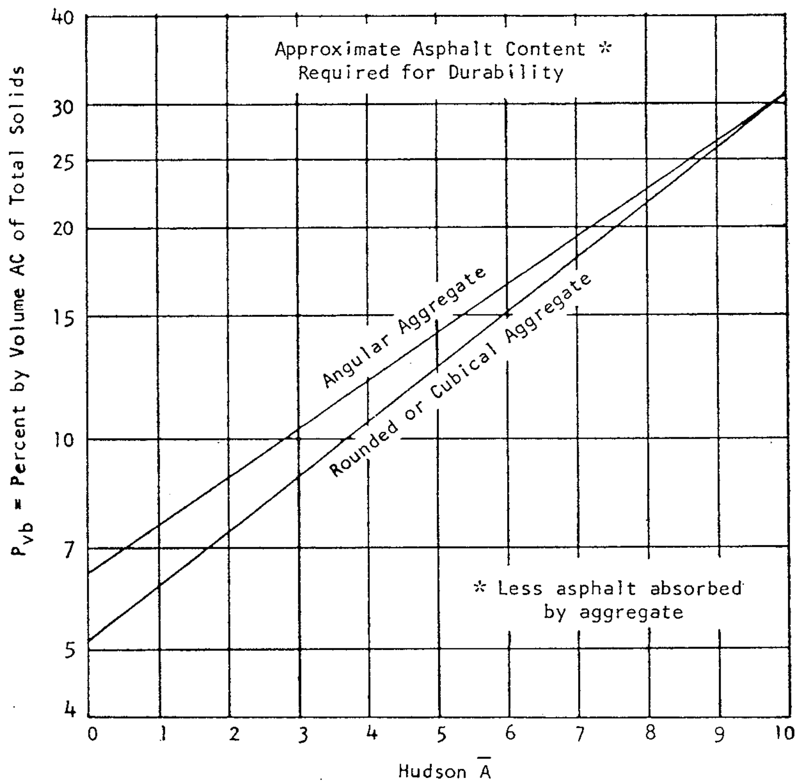


Figure 22. Relationship of $\bar{A}$ to asphalt demand.

binder courses, ¾ in. appears to be a practical maximum size, whereas asphaltic concrete wearing courses for highways usually are limited to ½ or ⅜ in.

PERCENTAGE OF FILLER

Most designers of asphaltic concrete paving mixtures prefer using a percentage by weight of filler, or minus No. 200 material, about equal to the percentage by weight of asphalt. Although the maximum allowable ratio depends largely on the type or source of the filler material, under general conditions there is increased danger of brittle pavement when the percentage by weight of effective minus No. 200 in the paving mixture exceeds 1.2 times the percentage by weight of asphalt.

GRADATION OF INTERMEDIATE AGGREGATE

Although, as previously mentioned, many types of gradations are in use with apparent success, an aggregate that is well graded from coarse to fine has the advantage of minimizing segregation. This type of gradation, which appears as a nearly straight line on a semilog plot, has been found to offer good resistance to post-compaction under heavy traffic. Most important, however, it usually provides sufficient void space between the aggregate particles to hold the asphalt required for pavement durability.

A suitable gradation, regardless of type, must provide a balance between the surface area of the aggregate and the voids between the aggregate particles. Initially the aggregate particles must be coated with a quantity of asphalt that will provide films of durable thickness, and after compaction the aggregate voids must be only partly filled with this quantity of asphalt. For wearing courses of asphaltic concrete the minimum percentage by volume of asphalt required for durability, as indicated by the value of the HUDSON $\bar{A}$, a measure of coarseness of a gradation, is shown approximately in Figure 22. The corresponding approximate aggregate voidage required may be found from

$$\text{VMA} = 1.2\ (S_b + 1.5) \tag{9}$$

in which VMA is the percentage of voids in the compacted mixture not filled with asphalt, and S_b is the percentage of asphalt by volume. Eq. 9 is essentially equivalent to the Marshall criterion that 75 to 80 percent of the VMA should be filled with asphalt and was derived from data contained in Technical Memorandum No. 3-254, "Investigation of the Design and Control of Asphalt Paving Mixtures," Department of the Army, Corps of Engineers, Mississippi River Commission, Waterways Experiment Station, Vicksburg, Miss. (May 1948) (see Fig. 23).

For typical wearing course mixtures the minimum asphalt by volume is about 13 percent. The corresponding required minimum aggregate voidage is about 16 percent.

Although it is customary to first select a gradation that will fall near the center of specification limits and then design a mixture by finding the percentage of asphalt that will satisfy empirical criteria, this procedure does not

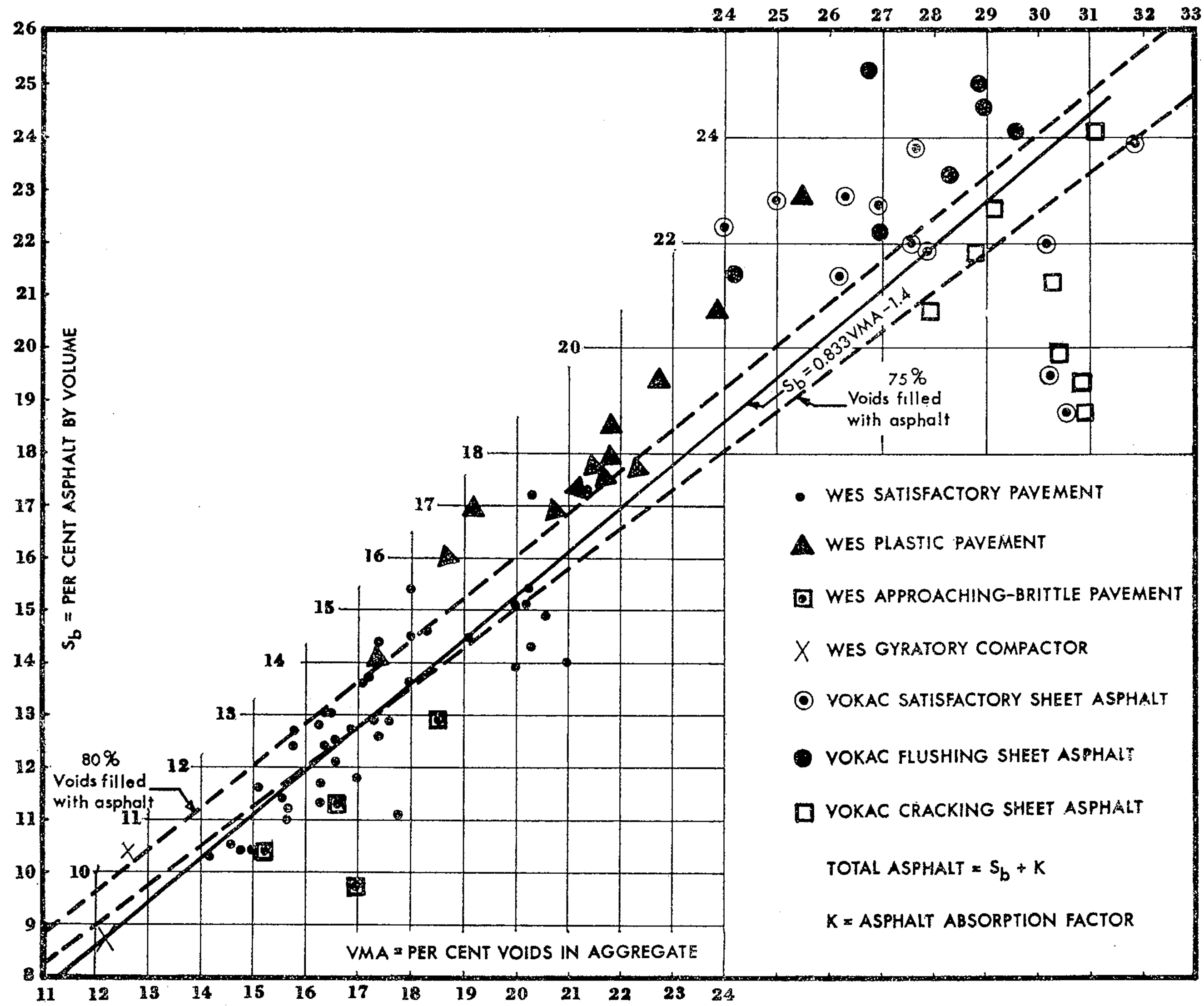


Figure 23. Optimum asphalt content of paving mixtures vs aggregate voids at pavement density.

necessarily insure a durable mixture. A more logical step would be to first design a gradation that would provide the proper aggregate voidage with the particular combination of aggregates to be used.

To further insure durability by minimizing permeability to air and water, the total volume of aggregate voids in a wearing course should be made up of relatively small voids. This means that the gradation must contain a considerable percentage of sand, as is usual in the case of a well-graded mixture of aggregate particles.

FINE AGGREGATE

Examination of current gradation requirements for fine aggregate for portland cement concrete by the various highway agencies shows that practically all specify that 100 percent shall pass the ⅜-in. sieve and 95 to 100 percent shall pass the No. 4 sieve. Requirements for percentages passing the other sieves vary over a wide range, which suggests that a practical fine aggregate gradation specification need include only the allowable range of percentages passing the No. 4, the maximum allowable percentage passing the No. 100 and a permissible range in fineness modulus, as in the example (Case 2-C) given in Chapter Three. This range in FM should be based on an investigation of gradations of available aggregate and a value engineering analysis of the possibilities of effecting savings in cost by using a wider or alternate range of acceptable FM values.

COARSE AGGREGATE

A study of the coarse aggregate gradations currently specified by highway agencies shows an extreme diversity in requirements. In connection with another study (NCHRP contract HR 10-2) wide variations were found in the gradations of coarse aggregates at the time of being batched into mixer trucks. Because the resulting concrete was

TABLE 11

GRADATION REQUIREMENTS FOR AGGREGATE BASES

AGENCY	MIX DESIGNATION	PERCENT PASSING, BY WEIGHT												
		2 IN.	1¾ IN.	1½ IN.	1 IN.	¾ IN.	½ IN.	⅜ IN.	NO. 4	NO. 8	NO. 10	NO. 30	NO. 40	NO. 200
A	Cl 1, 1½ in. max.	100		90–100		50–85			30–45			10–25		2–9
	Cl. 1, ¾ in. max.				100	90–100			35–55			10–30		2–9
	Cl. 2, 1½ in. max.	100		90–100		50–80			25–45			10–25		2–9
	Cl. 2, ¾ in. max.				100	90–100			35–55			10–30		2–9
B	Subbase	95–100							30–60					5–15
	Surface A				100	95–100			30–60		20–45			7–15
	Surface B	100		90–100		50–90			30–50					5–12
	Surface C					100			30–60		20–45			5–12
C	No. 1	100		70–100	45–80		30–60		20–50		15–40		5–25	0–10
	No. 2			100	60–100		30–65		20–50		15–40		5–25	0–10
	No. 3				100		40–70		20–50		15–40		5–25	0–10
D	A, 2 in. max.	100			55–85	50–80			30–60				10–30	5–15
	B, 1½ in. max.			100	70–95	55–85			30–60				10–30	5–15
	C, 1 in. max.				100	70–100			35–65				15–30	5–15
E	No. 7 Gravel				100	80–100	65–100		40–60	25–50			15–25	5–10
	No. 8 Crushed stone				100		60–90		40–60	25–50[a]				5–15
	No. 9 Crushed gravel				100		60–90		40–60	25–50[a]				5–15
F				100	85–100		40–60				20–35			3–7
G	Cl. 3 Crushed rock					100		65–90	35–70		25–45		12–30	5–13
	Cl. 5 Gravel				100	90–100		50–95	35–80		25–65		10–35	3–10
	Cl. 5A Gravel				100	90–100		50–95	35–80		25–70		10–35	3–10
	Cl. 5B Gravel				100	90–100		50–85	35–70		25–55		10–30	3–7
H	NS		100	90–100	70–100		45–100		30–85		25–65[b]			
	SS			100	95–100		70–100		40–85		28–65[b]			
	NC		100	80–100	65–100		35–90		30–70		25–50[b]			
	SC	100		95–100	75–100		45–90		30–63		25–50[b]			
I	Type A, Grade 1	[c]							25–60					12
	Type A, Grade 2	[d]							25–60					12
	Type A, Grade 3	[e]							25–60					12
	Type A, Grade 4	100							25–60					12
	Type A, Grade 5			100					25–60					12
	Type A, Grade 6				100				25–60					12
	Type B, Grade 1	100			50–80				25–50					8
	Type B, Grade 2			100					25–55					8
	Type B, Grade 3				100				30–60		20–50			8
J	Type 2A	100				70–100			35–75				15–30	4.5–12
	Type 2B	100				70–100			30–80				10–40	4.5–12
	Type 5A	100				55–90			25–60				15–30	5–12
K	Class 1				100	80–100			30–60		20–45			3–10
	Class 2				100	85–100			40–70		30–55			4–12
L[f]														
M		100			70–90	50–85			25–60				10–30	0–15
N	Type A			100		40–100		30–75	25–60		20–43		8–26	4–12
	Type B			40–100		30–75		25–60	20–50		15–35		7–22	3–10
O[f]														
P	Grade 1, Type A		100		[g]			50–70	35–55				20–30	
	Grade 2, Type A		90–100						25–55				15–40	
	Grade 3, Type A		90–100										15–40	
	Grade 2, Type B		90–100						25–70				15–30	
	Grade 3, Type B		95–100						25–70				15–35	
	Grade 2, Type C												15–50	
	Grade 3, Type C												15–55	
	Grade 2, Type D		90–100						35–55				30–50	
	Grade 3, Type D		90–100										35–55	
	Grade 2, Type E		100										35–55	
	Grade 3, Type E		100										35–55	
Q	No. 1 Crushed gravel			100	75–100			40–75	30–60		20–45		15–30	3–10
	No. 1 Crushed stone			100				30–65	25–55		15–40			3–12
	No. 2 Crushed gravel				100			50–85	35–65		25–50		15–30	3–10
	No. 2 Crushed stone				100			40–75	30–60		20–45			3–12
	T.B.M.				100	85–100		50–85	35–65				15–30	5–12

[a] 20–40 percent passing No. 16.
[b] Requirements for minus No. 10 fraction include clay and silt limitations; no master range for other fractions.
[c] 100 percent passing 4-in. sieve.
[d] 100 percent passing 3-in. sieve.
[e] 100 percent passing 2½-in. sieve.
[f] Agency does not specify a master range, but specifies gradation requirements for the component aggregates used to produce the finished product.
[g] 70–92 percent passing ⅞-in. sieve.

presumably satisfactory, and because investigators have found little or no effect of the gradation of the intermediate aggregate on concrete strength, simplified gradation requirements appear to be an area of possible cost savings. Special stockpiling procedures or rescreening of aggregates add appreciably to the cost of concrete. If coarse aggregate specification requirements could be reduced to a range of percentages passing a stated maximum sized sieve, a range of allowable percentages passing a minimum sized sieve, and a range of FM values for the intermediate gradation, acceptance testing could be simplified. A value engineering analysis would indicate the potential savings in product cost.

CURRENT PRACTICE

Gradation requirements for fine and coarse aggregate for portland cement concrete, as specified by the highway agencies in 1963, are given in Appendix B.

Base Courses

Aggregate base courses should be more or less dense graded, especially the fraction larger than the No. 4 sieve. The aggregate fraction passing the No. 4 sieve should be open graded. It is extremely important that the large spaces between the particles in the coarse fraction be filled completely with the fine fraction. Aggregate base courses containing large air voids that are not filled with finer material are subject to particle rearrangement, with subsequent change in volume or shape, and to degradation. Also, large air voids in aggregate base courses permit intrusion of subgrade material during periods when the subgrade becomes soft, which causes the base to become unstable.

As previously stated, the fine fraction should be open graded, with the material finer than the No. 40 sieve preferably not greater than about 50 to 60 percent of the minus No. 10 sieve material, and the amount passing the No. 200 sieve not more than two-thirds of the amount passing the No. 40 sieve. This latter stipulation is very important, because fines passing the No. 200 sieve contain material that may cause the mass to be frost susceptible, expansive, and plastic. Open-graded fines in an aggregate mass will, of course, cause the mass to be slightly less dense; on the other hand, the mass will be more permeable (free draining), and less likely to develop pore pressure that will cause elasticity.

As shown in Table 11, the majority of engineers prefers a 1- to 2-in. maximum size aggregate for base course construction, because a larger maximum size is more subject to segregation due to a wider range in particle size from coarse to fine. The objectives of having a fairly dense-graded aggregate with small-sized voids and allowing for a reasonable variation in gradation can be met by placing the gradation band above the maximum density curve for the maximum-sized aggregate. This is shown in Figure 24, where the gradation band is bounded by the maximum density curve for 1½-in. aggregate on the coarse side, and

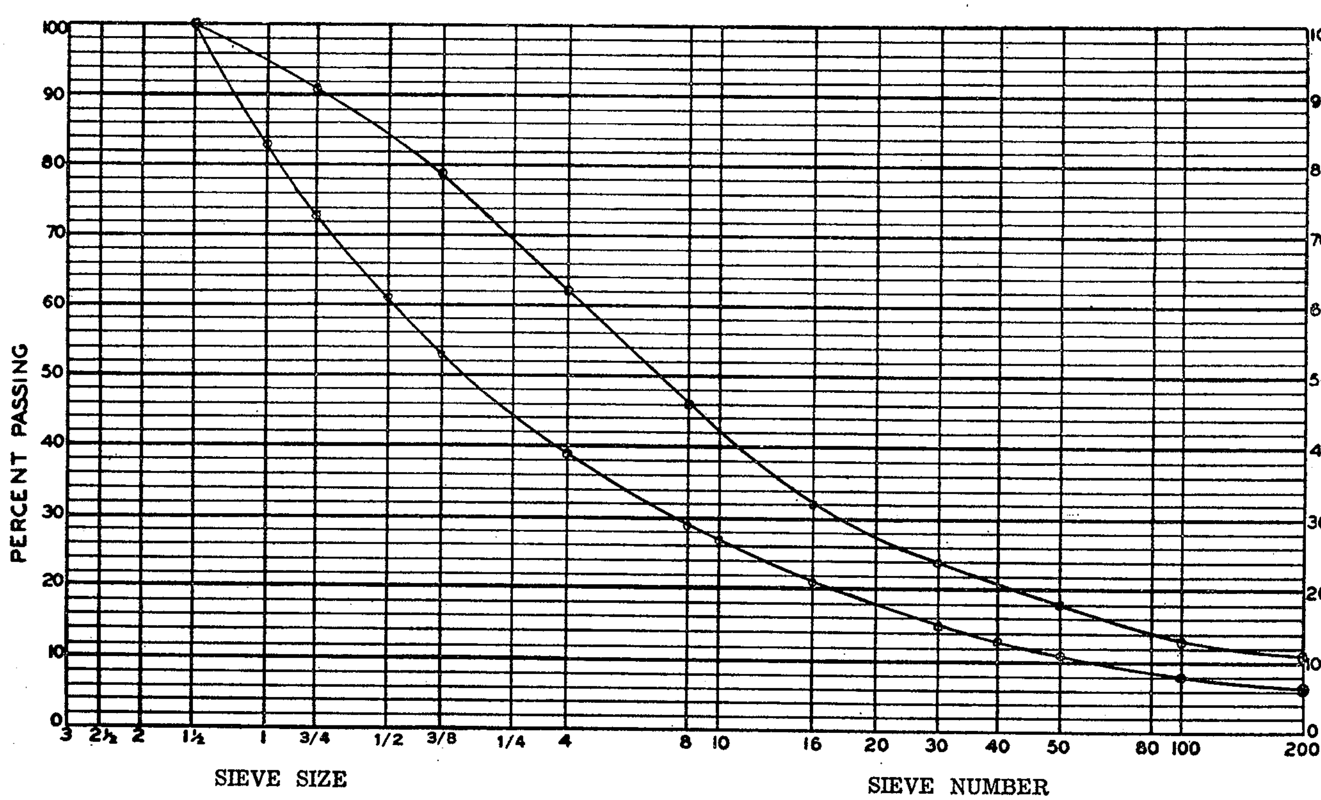


Figure 24. Practical gradation limits, aggregate base course.

by a nearly parallel band on the fine side. The curve for the coarse side is generated by dividing the percentages passing the standard sieves repeatedly by $R = 1.35$. From Figure 21 it can be seen that this gradation will provide nearly maximum density, and that any excess of voids will tend to be small, rather than large. Additional protection against plasticity, or frost effects, can be obtained by reducing the percentage passing the No. 200 to below the theoretically computed value.

The gradation limit on the fine side should be spaced a distance above the maximum density curve, which is the limit on the coarse side, that will allow for a realistic degree of variation. This will require a band width of about four standard deviation units. A typical curve based on tests of pavement samples of pugmill-mixed material is shown in Figure 24 and Table 12. If the job-mix formula is located at the midpoint of this band, the gradation of 95 percent of the material should fall within the specified gradation band.

TABLE 12

PRACTICAL GRADATION LIMITS, AGGREGATE BASE COURSES

	PERCENT PASSING		
SIEVE SIZE	COARSE LIMIT, L [a]	FINE LIMIT, U [b]	AASHO SPEC.
1½ in.	100	100	100
1 in.			80–100
¾ in.	74	91	70–90
½ in.			60–80
⅜ in.	55	79	
No. 4	41	62	40–60
No. 8	30	46	
No. 10			28–46
No. 16	22	32	
No. 30	17	24	
No. 40			16–33
No. 50	12	18	
No. 100	9	13	7–20
No. 200	7	11	3–12

[a] $R = 1.35$. [b] $L + 4\sigma$.

PARAMETERS FOR DEFINING GRADATION

To measure and assess the effects of changes in gradation by the use of statistical methods, it is necessary to describe the gradation by a single number rather than a multiplicity of percentages. Use of such a parameter makes possible the application of statistical methods of measuring variation and the derivation of significant limits.

The fineness modulus (FM), originated by Abrams, is such a parameter and is useful when dealing with aggregates for portland cement concrete. However, it was intentionally designed to exclude the influence of the minus No. 200 on the gradation. This makes the FM unsuitable for use when dealing with aggregates for bituminous concrete or when other aggregate mixtures contain a significant quantity of fines.

Recent studies have resulted in the concept of the so-called Hudson $\bar{A}$, which is simply 1/100th of the sum of the percentages passing the ten standard sieves starting with the 1½-in. and including the No. 200 sieve. Theoretical, and limited experimental, investigation indicates that $\bar{A}$ is a fundamental constant related to the relative surface area of the aggregate in any mixture of particle sizes. The relationship of $\bar{A}$ to the asphalt demand in hot-mix bituminous pavement is shown in Figure 22, which shows that, with asphaltic concrete aggregates in the usual range of $\bar{A}$ of from 4.00 to 6.00, a change of 0.50 in the value of $\bar{A}$ would change the asphalt demand by about 1 percent by volume, which is enough to affect the performance of the mixture. Thus $\bar{A}$ appears to be a sensitive measure which can be used in specifications. For example, the specifications for bituminous concrete could contain a provision that if the $\bar{A}$ value of the actual aggregate gradation, as shown by bin tests, cannot be maintained within 0.50 of the $\bar{A}$ value of the design mix, the mixture shall be redesigned. Although $\bar{A}$ is not directly correlated with aggregate voidage, it does afford a means of detecting significant changes in a gradation as a whole, and can be used as a measure of variation in any connection where changes in the surface area of an aggregate mixture are of importance.

The uniformity coefficient, C_u, is still another parameter that is useful in characterizing the properties of a gradation.

REAL AND APPARENT VARIATIONS IN AGGREGATE GRADATION

In connection with another study (NCHRP contract HR 10-2) probability samples of aggregates were taken from different points in the process stream, including the point at which the aggregates were incorporated into the product or item of construction. In general, unexpectedly large variations were found in the gradation of single-increment samples, including the samples taken at the point of use. Inasmuch as these samples were taken from aggregate streams going into actual products or items of construction, which were presumably satisfactory, the question arises as to the significance of these variations and related failure of many single-increment samples to fall within the limits of the gradation specification. The sources of the overall variation are shown in Figure 12. It will be seen that within-batch variation is a sizable component.

This is the difference in gradation found between two increments taken from the same batch of aggregate, such as that weighed out for a mixer-truck load of concrete. This variance has no significance as far as the quality of the concrete is concerned, because it will disappear and a new pattern of variance will be established when the concrete is mixed. However, a gradation test on a sample composed of a single increment may indicate an apparent failure to meet the gradation specification. For this reason, gradation requirements should be tied to a definite sampling plan that will average out temporary, within-batch, segregation. Such a plan would require taking several random portions of equal size from each batch, and mixing of these portions to form a composite increment. If this is not done, either specification limits must be very wide or it must be accepted that many test results will fall outside of the limits.

ACCURACY OF PERCENTAGES PASSING SIEVES FOUND BY TESTS ON INCREMENTS

Necessity for Accuracy in Gradation Tests

In a perfectly-mixed mass of aggregate containing particles of different sizes the distribution of any size of particle is randomized, as in Figure 11B. For this reason, there is some minimum size of test portion necessary if the percentage of particles of that size in the mixture must be found with some desired degree of accuracy. In fairness to the producer, practical and realistic specification limits should allow for variations in test results to be expected with a reasonably-sized test portion, as well as some variation in the actual gradation. The specification writer should be aware of the relationship between the accuracy of the gradation test and the test portion size.

Basic Equation

In a mass of perfectly-mixed graded aggregate, free from segregation, the particles are arranged in a statistically randomized pattern. As a result of this randomization, the proportions of the different sized particles in a sample taken from the mass are subject to natural law and will have an inherent variance which results in a standard deviation for each of the percentages of different sized particles separated by sieving. The size of this standard deviation is given by

$$\sigma_a = \sqrt{\frac{P(100-P)w}{W}} \tag{10}$$

in which

- P = percent, by weight, of the aggregate passing (or retained on) a designated sieve;
- σ_a = standard deviation of P;
- w = average particle weight of the aggregate retained on the designated sieve; and
- W = total sample (test portion) weight (weight of all particles placed on the sieves).

Results of sieve analyses are usually reported in terms of the percent by weight passing the sieve, to the nearest whole percent. For the percent to be entirely significant there must be at least an equal chance of obtaining the same value if another test is made on another test portion from the same sample increment. In other words, conditions must be such that it is possible to attain an accuracy of $\pm$ 1 percent. For this to be true 95 times out of 100, the results must fall within $\pm 2\sigma$ of the true mean, so $\sigma_a = 0.5$.

With this limitation, Eq. 10 may now be restated as

$$W = \frac{P(100-P)w}{0.25} \tag{11}$$

However, samples or test portions of coarse aggregate are usually measured in terms of pounds, whereas aggregate particle weights are most conveniently stated in terms of grams. Making these adjustments, Eq. 11 becomes

$$W = \frac{P(100-P)\bar{g}}{113} \tag{12}$$

in which

- W = minimum sample (test portion) weight, in pounds, required to attain an accuracy of $\pm$ 1 percent 95 times out of 100;
- P = percent by weight passing a designated sieve; and
- $\bar{g}$ = average particle weight, in grams, of all particles larger than the openings of the designated sieve.

Computing Average Particle Weight

The average particle weight, $\bar{g}$, can only be determined accurately by counting, then weighing, a large number of particles. However, a method based on theory, but slightly modified to conform to experimental results of counting and weighing many thousands of particles, has been developed for estimating this value. It is believed that this method is sufficiently accurate for estimating the value of $\bar{g}$ of either rounded or angular particles in the range of 2.60 – 2.70 bulk specific gravity. For very heavy or very light particles the value of $\bar{g}$ should be adjusted by use of the factor B.s.g./2.65.

The first step is to determine the average size, $\bar{d}$, of the particles passing a sieve having openings of size d_1 and retained on a sieve having openings of size d_2. It may be sufficiently accurate to take the geometrical mean of the two sieve openings ($\bar{d} = \sqrt{d_1 d_2}$), but a more precise estimate is

$$\bar{d} = \frac{0.4343(d_1 - d_2)}{\log\left(\frac{d_1}{d_2}\right)} \tag{13}$$

For example, suppose a base material has 99 percent passing a 2½-in. sieve and 50 percent passing a 1-in. sieve. The sieve openings are 2½ in. = 63.5 mm and 1 in. = 25.4 mm, respectively.

Substituting these values in Eq. 13 gives

$$\bar{d} = \frac{0.4343(63.5 - 25.4)}{\log\left(\frac{63.5}{25.4}\right)} = 41.23 \text{ mm.}$$

The next step is to compute the average particle weight, $\bar{g}$. The equation, based on counting-weighing many thousands of particles of different aggregates, is

$$\bar{g} = 0.003\ \bar{d}^{2.8} \tag{14}$$

which evaluates to $\bar{g} = 0.003 \times 41.23^{2.8} = 99.9$.

Computing Required Weight of Test Portion

Then, from Eq. 12, $W = 50(100 - 50)\ 99.9/113 = 2{,}210$ lb.

Accuracy of Small Samples

These computations indicate that more than a ton of aggregate would have to be passed through the sieves in order to measure the percent passing the 1-in. sieve with a 95 percent assurance of an accuracy of $\pm$ 1 percent. Use of such large samples may be too impractical to consider, but use of smaller samples leads to a loss of accuracy. The size sample required by AASHO T-27 for a 2½-in. maximum size aggregate is 25,000 grams, or about 55 lb. To find the accuracy obtainable with this size sample, Eq. 10 may be stated as

$$\sigma_a = \sqrt{\frac{P(100-P)\bar{g}}{453.6\,W}} \qquad (15)$$

which for the values used in the example gives $\sigma_a = 3.17$.

For a 95 percent degree of assurance, $z = 1.96$. Therefore, $\pm\,\Delta = \pm\, z\,\sigma_a = 1.96 \times 3.17 = \pm\, 6.2$ percent.

This means that if the AASHO sized sample is used, the results should be reported as

Sieve Size	Percent Passing
1 in.	50 ± 6

If the specification limits were 35-65 percent passing the 1-in. sieve, under the foregoing conditions the actual gradation would have to be maintained between 41-59 percent, otherwise the ± 6 percent inaccuracy of the test would cause a percentage of the test results to indicate that the aggregate did not meet the gradation specification.

Checking for Governing Percentage

In most cases the required test portion size will be determined by the percentage passing the second largest sieve in the gradation; that is, the one following that which passes 95-100 percent of the aggregate. In doubtful cases, the test portion weight required by other sieve sizes can be checked by substituting the proper value for $\bar{g}$ in Eq. 12.

For example, an aggregate has the following gradation:

Sieve Size	Percent Passing	Sieve Size	Percent Pass.-Ret.	Avg. Particle Weight, $\bar{g}$ (gm)
1½ in.	100			
¾ in.	97	1½–¾	3	32
⅜ in.	40	¾–⅜	57	4.1
No. 4	8	⅜–No. 4	32	0.6

For the percent passing the ¾-in. sieve the required test portion weight is $W = 97(100 - 97) \times 32/113 = 82.5$ lb.

To find the required test portion weight with respect to the percent passing the ⅜-in. sieve, the average weight of the particles retained on that sieve must be found. There are 3 percent of 1½- to ¾-in. particles and 57 percent of ¾- to ⅜-in. particles, so the average weight is $\bar{g} = \frac{(3 \times 32) + (57 \times 4.1)}{3 + 57} = 5.5$ and the required test portion weight is $W = (3 + 57)(100 - 3 - 57) \times 5.5/113 = 117$ lb.

In this case, the percentage passing the second largest sieve was high enough to require a lower sample weight than the percentage passing the third largest sieve. Of course, the largest sample weight governs.

Use of Nomograph

In lieu of making the preceding computations the nomograph of Figure 25 may be used to estimate either test portion (sample) size or the accuracy of the gradation test.

CHAPTER SEVEN

SURFACE SMOOTHNESS

Pavement rideability is a term used to describe the relative absence of discomfort experienced by the occupants of vehicles, usually automobiles moving over a pavement at high speeds. Paving engineers, contractors, and others concerned with the construction of pavements need some quantitative method of measuring the quality of rideability. Such a method would provide a criterion of roughness or smoothness that could be incorporated in specifications and construction controls.

Three factors contribute to what is commonly called pavement roughness. A coarse-textured surface and pavement joints create rumbles and thumping noises, small and closely-spaced deviations from grade set up vibrations in the unsprung parts of the vehicle, and large deviations from grade, even if widely spaced, cause the car body and passengers to be accelerated vertically.

SPECIFIED METHODS AND CRITERIA

Most current specifications for surface smoothness are concerned with small, closely-spaced deviations from grade, and require that the pavement surface be tested by placing a straightedge on the surface of the completed pavement in successive positions parallel to the center line, covering the entire width of the pavement from edge to edge. The straightedge is advanced in this manner continuously or in successive stages of not more than one-half the length of the straightedge. The straightedge length most often specified is 10 ft, although some agencies specify lengths of 12 or 16 ft. Most specifications limit deviations of the pavement surface from the bottom of the straightedge to ⅛ in., although deviations of ¼ in. are permitted by some.

Some specifications require that the pavement cross sec-

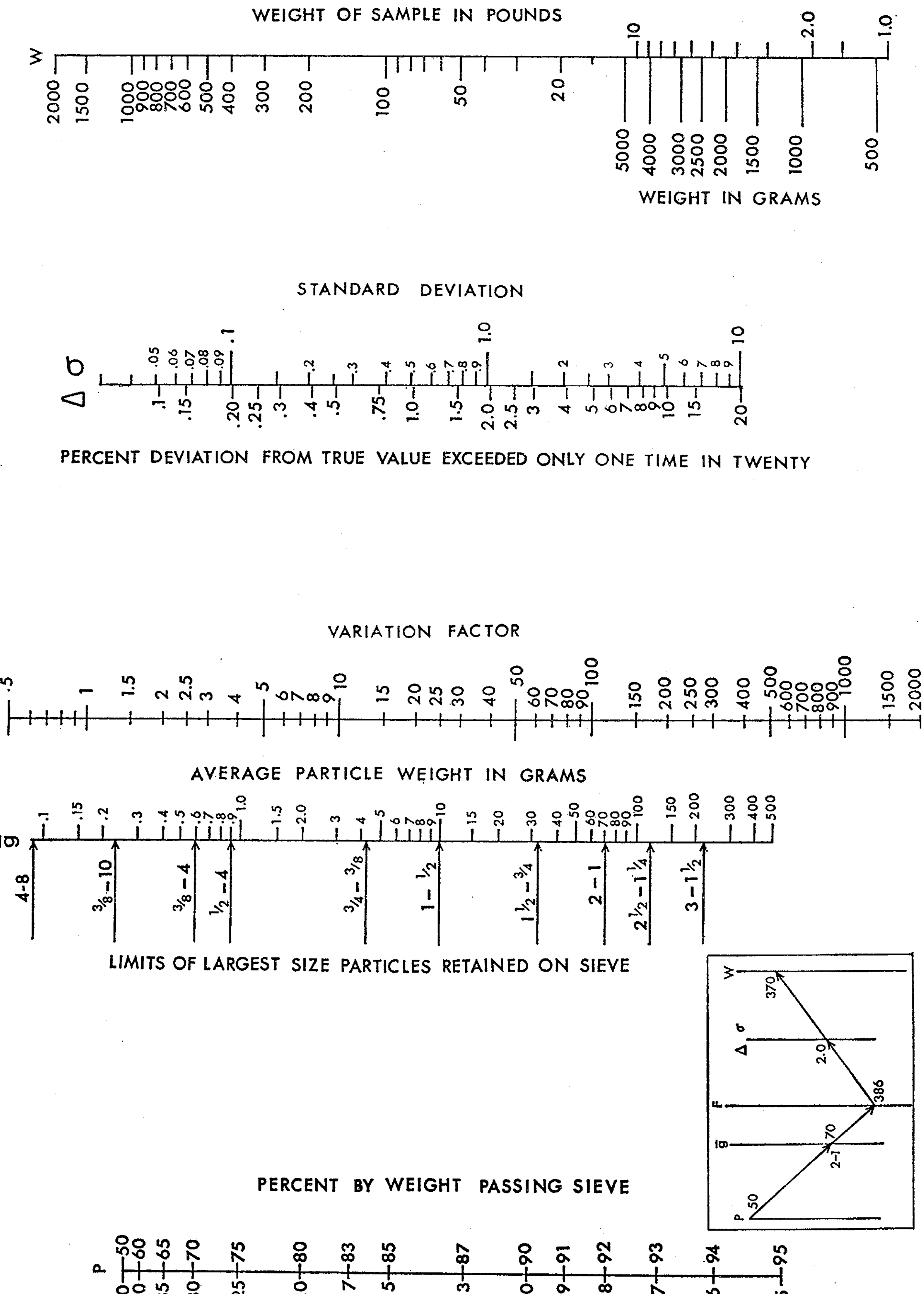
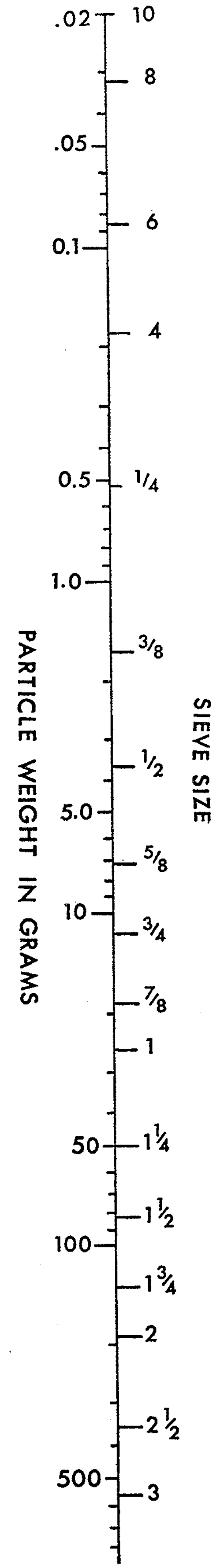


Figure 25. Chart for estimating weight of aggregate sample for gradation test.



USE OF NOMOGRAPH TO ESTIMATE SAMPLE WEIGHT

1. Select the critical sieve size. This is usually the size following that sieve which passes 90-100% of the aggregate.

   For Example: If 99% passes the 2" sieve and 50% passes the 1" sieve, the 1" sieve is the critical size.

2. Determine the average particle weight of all particles retained on the critical sieve. If this is unknown, it can be estimated roughly from the values shown on the left of the $\overline{g}$ scale.

3. To find $\overline{g}$ approximately by use of the scale on this page, find the weight opposite the mid-point of the distance between the sieve size that the particles pass and the sieve size on which they are retained. Then calculate a weighed average for the total material retained on the designated sieve.

   For Example:

Sieve Size	Percent Pass-Ret	Particle Weight
3/4-3/8	30	4.1
3/8-4	50	0.6
4-8	10	0.09

$$\overline{g} = \frac{30 \times 4.1 + 50 \times 0.6 + 10 \times 0.09}{30 + 50 + 10} = 1.7 \text{ g}$$ (Av. wt. particles Ret on No. 8 sieve)

4. From the percentage passing the critical sieve on scale P, project a line through the average particle weight on scale $\overline{g}$ to scale F.

   For Example: If 50% passes the 1" sieve and the average particle weight of the aggregate retained on the sieve is 70 grams, project a line from 50 on scale P through 70 on scale $\overline{g}$ to 386 on scale F.

5. From the point on scale F, project a line through the desired degree of accuracy on scale Δ to the required total sample weight on scale W.

   For Example: With an F factor of 386 and a desired degree of accuracy of ± 2%, the line projected through these points indicates a required sample weight of 370 pounds on scale W.

6. The accuracy obtained by the use of a larger or smaller sample can be found by projecting a line from the F factor to the actual sample weight and reading the result on scale Δ.

   For Example: With an F factor of 386 and an actual sample weight of 50 pounds, the percent passing the 1" sieve will be correct to within ± 5%, 95 times in 100 determinations.

TABLE 13

TOLERANCES FOR SURFACE SMOOTHNESS AND THICKNESS OF PAVEMENT COURSES

AGENCY	TOLERANCE IN SMOOTHNESS			NUMBER OF MEASUREMENTS[a]	PENALTY OR CORRECTION	THICKNESS MEASUREMENTS AND NUMBER		TOLERANCE ALLOWED		PENALTY OR ADJUSTMENT	
	SUBGRADE	BASE	SURFACE			BASES	SURFACES	BASES	SURFACES	BASES	SURFACES
A	None spec.[b]	—[c]	0.01 ft/12 ft	Continuous	Correct or replace	Cores as directed	Cores as directed	—[d] None spec.[d]	—[d] 0.01 ft[e]	Correct or replace	Correct or replace[f]
B	None spec.	None spec.	¼ in./12 ft bit.; ⅛ in./12 ft conc.	Continuous	Correct or replace	Cores as directed	Cores as directed	—[d] Not spec.[d]	—[d] None[e]	Correct or replace	Correct or replace
C	⅜ to ¾ in. /10 ft	⅜ in./10 ft	⅛ in./12 ft	Cont. at 5-ft interv.	Correct or replace	Cores every 500 sq yd	Cores every 2,000 ft	½ in.	¼ in.	Correct	Correct or replace[e, g]
D	½ in./16 ft[h]	⅜ in./16 ft	Bit. and conc. ¼ in/16 ft	As directed	Correct or replace	Cores every 300 sq yd	1 Core for each day's work	½ in.	¼ in.	Correct	Correct or replace[e, g]
E	None spec.	½ in./10 ft	⅛ in./10 ft	Continuous	Correct or replace	Cores every 250 ft	Cores and levels at 250 ft	—10% to +8% plan thickness	—[i] 0.2 to 1.0 in.[e]	Correct or replace	Correct or replace
F	None spec.	⅜ in./10 ft.	—[j]	Continuous	Correct or replace	None	Cores every 1,000 ft	Not spec.[d]	—[k] ½ in.[e]	Correct or replace	Correct or replace
G	0.05 ft of est. grade	¼ in./10 ft[l]	⅛ in./10 ft	At random loc.	Correct or replace	Cores every 333 ft	Cores every 1,000 ft	½ in.	½ in.[e, m]	Correct or replace	Correct or replace
H	½ in. of est. grade	⅜ in./10 ft[n]	⅛ in./10 ft[o]	Continuous	Correct or replace	Cores every 200 ft	Cores every 400 ft	½ in.	⅜ in.	Correct or replace	Correct or replace
I	0.10 ft of est. grade	⅜ in./10 ft[p]	⅛ in./10 ft	At random loc.	Correct or replace	Cores every 500 ft	Cores every 500 ft	½ in.	½ in.[e, q]	Correct or replace	Correct or replace
J	None	½ in./16 ft[r]	⅛ in./10 ft	At random loc.	Correct or replace	Cores every 2,000 sq yd[s]	Cores every 1,000 sq yd[s]	—[t]	¼ in. for bit; none for PC conc.	Correct or replace	Correct or replace
K	0.1 ft of est. grade	⅜ in./10 ft	—[j]	At random loc.	Correct or replace	Random cores	Cores every 1,000 ft	½ in.	½ in.[e, q, u]	Correct or replace	Correct or replace
L	True to grade and cross sect.	¼ in./16 ft	—[v]	As ord. by eng.	Correct or replace	Grade elev.	Cores every 1,000 ft	¼ in.	—[w]	Correct or replace	Correct or replace
M	⅜ in./10 ft	—[x]	—[j]	Continuous	Correct or replace	—[y]	—[y]	—[y, z]	—[z]	Correct or replace	Correct or replace
N	½ in./10 ft	¼ in./10 ft	1/16 in./ft[aa]	Subg. every 100 ft Bases every 50 ft Surf. every 5 ft	Correct or replace	Cores every 250 ft	Cores every 2,000 sq yd[e] Cores every 500 ft	½ in.	½ in.[bb]	Correct or replace	Correct or replace
O	Not spec.	—[cc]	—[dd]	Continuous	Correct or replace	3 cores every 600 sq yd	1 core every 3,000 sq yd	—[ee]	—[ff]	Correct or replace	Correct or replace
P	½ in./16 ft	¼ in./16 ft	—[gg]	As ord. by eng.	Correct or replace	Not spec.	Cores at random	Not spec.	—[hh]	Correct or replace	Correct or replace
Q	Not spec.	¼ in./10 ft[e]	⅛ in./10 ft	Continuous	Correct or replace	1 core every 1,000 ft[e]	1 core every 1,000 ft[e]	¼ in.[e, hh]	¼ in.[e, hh]	Correct or replace[e]	Correct or replace[e]

[a] All measurements by straightedge.
[b] Subgrade required to be within 0.10 ft of established grade.
[c] Subbase required to be within 0.08 ft, untreated and treated base 0.05 ft of established grade. Surface of treated base must conform to 12-ft straightedge with maximum deviation of 0.03 ft.
[d] Treated and untreated base materials and bituminous concrete surfaces spread uniformly as directed, and paid for by the ton.
[e] For portland cement concrete.
[f] Portland cement concrete pavement with thickness deficiencies between 0.01 and 0.05 ft accepted with graduated penalty; areas of pavement with deficiencies in thickness in excess of 0.05 ft not acceptable and to be removed and replaced at the discretion of the engineer.

[g] Accept with penalty for deficiencies in thickness between ¼ and ½ in; remove and replace if more than ½ in.
[h] Subgrade to be within 0.05 ft of grade elevation.
[i] Bituminous concrete binder and surface, adjustments in payment for thickness deficiencies between ⅛ to ½ in.; pavement removed and replaced when thickness deficiency is above ½ in.
[j] Bituminous concrete surface, ¼ in. in 10 ft; PC concrete surface, ⅛ in. in 10 ft; sheet asphalt, ⅛ in. in 10 ft.
[k] Bituminous pavements paid for by the ton.
[l] Bituminous-treated base, maximum deviation from grade 0.05 ft; soil-cement base 0.08 ft. Maximum deviation from 10-ft straightedge for both base types, ¼ in.
[m] Unit price adjustments made for areas showing deficiencies in thickness of 0.1 to ½ in.
[n] Cement-treated base to be within ½ in. of established grade and cross section. Maximum deviation from 10-ft straightedge or stringline, ⅜ in.; 25-ft stringline, ½ in.; 50-ft stringline, ⅝ in.
[o] Bituminous concrete pavement, maximum deviation from grade and cross section, ¼ in. Maximum deviation from 10-ft straightedge, ⅛ in.; 25-ft stringline, ¼ in.; 50-ft stringline, ⅜ in.
[p] Soil-cement base.
[q] Unit price adjustments made for areas showing deficiencies in thickness of ⅛ to ½ in.
[r] Macadam base, must be finished to within ½ in. of prescribed grade.
[s] Macadam base thickness; bases checked for grade and cross section; quantities of materials used as check on thickness; as a quality check, cores taken for every 500 cu yd of completed base or subbase. Bituminous surface and base, 1 core for each 2,000 sq yd. PC concrete pavement, 1 core for each 1,000 sq yd.
[t] Macadam base tolerance in thickness not specified; bituminous base not less than 92 percent and not more than 108 percent of specified thickness.
[u] Bituminous concrete surface no tolerance in thickness specified; material spread uniformly to produce required thickness and paid for by the ton.
[v] Bituminous concrete tolerance ¼ in. in 16 ft measured by straightedge or stringline; PC concrete tolerance ⅛ in. in 10 ft.
[w] Bituminous concrete surface ¼ in. variation in thickness; PC concrete deficiency of ½ in. in pavement thickness permitted without penalty.
[x] Granular base ⅜ in. in 10 ft; bituminous and portland cement concrete base ¼ in.
[y] Base course and bituminous surface thickness controlled by weight or volume per unit of area.
[z] PC concrete pavement and bases, deficiency of 0.10 in. accepted without penalty; graduated adjustment made for deficiencies between 0.11 and 0.50 in.
[aa] Bituminous concrete and PC concrete surfaces tested with 10-ft straightedge; permissible variation 1⁄16 in. per foot with maximum of 3⁄16 in. for bituminous concrete and ⅛ in. for PC concrete.
[bb] Bituminous surface thickness controlled by weight per unit of area and payment made by the ton. PC concrete deficiencies in thickness up to ¼ in. permitted without penalty; adjustment in unit price bid for thickness deficiencies of ¼ to ½ in.
[cc] Permissible variation from 16-ft straightedge: PC concrete base ¼ in.; aggregate base ½ in.
[dd] Permissible variation from 16-ft straightedge: bituminous concrete surface on flexible base ¼ in.; rigid base ⅛ in.; PC concrete ⅛ in.
[ee] Permissible deficiency in thickness aggregate and PC concrete base 0.25 in. Deficiencies in excess of 0.25 in. but not more than 0.65 in. in PC concrete base acceptable wth graduated reduction in contract price.
[ff] Permissible deficiency in thickness bituminous surface ¼ in. in 1,000-sq yd sections. When 3 or more adjoining sections are uniformly more than ⅛ in. deficient, replacement or correction is made. PC concrete surface permissible deficiency of 0.25 in. acceptable without penalty; Deficiencies between 0.25 and 0.65 in. acceptable with graduated reduction in contract price.
[gg] Bituminous surfaces tested with 16-ft straightedge, deviations restricted to 1⁄16 in. per ft with maximum of ¼ in. PC concrete surfaces tested with 10-ft straightedge, deviations restricted to 1⁄16 in. per ft with maximum of ⅛ in. ordinate at any point.
[hh] Deficiencies in thickness of PC concrete pavement up to ¼ in. permitted without penalty. Deficiencies of more than ¼ in., but not more than ½ in., acceptable with graduated reduction in contract unit price. Thickness of bituminous surfaces controlled by spread and paid for by the ton.

tion be checked with a template, usually cut to the plan cross section and of a length equal to the width of one travel lane of the pavement. This permits checking not only the shape of the pavement cross section with the template, but also the elevation of the sides with respect to plan elevation. Some agencies require the use of stringlines 25 and 50 ft long, stretched parallel to the center line of the pavement, and limit variations to ⅜ in. and ½ in., respectively.

Table 13 gives this information for 15 state highway departments and 2 federal agencies. By agreement, these agencies are not identified, but include California, Colorado, Corps of Engineers, Federal Aviation Agency, Illinois, Michigan, Minnesota, Mississippi, Montana, New Jersey, New Mexico, New York, Ohio, Oklahoma, Pennsylvania, Texas, and Wisconsin, not necessarily in the order given. This sampling is believed to represent a typical cross section of the highway industry. Attention is also called to the data presented in Appendix B. In addition, a review of the latest available State Highway Specifications, the Bureau of Public Roads FP-61, and the AASHO Guide Specifications is summarized in the following. This summary is based on the latest available data, but without verification check as to the date of the most recent revision.

Considerable variation is found in the tolerances permitted longitudinally, as shown by Table 14.

Tolerances in cross section are specified by 15 of the state highway departments and the Bureau of Public Roads (Table 15). Thirty-five state highway departments and the AASHO Guide Specifications for Highway Construction make no stipulation for tolerance in cross section.

OTHER METHODS

Two devices that have been used for measuring the roughness of completed pavements are the roughometer and the AASHO profilometer.

TABLE 14

SUMMARY OF PERMITTED LONGITUDINAL DEVIATIONS FROM STRAIGHTEDGE OR STRINGLINE

PERMITTED DEVIATION	NO. OF AGENCIES
⅛ in. in 10 ft	18 SHD
⅛ in. in 10 ft, 90% of meas.; ¼ in. in 10 ft, 10%	2 SHD
⅛ in. in 12 ft	1 SHD
0.01 ft in 12 ft	1 SHD
⅛ in. in 14 ft	BPR
⅛ in. in 16 ft	2 SHD
3⁄16 in. in 10 ft	2 SHD, AASHO
3⁄16 in. in 15 ft	1 SHD
3⁄16 in. in 16 ft	1 SHD
¼ in. in 10 ft	13 SHD
¼ in. in 12 ft	1 SHD
¼ in. in 16 ft	5 SHD
¼ in. in 20 ft, 3⁄16 in. in 10 ft, ⅛ in. in 3 ft	1 SHD
±¼ in. from grade elev.	1 SHD
±5⁄16 in. from grade elev.	1 SHD
±0.05 ft from grade elev.	1 SHD

TABLE 15

SUMMARY OF PERMITTED CROSS-SECTION DEVIATIONS FROM TEMPLATE

PERMITTED DEVIATION	NO. OF AGENCIES
⅛ in.	2 SHD, BPR
0.02 ft	1 SHD
¼ in.	8 SHD
3⁄16 in.	2 SHD
½ in.	2 SHD

The roughometer is a device that records the vertical oscillations of a wheel with reference to a suspended mass. The vertical oscillations are cumulative and are expressed in inches per mile.

Another device for measuring pavement roughness was designed at the AASHO Road Test. This device is a longitudinal profilometer which constantly measures the slopes of all inequalities on the pavement surface (see Fig. 26). The slopes are sampled at 1-ft intervals and analyzed statistically for determination of a factor called SLOPE VARIANCE (SV) used in the AASHO equation for determining the PRESENT SERVICEABILITY INDEX (PSI) of the pavement.

The BPR roughometer and AASHO pavement ratings are compared in Table 16.

SLOPE VARIANCE CRITERIA

The present serviceability index of a pavement is an expression of its ability to serve high-speed, high-volume, mixed traffic in its present condition. The factors used in its determination are roughness, cracking, patching, and in bituminous pavements, rutting. The equation developed at the AASHO Road Test for present serviceability index is:

For rigid (portland cement concrete) pavements

$$PSI = 5.41 - 1.80 \log (1 + \overline{SV}) - 0.09 \sqrt{C + P} \qquad (16)$$

in which,

PSI = present serviceability index;

$\overline{SV}$ = mean slope variance in the two wheelpaths as measured by the AASHO profilometer, $\times 10^6$;

C = linear feet of cracking per 1,000 sq ft of pavement area (including the lengths taken parallel or perpendicular to the center of the pavement, whichever is greater, of all cracks that are sealed, opened, or spalled at the surface for the width of ¼ in. or more for at least one-half their length); and

P = bituminous patching, in sq ft per 1,000 sq ft of pavement area.

TABLE 16

COMPARISON OF PAVEMENT RATINGS

PAVEMENT RATING	BPR ROUGHOMETER (IN.) CONC.	BIT.	AASHO PSI [a]
Outstanding	67	54	4.5
Excellent	67–81	54–66	4.5–4.1
Good	81–99	66–82	4.1–3.7
Fair	99–121	82–102	3.7–3.3
Poor	121	102	3.3

[a] Present serviceability index.

Figure 26. Principle of AASHO longitudinal profilometer.

For flexible (bituminous concrete) pavements

$$PSI = 5.03 - 1.91 \log (1 + \overline{SV}) - 0.01 \sqrt{C + P} - 1.38\, \overline{RD}^2 \qquad (17)$$

in which

C = cracking, in sq ft per 1,000 sq ft of pavement area (including only cracking that has progressed to the stage where cracks have connected together to form a grid-type pattern or where the surfacing segments have become loose); and

$\overline{RD}$ = mean depth of rutting in both wheelpaths, measured in inches under a 4-ft straightedge.

Eqs. 16 and 17 reveal that the value of PSI is influenced more by the expressions 1.80 log $(1 + \overline{SV})$ and 1.91 log $(1 + \overline{SV})$, the roughness factors, than by the other variables. It follows that newly constructed pavements must be constructed quite smooth in order to have as high an initial PSI as possible, to allow for a decrease after the surface has been deformed by traffic or by consolidation of the underlying courses.

At the AASHO Road Test, the average initial PSI for the portland cement pavements was found to be 4.5. Assuming that there were no cracks or patching in the new pavements, the expression for roughness, 1.80 log $(1 + \overline{SV})$, in Eq. 16 had a value of $5.41 - 4.5 = 0.91$. It follows then, that 1.80 log $(1 + \overline{SV}) = 0.91$, from which $\overline{SV} = 2.20$ for portland cement concrete pavements.

Similarly, the average initial PSI for the bituminous concrete pavements was found to be 4.2. Assuming that there were no cracks or patching, and that there was no rutting in the new pavements, the expression for roughness, 1.91 log $(1 + \overline{SV})$, in Eq. 17 had a value of $5.03 - 4.2 = 0.83$. It follows then, that 1.91 log $(1 + \overline{SV}) = 0.83$, from which $\overline{SV} = 1.72$ for bituminous concrete pavements.

RELATING SLOPE VARIANCE TO STRAIGHTEDGE DEVIATIONS

Computing Slope Variance

Slope variance by definition is the variance (mean square deviation) of a set of slopes about the mean slope. This is the same basic measure of variability as that discussed in Chapter Three and is calculated by

$$s^2 = \frac{\Sigma(X - \bar{X})^2}{n - 1} \tag{18}$$

in which

s^2 = variance;
X = slope;
$\bar{X}$ = arithmetic mean; and
n = number of values.

Mean slope variance, $\overline{SV}$, as used in the AASHO equations, is $s^2 \times 10^6$.

Limiting or Critical Values of Slope Variance

Inasmuch as the construction specifications for the subgrade and pavements at the AASHO Road Test followed the average for the country, the values of $\overline{SV}$—2.20 for portland cement concrete pavement and 1.72 for bituminous concrete pavement—may be considered to be optimum limiting values (critical values) for this parameter on newly constructed pavements. (Note: The word "critical" as used in this context refers to the optimum limiting value and is not related to the "criticality" of the specification requirement.) These are the average values required to produce initial PSI values of 4.5 and 4.2 for new pavements assumed to be free of cracking, patching, and rutting or distortion. Whether or not these are practical and realistic guidelines for good average construction may be debatable at this time. On the one hand, the closer control and the "test" aspects of the Ottawa construction might have resulted in better than average workmanship. On the other, the chopped-up nature of the test sections may have resulted in lower than average smoothness. Nevertheless, these $\overline{SV}$ values of 2.20 for portland cement concrete and 1.72 for bituminous concrete pavement may be taken as the best interim target values now available, representative of optimum average smoothness attainable with present-day equipment.

Obviously, a realistic specification for smoothness should allow for some practical and reasonable divergence from these optimum targets. An attribute sampling plan is recommended which allows for some percentage of defectives in each lot of pavement. On a purely arbitrary basis, 4 percent of pavement area defective is suggested as an initial acceptable quality level. As is developed later, when using a straightedge the definition of a defective will involve both span and the number of vertical deviations in the test segment.

Relating Slope Variance to Deviations and Span

Because it is not practical to use a roughometer or a profilometer for acceptance testing of fresh pavements (when corrections could still be made), it is desirable to develop a relationship between these criteria and the lowly straightedge. Slope variance is a function of both the vertical height (or depth) of a bump (or depression) in the pavement and the rate of change of slope, which is a function of span of the deviation from the plane surface. By assuming that the profilometer wheel always starts at the inception of the deviation (rise or depression) and that the average slope may be represented by a straight line from the peak (or depth) to this initial point of deviation, it is possible to calculate the theoretical slope variance corresponding to the number of deviations and their spans in a given length of pavement. These calculations have been made for both ⅛-in. and ¼-in. deviations occurring at different span lengths in 100 ft of pavement. The results were then analyzed to explore the relative magnitude and direction of the relationships based on these assumptions.

Figures 27 and 28 show that there is a relationship between $\overline{SV}$ and the spans of deviations in 100 ft of pavement. Figure 27 gives curves for 1, 2, 3, 4, 5, and 50 ⅛-in. deviations from the surface plane per 100 ft. Figure 28 gives curves for 1, 2, 3, and 50 ¼-in. deviations from the surface plane per 100 ft.

Figure 27 shows that:

1. Spans of ⅛-in. deviations in 100 ft of P.C. concrete pavement become critical (producing values of $\overline{SV}$ in excess of 2.2) only when they are less than about 7.1 ft in length, regardless of number. The following numbers of ⅛-in. deviations are critical in 100 ft of P.C. concrete pavement: 1 of less than 2.0 ft, 2 of less than 3.6 ft, 3 of less than 5.2 ft, 4 of less than 6.0 ft, 5 of less than 6.7 ft.
2. Spans of ⅛-in. deviations in 100 ft of bituminous concrete pavement become critical (producing values of $\overline{SV}$ in excess of 1.72) only when their lengths are less than about 8 ft, regardless of number. The following numbers of ⅛-in. deviations are critical in 100 ft of bituminous concrete pavement: 1 of less than 2.4 ft, 2 of less than 4.7 ft, 3 of less than 6.2 ft, 4 of less than 7.1 ft, and 5 of less than 7.8 ft.

Figure 28 shows that:

1. Spans of ¼-in. deviations in 100 ft of P. C. concrete pavement become critical only when they are less than about 14.1 ft in length, regardless of number. The following numbers of ¼-in. deviations are critical in 100 ft of P. C. concrete pavement: 1 of less than 7.3 ft, 2 of less than 12 ft, 3 of less than 13.9 ft.
2. Spans of ¼-in. deviations in 100 ft of bituminous concrete pavement become critical only when their lengths are less than about 15.9 ft, regardless of number. The following numbers of ¼-in. deviations are critical in 100 ft of bituminous concrete pavement: 1 of less than 9.3 ft, 2 of less than 14.5 ft, 3 of less than 15.9 ft.

Inferences Affecting Guidelines for Smoothness Requirements

It can be seen from the foregoing analysis that specifications limiting irregularities, as shown by the straightedge test, unconditionally to ⅛ in. are not sufficiently restrictive to prevent acceptance of pavements that can have $\overline{SV}$ values above those critical for P.C. concrete and bituminous concrete pavements. To prevent this possibility, specifications should also restrict the number of deviations

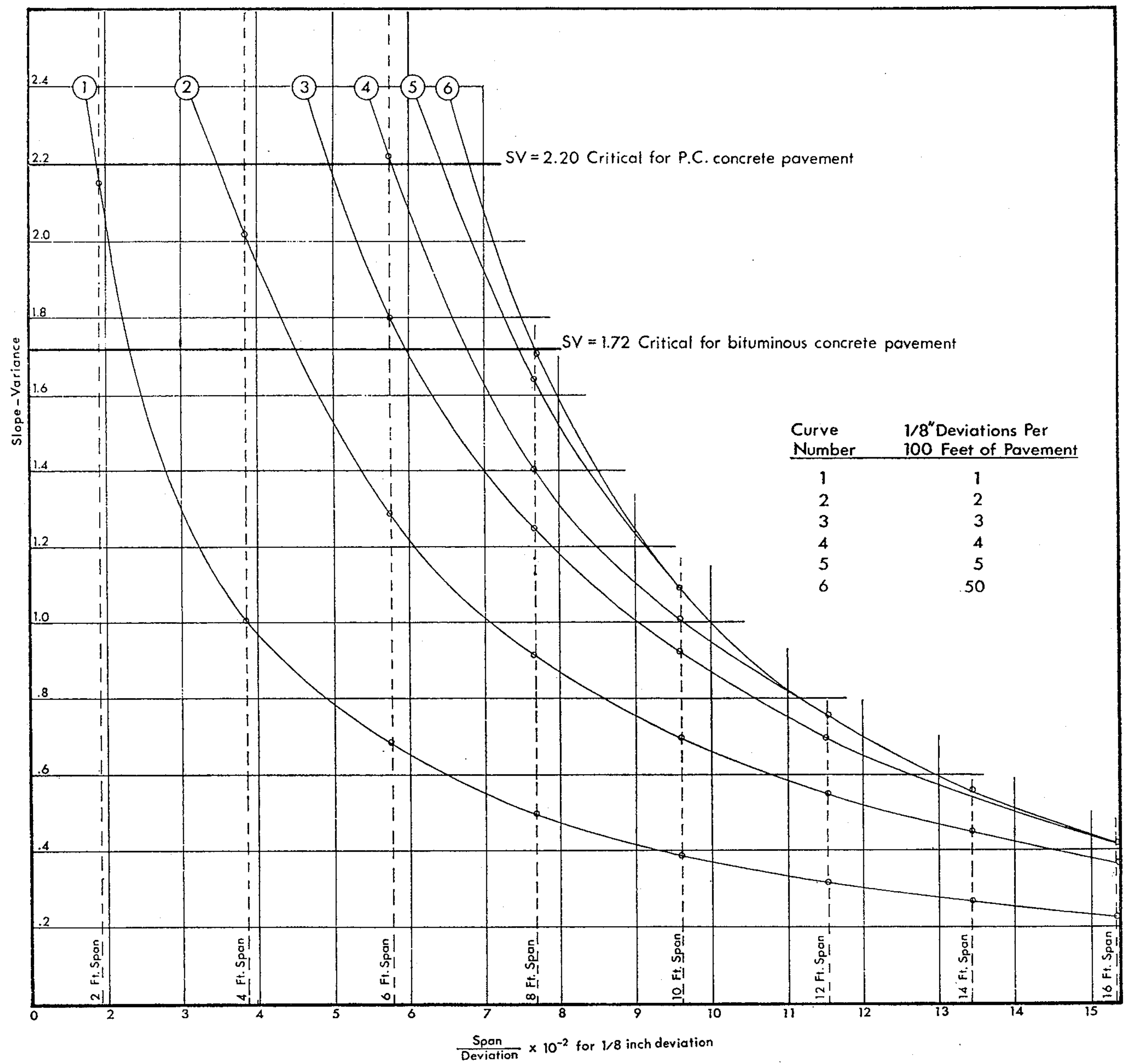


Figure 27. Critical number of ⅛-in. deviations per 100 ft of pavement; relationship between slope-variance and span.

and their corresponding spans in a given length of a section of P.C. concrete and bituminous concrete pavements to that given in the previous section. Criteria based on deviations of less than ⅛ in. are not believed practicable at this time from the standpoint of accuracy of measurement and the ability of paving equipment to perform.

Limiting the irregularities to ¼ in., with restriction of their number and corresponding span lengths, in a given length of pavement section will lead to acceptance of more sections of pavement with $\overline{SV}$ values greater than critical. It will be noted that 1 deviation of ¼ in. in 100 ft of pavement must not have a span length less than 7.3 ft for P.C. concrete pavements and 9.3 ft for bituminous concrete pavements. Usually longer straightedges are specified for ¼-in. deviations; however, as may be seen from the foregoing analysis, this is no solution of the problem.

PAVEMENT CROSS SECTION

Another factor that affects the rideability of bituminous pavements is the uniformity of transverse grade. Many current specifications ignore this factor, although some agencies are becoming conscious of its importance.

It is important that the surface of the pavement follow the established transverse grade in order to avoid sags and humps that cannot be detected by the straightedge along the pavement edges. One way to eliminate sags and humps in the finished surface is to set grade stakes at 25-ft inter-

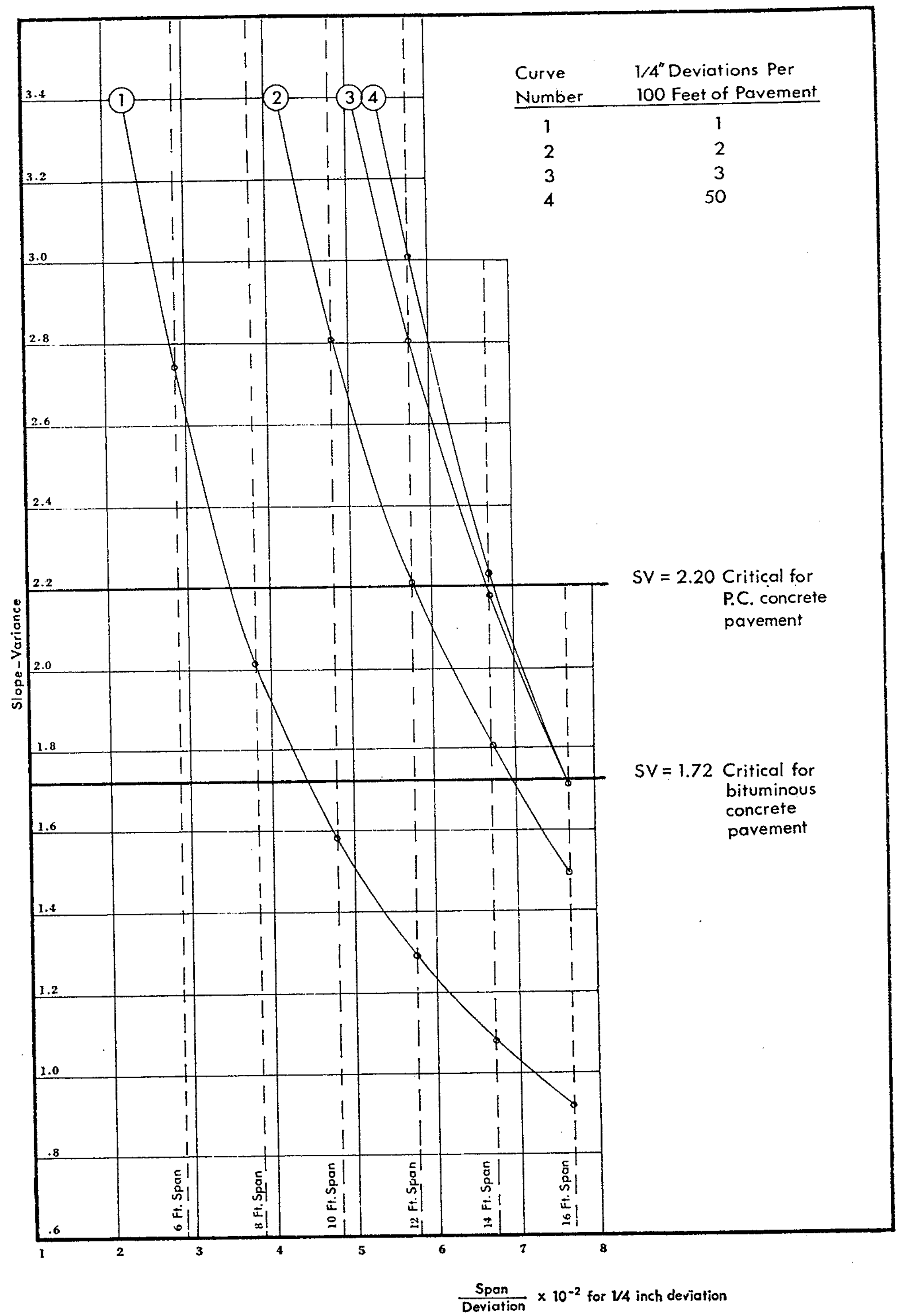


Figure 28. Critical number of ¼-in. deviations per 100 ft of pavement; relationship between slope-variance and span.

vals along both sides of the pavement and to stretch string-lines between them.

Several equipment manufacturers have developed paving equipment that is capable of laying pavement surfaces to relatively narrow tolerances from both longitudinal and transverse grade.

RECOMMENDATIONS FOR SPECIFICATION REQUIREMENTS

Methods of Testing Pavement Surface

STRAIGHTEDGE

Pavement smoothness as affected by small, closely-spaced deviations from grade is dependent on the value of the

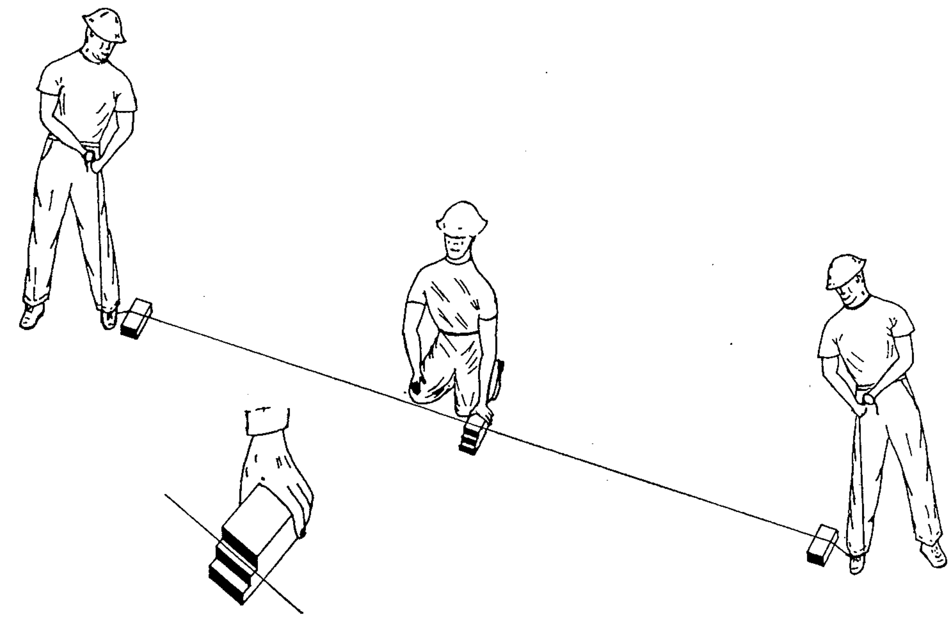


Figure 29. Stringline method of checking smoothness of pavement surface.

slope variance, which may be estimated by the straightedge test, provided both vertical deviation and span length are taken into account.

It should be understood that the charts developed herein for ⅛- and ¼-in. deviations (Figs. 27 and 28) are approximations only and are not intended for use without further checking and verification. They are presented here primarily to illustrate a new approach to real smoothness requirements based on AASHO Road Test criteria, but using a practical field tool, the straightedge, to measure the combined effect of vertical deviation and span length.

STRINGLINE

Pavement smoothness as affected by widely-spaced deviations may be determined by use of a stringline by stretching a light, strong line parallel to the centerline over blocks of equal height placed on the pavement surface. Deviation of the pavement surface from the stringline should be measured with a stepped gage block, slid along the pavement surface underneath the line as shown in Figure 29.

GRADE STAKES

Pavement smoothness as affected by both longitudinal and transverse deviations from grade can be determined by use of grade stakes, provided the stakes are set accurately to grade on both sides of and spaced 25 ft apart along the pavement. Measurements should be made from stringlines stretched transversely across the pavement, parallel to the pavement surfaces.

Specification Tolerances

10-FOOT STRAIGHTEDGE PARALLEL TO CENTERLINE

For measurement with a 10-ft straightedge parallel to the centerline the specification tolerances should be not more than 4 percent of 100-ft sections having more than (a) no deviations of ⅛ in. or greater in a 30-in. span, (b) one deviation of ¼ in. or greater in a 10-ft. span, and (c) three deviations of ¼ in. or greater in a 16-ft. span. All pavement more than ± ½ in. from the plan grade should be rejected.

50-FOOT STRINGLINE PARALLEL TO CENTERLINE

Ninety-five percent of 50-ft measurements with a stringline parallel to the centerline should be within ± ⅜ in. All pavement more than ± ½ in. from the plan grade should be rejected.

TRANSVERSE STRINGLINE FROM GRADE STAKES

Ninety-five percent of measurements with a transverse stringline from grade stakes should be within ± ¼ in. of the plan grade. All pavement more than ± ½ in. from the plan grade should be rejected.

The foregoing are primarily for purposes of illustration; other tolerances may be substituted as appropriate. The general guideline is that both the vertical distance and the span be taken into consideration in writing meaningful specification requirements for pavement smoothness.

CHAPTER EIGHT

THICKNESS OF PAVEMENT COURSE

THEORETICAL BASIS FOR THICKNESS REQUIREMENTS

Flexible Pavement

Of the many available methods for computing the required thickness of flexible pavement courses, the method developed by the AASHO Operating Committee on Design from data obtained from the AASHO Road Test seems to be the most logical and practical. However, there still remain several factors that must be assumed or estimated. Variations in these estimates lead to differences in the computed thickness of the various pavement components, or courses, that exceed the tolerances permitted in their thicknesses by current specifications. Some of these factors are discussed in the following.

The soil support value is selected from tests made on samples of the soil taken to represent the proposed subgrade, and the test values are correlated with the value obtained, using the same test method, on a sample of the soil representing the subgrade at the AASHO Road Test. The data in *HRB Special Report 66* show the variations in test values obtained by the many agencies participating. Relatively small differences in the selection of the soil support value produce differences in pavement thicknesses that exceed the tolerances permitted by specification.

The pavement is designed to withstand an estimated number of equivalent 18,000-lb single-axle load applications over a 20-year period. This estimate is based on the volume and character of the present traffic (often not too accurate) projected over a 20-year period. The method of converting the mixed traffic to equivalent 18,000-lb single-axle load applications is questioned by some traffic analysts.

The selection of a regional factor is a matter of judgment on the part of the pavement design engineer. A regional factor of 1.0 represents the environmental conditions at the AASHO Road Test. Values of 0.5 to 3.0 are suggested for the continental United States by the "AASHO Interim Guide for the Design of Flexible Pavement Structures." The value of the regional factor has an appreciable effect on the pavement thickness obtained.

The strength coefficients of only three flexible pavement components were established at the AASHO Road Test. They are bituminous concrete surface (including binder), 0.44 *SN* per inch; crushed stone base, 0.14 *SN* per inch; and gravel subbase, 0.11 *SN* per inch. The coefficients of other materials have been estimated based on rationalization and tests, but not to the accuracy of these three materials.

The details of this design method for flexible pavements are contained in the "AASHO Interim Guide for the Design of Flexible Pavement Structures." A nomograph is used to relate the support value of the subgrade, the volume and character of the traffic, the prevailing environmental condition, and a pavement consisting of two or more components of specified thicknesses that are selective. The support value of the subgrade, determined by test and judgment, is represented by an abstract number from 1 to 10. The volume and character of the traffic, determined from current traffic data extrapolated to that expected over a 20-year period, is analyzed to determine the number of equivalent 18,000-lb (18-kip) single-axle load applications. This number may be expressed as a daily average by dividing by 7,300 (365 days $\times$ 20 years). The prevailing environmental condition or regional factor is expressed in numbers, 0.5 to 3.0, and is based on a value of 1.0 for the conditions that prevailed during the AASHO Road Test. The pavement thickness is expressed as a STRUCTURAL NUMBER, which is the sum of the thickness of the pavement components multiplied by their respective strength coefficients.

Rigid Pavements

Portland cement concrete pavements are usually designed by a theoretical method originally developed by Westergaard. The original equations have since been modified in an attempt to bring them into better agreement with research findings, and to allow for variations in subgrade support due to warping of the concrete slabs.

The design thickness is based on:

1. Supporting power of the subgrade soil. This is expressed as the modulus of subgrade reaction, k, determined by plate bearing tests, and usually varies rather widely at different locations. Furthermore, the correction to compensate for the loss in strength which might occur if the soil ever became saturated during future use is not fully satisfactory.
2. Flexural strength of the pavement concrete as measured on laboratory test specimens after 28-day curing. For most conditions a flexural strength of 600 to 700 psi is specified. An allowance must be made for the effects of fatigue, which may decrease the design strength to as little as 50 percent of the test strength, depending on the judgment of the designer.
3. Anticipated equivalent wheel loads. In some cases an additional correction factor of about 1.2 is applied to allow for the effects of impact.

As a result of the uncertainties introduced by the use of assumed values and correction factors, the design pavement thickness is usually selected as the whole number of inches next greater than the computed value.

Thus, it should be noted that for both flexible and rigid pavements the thickness design for each course is subject to a number of approximations. The magnitude of these approximations is such that design theory does not afford a sound basis for justification of very close thickness tolerances for any of the courses of either flexible or rigid pavements.

EFFECTS OF VARIATION IN THICKNESS

In spite of the foregoing conclusion, the effects of variation in thickness are calculated in the following to show the theoretical loss of performance versus construction cost.

Flexible Pavement

Studies have shown that a deficiency of 0.24 in. in the design thickness of a 3-in. bituminous concrete component of a flexible pavement would theoretically reduce its traffic carrying capacity from 120 daily equivalent 18-kip single-axle load applications to 100, or a reduction of 17 percent, whereas the monetary value of the pavement deficiency amounts to only 8 percent of the cost of the 3 in. of bituminous concrete surface. Continuing this analysis to include also deficiencies of ½ in. in the 6-in. crushed stone base and ½-in. in the 10-in. gravel subbase, the carrying capacity of the hypothetical pavement would be reduced to about 80 daily equivalent 18-kip single-axle load applications, or 33 percent.

Rigid Pavement

Assuming that a specified 9-in. thickness of concrete slab would carry 610 single-axle loads per day, a deficiency of ¼ in. in thickness would reduce the theoretical carrying capacity to about 510 daily single-axle loads. This is a reduction of about 16.5 percent in performance and 2.8 percent in monetary value. A deficiency of ½ in. in thickness would reduce the carrying capacity to about 410 single-axle loads per day. This is equivalent to a 33 percent loss of performance and 5.6 percent in monetary value.

THICKNESS TOLERANCES

AASHO Road Test Tolerances

At the AASHO Road Test the specifications permitted variations of ± ¼ in. from the specified thicknesses of the bituminous concrete surface. The records show that of the cores taken 2.7 percent exceed this tolerance on the minus side and 2.6 percent exceed it on the plus side. The mean of the deviations is zero, the range being from — ½ in. to + ⅝ in.

The AASHO Road Test specifications permitted a variation of ± ½ in. from the specified thicknesses of the crushed stone base and gravel subbase. According to the records, of the cores taken from the crushed stone base 0.8 percent exceed this tolerance on the minus side and 15.0 percent exceed it on the plus side. The mean of the deviations is + ¼ in., the range being from — 1 in. to + 1½ in. The records show that of the cores taken from the gravel subbase 3.6 percent exceed the tolerance on the minus side, and 10.5 percent exceed it on the plus side. The mean of the deviations is + 1⁄16 in., the range being from — 1 in. to + 2 in.

The pavements at the AASHO Road Test were constructed under rather rigid inspection, so it is indicated that limits of the variations in thickness specified for the three pavement components of the flexible pavements are about as narrow as is practicable at this time. The same can be said for the tolerances permitted for the P.C. concrete pavements. A deviation of ± ¼ in. from the specified thickness was permitted by the specifications. The record shows that of the cores taken 2.7 percent exceed this tolerance on the minus side and 3.5 percent exceed it on the plus side. The mean of the variations is + 1⁄32 in., the range being from — ⅝ in. to + ⅞ in.

State Highway Tolerances

As shown in Table 13, the listed agencies either do not specify a tolerance for base thickness or, in most cases, allow ½ in. The tolerance for surface course thickness varies from ⅛ to ½ in.

Practical Tolerances and Penalties

Specification tolerances for the thickness of pavement components should be kept within the limits of the ability of modern paving equipment to produce. Specifying too narrow limits may cause expensive construction procedures that cannot be justified. It is questionable whether pavement design methods have been developed to the point where the thickness produced by any method is sufficiently precise to warrant a very close tolerance in thickness. On the other hand, very wide variations in pavement thickness should not be permitted, as they are not necessary from the standpoint of placement, do not reduce the cost of construction, and are conducive to poor workmanship. Also, there is some extreme limit where the thickness of a pavement course becomes critical from a performance standpoint; if the deficiency in thickness exceeds this limit the pavement should not be accepted.

When pavement components such as subbase, base, or bituminous surface courses are paid for on a unit weight or unit volume basis, considerable variation in the thickness of individual courses can be allowed without penalty, provided the extreme limits are not exceeded. However, it should be stipulated that excess tonnage required for surface courses thicker than the nominal thickness, plus a reasonable tolerance, will not be paid for. Omission of this requirement can result in a serious overrun of quantities.

When payment for pavement courses is on a lump sum or square yard basis, it is necessary, in order to insure full measure, that only small deficiencies be allowed without penalty. In fact, some agencies allow no tolerance on the minus side without penalty. A reasonably wide tolerance, with penalty, makes it possible for the contractor to bring the wearing course of the pavement to plan grade and have the thickness within the acceptance tolerances. If the grade of each course is properly controlled there will be no penalty.

The basis for the penalty to be assessed when the deficiency of a course exceeds the tolerance is largely a matter of judgment. Theory indicates that loss of performance is greater than the reduction in cost of construction, and that graduated penalties for deficiencies in thickness of flexible pavement course should be roughly twice the cost on a fractional-inch thickness basis, while the graduated penalty for P.C. concrete pavement should be roughly five times the cost on a fractional-inch thickness basis. As previously discussed, it is doubtful that this basis for assessing penalties is justified from the standpoint of actual loss of use value. However, a penalty on a straight fractional-inch thickness basis invites nonuniformity of thickness, because it may be cheaper to do sloppy work and accept the penalty than to control the grade properly. On an entirely arbitrary basis, a penalty of 1½ times the fractional-inch cost is suggested for flexible pavement courses and 2½ times the fractional-inch cost for P.C. concrete pavement.

When the deficiency in thickness of any course exceeds the extreme limit it should be removed and replaced, or it may be accepted without payment.

Practical and Realistic Specification Requirements

In view of the factors discussed in the foregoing it is suggested that specifications dealing with the thickness of pavement courses for which payment is made on a lump sum or square yard basis contain the following:

1. A statement as to the nominal, or desired, thickness of the course.
2. An allowable tolerance from this thickness.
3. The percentage of area that must fall within this tolerance for acceptance without penalty.
4. The penalty that will be assessed against lots having an excessive percentage outside of the tolerance.
5. The size of the lot that will be tested for acceptance.
6. The acceptance plan on which the acceptance decision will be based and the stage of construction at which the lot will be sampled and tested.
7. The extreme limit of deficiency which will lead to rejection of that area of the course which is defective.

Appropriate acceptance plans have been described and exemplified elsewhere in this report. Numerical limits and tolerances should be based on the normal variation found in acceptable construction by probability sampling.

From available data, these tolerances probably should be of the following orders:

	TOLERANCE FROM PLAN THICKNESS (IN.)	
PAVEMENT COURSE	80% OF COURSE TO BE WITHIN	100% TO EXCEED
Asphaltic concrete wearing	− 0.00 to + 0.50	− 0.25
Asphaltic concrete binder	− 0.25 to —	− 0.50
Asphaltic concrete base	− 0.25 to + 0.50	− 0.75
Aggregate base	− 0.75 to + 1.00	− 1.25
Bituminous-stabilized base	− 0.50 to + 1.00	− 1.25
Cement-treated base	− 1.00 to + 1.50	− 1.75
P.C. concrete	− 0.00 to —	− 0.50

CHAPTER NINE

EDITORIAL GUIDELINES

In addition to being technically competent, accurate, and complete, specifications must be written as clearly and concisely as possible. Certain conventions peculiar to specifications must be observed, and the specifications must be written in accordance with contemporary usage and grammar. This chapter has been prepared as a reference to which the specifications writer may turn for guidance in the final writing and editing of specifications. Only the more important matters of usage and grammar can be treated here. Further information can be obtained from any of the many textbooks dealing with technical writing.

PROPER USE OF WORDS

Use Simple Language

Specifications should be written in language that both the contractor and the engineer can understand. High-sounding words and phrases and pseudo-legal terms should never be used. When there is a choice between a long word and a short word that both mean the same thing, the shorter word should always be used.

It is much easier for construction personnel to understand two two-syllable words than one four-syllable word that means the same thing. Even some college-level people are unable to read and understand relatively simple English. Furthermore, many people who need to understand specifications do not have a background that enables them to "tie-in" and understand technical information regarding materials and methods used in highway construction. Consequently, every effort must be made to write specifications as accurately, briefly, and clearly as possible.

Avoid Confusing or Ambiguous Words

Even though the meaning of a technical term may seem obvious, it is advisable to define the term. Because most technical terms used in specifications occur fairly often, it is best to include in a separate subsection an extensive list of definitions. It will be helpful if a separate series of sheets giving definitions of technical terms is prepared. Even common words should be defined. For example, "tons" should be defined as short tons or long tons, and "days" as calendar days or working days.

Confusion often is caused by the use of different words which are intended to have the same meaning. For instance, the words "embankment" and "fill" usually are considered to have the same meaning. In the specifications, under definitions, it should be said that "embankment" is also called a "fill." However, only one of these words should be used in the body of the specifications.

A common word that is often used in a faulty manner is "either." Do not say: "A stable shoulder shall be constructed on *either* side of the traveled way." This statement could be interpreted to mean that a shoulder is required on only one side. The correct statement would be: "A stable shoulder shall be constructed on *each* side of the traveled way."

Another word that may have a vague meaning is "any." This word is sometimes used where "all" or "every" would be better. For instance, it is better to say "*All* oversize material shall be crushed," rather than "*Any* oversize material shall be crushed." Also, "*Every* pit or quarry used as a source of material shall be approved by the Engineer," is clearer than "*Any* pit or quarry used. . . ." However, use of the word "any" is correct in the following statement: "Before *any* material is removed from a pit or quarry for use in construction, the source shall be approved by the Engineer."

Another important consideration in the choice of a word is to be sure that the word will be given its intended meaning. For instance, the word "grade" may refer to the quality of material, to the rate of slope of a road, or to the desired elevation of a certain point. Also, the word "graded or "grading" may refer to the shaping of a roadbed or to the gradation of sizes of particles of aggregate. If the meaning of any one of these words is not evident from the other terms used in connection with it, its meaning must be specified. In the sentence, "This work shall consist of a pavement composed of dense-graded bituminous concrete, constructed on a prepared roadbed in accordance with these Specifications and in conformity with the lines, grades, thickness, or weight per square yard, and typical cross section shown on the Plans," the expression "dense-graded" and the word "grades" are used with different senses. In this case, the meaning of the sentence will probably be clear. However, it is advisable to avoid use of the same word, or two forms of a word, with two different meanings in a single sentence, or in two sentences close together.

Put Controlling Words in the Right Places

The meaning of a sentence often depends on the position of the word "only" in the sentence. In the following three statements, the word "only" appears in different places, but the other words are the same:

1. *Only* the Engineer shall decide whether or not this method can be used.
2. The Engineer shall decide *only* whether or not this method can be used.
3. The Engineer shall decide whether or not *only* this method can be used.

The first sentence means that the engineer is the only person who can decide. The second sentence means that the engineer can decide whether or not the method is suitable, but he cannot decide, for example, when the work will be done. The third sentence means that the engineer shall decide whether the method described must be used or whether some other method may be substituted.

An error is often made when the words "either" and "or" are used. In the following sentence, the word "either" is in the wrong place. "Burlap and cotton mats may be *either* left in place for at least 72 hours *or* may, after 12 hours, be removed and replaced with. . . ." The correct arrangement is: "Burlap and cotton mats *either* may be left in place for at least 72 hours *or* may be removed after 12 hours and replaced with. . . ." In a correct sentence, the same construction must be used after both "either" and "or."

PROPER CHOICE OF WORDS

Use of "Shall" and "Will"

When reference is made to a responsibility of the contractor or to a requirement of a material, the word "shall" should be used in preference to "will." Examples are the following: "The aggregate *shall* be spread uniformly," or "Bituminous material *shall* be of the type and grade called for."

Even if the contractor is responsible for an operation, however, it is usually advisable to avoid the use of the word "contractor" if possible. For example, it is best to say "The aggregate shall be spread uniformly," rather than "The Contractor shall spread the aggregate uniformly."

The word "will" is preferred where something is to be done by the engineer; for instance, "Construction stakes *will* be set by the Engineer."

Use of Technical Words

Technical words should be used in their *exact* technical meaning. The words "lineal" and "linear" are confused in many specifications. The latter word is preferred when referring to a unit of measure that has a single dimension. A linear foot means that the unit of measure is not square or cubic.

Similarly, "amount" is preferred when referring to money, but "quantity" when referring to materials or items of construction.

Use of "and/or"

The expression "and/or" should not be used. For instance, do not say "The equipment used by the Contractor shall include a roller, a power broom *and/or* a power blower, a self-powered pressure distributor for spreading bituminous material, and equipment for heating bituminous material." Instead say, "The equipment used by the Contractor shall include the following items: a roller; a power broom or a power blower, or both a broom and a blower; a self-powered . . .".

Use of "the"

In order to avoid the "telegraphic" style occurring when the article "the" is omitted, "the" should be used in a specification in any place where it would appear in normal writing. For instance say, "After *the* rough grading is completed, *the* area of *the* old roadbed shall be scarified or plowed. . ." rather than, "After rough grading is completed, area of old roadbed shall be scarified or plowed. . . ."

LENGTH OF SENTENCES

How many words should a sentence contain? The best answer is that a sentence should be as short as possible, but its meaning must be clear. A long sentence usually cannot be easily understood by the average person. However, it is often necessary to use a fairly long sentence in order to express an idea properly. But a long, rambling sentence which can easily be broken up into two or more sentences should be avoided. An example of a poor long sentence is as follows:

"It is mutually agreed that it is inherent in the nature of highway construction that some changes in the Plans and Specifications may be necessary during the course of construction to adjust them to field conditions and that it is of the essence of the contract to recognize a normal and expected margin of change within the meaning of the clauses 'Changes' and 'Changed Conditions' in the 'General Provisions' of the contract as not requiring or permitting any adjustment of contract prices, provided that any change or changes do not result in (1) an increase or decrease of more than 25 percent in the original contract amount, in the quantity of any major item, or in the length of project, or (2) a substantial change in the character of the work to be performed under a contract pay item or items that materially increases or decreases the cost of its performance."

A long sentence is usually the result of trying to include too many details with the principal statement. A suggested revision of the foregoing sentence is as follows:

"During the course of highway construction, it is to be expected that some changes in the Plans and Specifications will be necessary to make them suitable for the actual conditions in the field. Within the meaning of the terms 'Changes' and 'Changed Conditions' in the 'General Provisions' of the contract, the Contractor must accept the provision that certain changes will not require or permit any adjustment of the contract prices. A change or a group of changes will be so classified if it meets both of the following requirements: (1) the increase or decrease in the original amount of the contract, in the quantity of any major item, or in the length of time covered by the contract will not exceed 25 percent; (2) the character of the work to be performed under any pay item in the contract will not be changed enough to cause a substantial increase or decrease in the cost of such work."

Occasionally, a sentence contains words that do not really give useful information. Such words not only make the sentence unnecessarily long, but may even tend to make the meaning of the sentence obscure.

USE OF CAPITALS

A capital letter should be used at the beginning of title words such as: Article, Contractor, Engineer, Plans, Section, Special Provisions, Specifications, Table, and Type (of material).

PUNCTUATION

The three most useful marks of punctuation within sentences are the comma, the semicolon, and the colon. An exhaustive discussion of their uses is beyond the scope of this report, but listed in the following, with examples, are the major uses of the three marks:

Use of the Comma

The comma is used:

1. To separate two main clauses (two complete ideas that could actually be sentences) when they are joined by a coordinating conjunction (and, but, yet, or, nor). *Example: The word "shall" is used when reference is made to a responsibility of the Contractor,* but *"will" is used when something is to be done by the Engineer.*

2. To separate elements in a series. *Example:* The Contractor shall bear all expenses of constructing and maintaining such *roads, detours, approaches, and intersections.* (NOTE: The comma before "and" should never be omitted.)

3. To set off an interrupting phrase or construction. *Example:* The Engineer may, *by written order,* suspend the performance of the work.

4. To set off a nonrestrictive modifier, usually a clause beginning with "which" or "whichever." *Example:* The quantity of bituminous material to be paid for shall be the number of gallons or tons, *whichever is called for in the bid schedule,* used as ordered in the accepted work.

In this sentence, the "whichever" clause is nonrestrictive because it is not essential to the meaning of the sentence; it is simply an additional fact included by the writer. On the other hand, in the following sentence the "which" clause is restrictive because it specifies a required characteristic of the telltale device. *Example:* Beam scales shall be equipped with a telltale device *which will start to function when the load being applied is within 10 lb of the desired load.*

A good test of whether a clause is restrictive or nonrestrictive is to determine whether it can be omitted from the sentence without changing the intended meaning of the sentence.

5. To separate an adverbial (or conditional) clause from the main clause which follows. *Example: Before*

any material to be incorporated in the work is removed from a pit or quarry, the source shall be approved by the Engineer.

6. To separate long prepositional phrases or verbal phrases that begin sentences.

Example 1—Prepositional Phrase: *Before delivery to the site of construction,* one-half of the length of each dowel bar shall be painted with one coat of red lead or bituminous material.

Example 2—Verbal Phrase: *Before beginning the grading operation,* the Contractor shall. . . .

Example 3—Verbal Phrase: *To insure the safety of the public,* the Contractor shall. . . .

Use of the Semicolon

The semicolon is used:

1. To separate closely related main clauses not connected by a coordinating conjunction. *Example: The spacing between the sidewalls of adjacent tires shall not exceed 5 inches; the rear tires shall be staggered with relation to the front tires.*

2. Before a transitional conjunction between two main clauses. *Example:* Specifications must be technically correct; *furthermore,* they must be capable of immediate comprehension by the reader.

Use of the Colon

The colon is used to indicate that a list follows. *Example:* The aggregate shall be placed on the pile by *one of the following:* a front-end loader, a dump truck, or a portable conveyor.

COMMON TYPES OF GRAMMATICAL MISTAKES

Faulty Pronoun Reference

A pronoun must always have an absolutely clear antecedent; in other words, what the pronoun stands for must be immediately evident. The pronouns most frequently misused are "this" and "which."

Incorrect: The wearing surface shall then be rerolled, *which* must be completed before cooling to 120 F. (Here, the "which" refers to the whole concept of rerolling the surface; the word has no clear and precise antecedent.)

Improved: The wearing surface shall then be rerolled before the paving mixture has cooled to 120 F.

Incorrect: Coning of stockpiles results in segregation. *This* is not permitted.

Improved: Coning of stockpiles is not permitted.

Dangling Modifiers

A dangling modifier is a group of words, usually containing a participle or an infinitive, which seems to operate on the wrong word. The word that names the doer of the action in the participle or infinitive phrase is the wrong word.

Incorrect: *When scarifying or discing, care* shall be taken. . . . ("Care" is not doing the scarifying; a piece of equipment or an operator of a piece of equipment is doing the work.) The dangling modifier may be eliminated by (1) making it into a complete dependent clause, or (2) changing the subject of the main part of the sentence.

Improved: (1) *When the surface is being scarified or disced,* care shall be taken. . . .

(2) When scarifying or discing, the operator shall take care. . . .

Incorrect: The wearing surface shall then be rerolled, *using* first the pneumatic-tired roller and finishing with the steel-wheeled roller.

Improved: The wearing surface shall then be rerolled, first with the pneumatic-tired roller and then with the steel-wheeled roller.

Lack of Agreement Between Subject and Verb

Where other words come between the subject of a sentence and the verb, an incorrect form of the verb is often used. Because most verbs in specifications are in a form involving the auxiliary verb "shall" or "will," this type of mistake does not often occur. However, three examples follow:

(1) *Incorrect:* Good *agreement* between the results of tests and the measured values *indicate* that the work is satisfactory.

(2) *Incorrect:* An *estimate* of the number of pieces of equipment that will be available *are* helpful in. . .

(3) *Incorrect:* Unless sufficient *measurements* for establishing the average thickness of the slab *is* made. . .

In the first sentence the subject is "agreement," which is singular, and the verb should be "indicates." In the second sentence, the subject is "estimate" and the verb should be "is." In the third sentence, the subject is "measurements" and the verb should be "are made."

Different Forms in Parallel Construction

Care must be taken to use the correct form of expressions where two or more conditions are listed as a series. Here are two examples of incorrect construction:

(1) *Incorrect:* A vibrator may be attached to the spreader, finishing machine, or may be mounted on a separate carriage.

(2) *Incorrect:* The front screed shall be lifted and brought directly over the joint, set upon it, and the forward motion of the finishing machine shall be resumed.

An easy way of correcting the first sentence would be: "A vibrator may be attached to the spreader or to the finishing machine, or it may be mounted on a separate carriage."

The idea in the second incorrect sentence may be expressed correctly in this way: "The front screed shall be lifted, brought directly over the joint, and set upon it. Then the forward motion of the. . ."

USE OF ABBREVIATIONS

In order to save space, standard * abbreviations should be used for the names of units of measurement. Some standard abbreviations are as follows:

spell out	= acre(s)
avg	= average
bbl	= barrel(s)
bu	= bushel(s)
c to c	= center to center
cm	= centimeter(s)
cir	= circular
cu	= cubic
cu ft	= cubic foot (feet)
cu yd	= cubic yard(s)
F	= degree(s) Fahrenheit
diam	= diameter(s)
$	= dollar(s)
doz	= dozen(s)
el	= elevation
ft	= foot (feet)
fpm	= feet per minute
gal	= gallon(s)
gpm	= gallon(s) per minute
hp	= horsepower
hp-hr	= horsepower-hour(s)
hr	= hour(s)
in.	= inch(es)
ID	= inside diameter
kg	= kilogram(s)
lin ft	= linear foot (feet)
max	= maximum
spell out	= mile(s)
mph	= mile(s) per hour
min	= minimum
min	= minute(s)
spell out	= month(s)
ppm	= part(s) per million
pt	= pint(s)
lb	= pound(s)
lb-ft	= pound-foot (feet)
lb per cu ft	= pound(s) per cubic foot
psf	= pound(s) per square foot
psi	= pound(s) per square inch
qt	= quart(s)
spell out	= rod(s)
shp	= shaft horsepower
sp gr	= specific gravity
sq ft	= square foot (feet)
sq in.	= square inch(es)
std	= standard
tan	= tangent
M	= thousand(s)
kip	= thousand pound(s)
spell out	= ton(s)
v	= volt(s)
wt	= weight
yd	= yard(s)
yr	= year(s)

* American Standards Association.

Note that no "s" is used for the plural of any measurement unit abbreviation, and that no period is used except when the abbreviation spells a word in itself; for example, in. for inch(es).

Abbreviations should also be used for certain well-known organizations, such as AASHO, ASTM, ASA, BPR, HRB.

SUMMARY

Basic Principles

In order that a specification will be interpreted correctly and that there will be no chance of misunderstanding by the contractor, a few simple principles should be kept in mind, as follows:

1. The simplest possible language should always be used.
2. Confusing and ambiguous words must be avoided or clarified.
3. Controlling words must be properly placed.
4. Sentences should be kept as short as is consistent with comprehension and meaning.
5. Punctuation must be handled with great care.

Things to Do

1. Use the words "shall" and "will" properly.
2. Use the best word.
3. Put each word in the right place.
4. Use the word "the" wherever it belongs.
5. Use short sentences.
6. Use capital letters for the beginnings of words which resemble titles.
7. Use commas properly.

Things Not to Do

1. Do not include vague expressions in requirements.
2. Do not use the expression "and/or."
3. Do not include unnecessary words.
4. Do not use dangling participles.
5. Do not use the word "same" as a pronoun or the word "said" as an adjective.
6. Do not use symbols such as % or #.

CHAPTER TEN

ASTM PRECISION STATEMENTS

The material of this chapter is, in part, historical in nature, reflecting as it does the status of ASTM precision statements as of June 1963. Since that date ASTM Committee D-4 has been active in restudying and making recommendations for changes in the format of precision statements. Much of the emphasis of these changes will be directed towards reducing reliance on the terms "repeatability" and "reproducibility" and giving greater significance to the standard deviation, σ, and the relation that various multiples of this parameter have to a set of data. This will be done by reference to ASTM Designation E-177, *Recommended Practice for the Use of Terms Precision and Accuracy as Applied to Measurement of a Property of a Material,* and to the new ASTM Manual STP 335 for conducting an *Interlaboratory Study of a Test Method.* The tables in this chapter listing methods having precision statements do not include actions taken in the June 1964 meeting, at which time several statements were revised or newly adopted.

FUNCTION OF ASTM

The investigations and researches of ASTM technical committees have led to the development of more than 3,200 standards, specifications, and methods of test. Many of these standards serve as the backbone of the highway construction industry by providing uniform guidelines for specifying and testing materials. Each test method describes an orderly procedure for measuring a property of a material, and includes all of the details essential to obtaining satisfactory precision of measurement. Defining this degree of precision is one of the advisory functions of ASTM Committee E-11 on Statistical Methods. Such precision statements take into account the normal variability that will result from different equipment, different operators, sampling variations, and other influencing factors. The realization of the necessity of required statistical studies to provide a basis for these statements has caused some of the tests lacking precision statements to be viewed with some degree of skepticism, or at least has caused the obtained test values to be examined and applied with extreme caution.

FACTORS AFFECTING PRECISION

Any test procedure involving operator and equipment may be subject to both random and systematic error, resulting in a variation of the individual results of a group of test data by the same or different operators. Users of the test should be posted as to the magnitude of such variations that may reasonably be expected. The precision statement section of a method of test is intended to accomplish this result. To use a method of test without a precision statement is none other than buying the proverbial "pig in a poke."

Random errors in testing will result in a spread of the test data about a mean or central value. The greater the number of test results and the tighter the operational control of all steps in the testing procedure, the smaller will be this variation or spread of individual values about the mean value. Statistically, the measure of this variation about the mean is the standard deviation, σ, or, more strictly speaking, the estimate of the standard deviation, s, because it is based on a small amount of experimental data rather than on all possible data. This spread of the data about its mean as the result of random error is the measure of the precision of the test method.

It should be recognized, however, that the foregoing mean or central value is not necessarily the true value, regardless of the amount of experimental data used in its evaluation. If systematic error is present as between several groups of the experimental data, there will be a shift of the previously described mean value away from the true value, although the spread of the several groups of the experimental data about their means may not be affected. This variation of the mean from the true value, as the result of systematic error, is called the BIAS of the system, and measures the accuracy of the data. Unfortunately, in many ASTM methods of test there is no simple or sure way of determining the true value of the property being measured. Who may say, for instance, what is the true measure of the penetration or softening point of a given sample of asphalt? Thus, the variation of the measure of a property usually includes, in a group of results, both random and systematic error. For this reason the estimate of the standard deviation has within itself elements of both precision and accuracy. Therefore, the cooperative testing committee engaged in devising a given method of test should give careful consideration to the elimination of sources of systematic error. In general, in ASTM development of test methods this elimination of systematic error is not so much a conscious technical procedure as it is a rule of common sense. Ordinarily, after a common sense appraisal of a proposed test method by some group of experts in the field, the mean or central value of some considerable number of replicate results is accepted as the true value, from which error deviations are measured. There is a certain laxity here, it must be admitted; as a result, the terms precision and accuracy are frequently loosely regarded as identical, whereas in reality they are, by definition, different quantities.

METHODS OF DETERMINING PRECISION

In general ASTM practice the cooperative test program employed in developing a proposed method of test is itself necessarily limited in terms of operators, samples, laboratories, and test machine assemblies. It is therefore necessary that the developers of a method of test concern themselves not only with the potential precision and accuracy of the several steps in the proposed procedure, and with the balance between operators, samples, laboratories, and equipment, but also with the establishment of the linkage between their limited experimental data and the statistical universe of results from all other possible operators, laboratories, and equipment assemblies working with other samples of the material in question at other times and places, but still under the restrictions and procedures prescribed by the method of test in question.

A subcommittee of ASTM D2 has considered this situation and in *ASTM Proceedings* 53: 379 (1953) has made certain proposals as to processing the data and as to the format for a precision statement to be a part of all ASTM methods of test. Although the statistical analyses on which the arguments of this article are based involve certain approximations, their results are straightforward, readily understandable, and sufficiently exact for the purposes intended. It would be a significant advance if all cooperative testing committees were to follow this method of processing the data for definition of permissible variation between results by the same or different operators.

REPEATABILITY AND REPRODUCIBILITY

The D2 sub-committee, in the 1953 *Proceedings* article previously referred to, evaluated the variability in the results of a test procedure for two different situations, as follows:

1. For *repeatability,* which is the quantitative measure of the variability associated with a single operator in a given laboratory, generally using the same apparatus, and producing his group of test results over a short interval of time;
2. For *reproducibility,* which is the quantitative measure of the variability associated with two different operators working in two different laboratories with similar but different assemblies of test apparatus and with each operator generally producing his group of test data on different sample aliquots and, normally, over a short interval of time.

In case of both repeatability and reproducibility these measures of variabilities are, more specifically, defined as the greatest difference between two simple and independent test results that can be considered acceptable (i.e., not significantly different) at some stated probability level of being within a given magnitude under the testing methods of the recommended practice. Each of the two independent test results to be compared may be the average of a few replicates. The probability level advocated for purposes of this study is the 95 percent level, meaning that in the long run two randomly selected values will be found not to exceed the stated difference 95 times out of 100.

This greatest difference between two independent results, that is not expected to be exceeded more than 5 percent of the time, is geared to the estimate of the standard deviation of the data produced by the cooperative study setting up the method of test procedure. More specifically, this greatest difference value is made up of the product of the estimate of the standard deviation and a factor which varies with the degrees of freedom (i.e., number of independent test values less one) in the cooperative development data under repeatability and reproducibility conditions.

In repeatability, the estimate of the standard deviation, S_r, is normally derived by pooling the replicate values of a number of operators in the different cooperating laboratories, and is given as

$$S_r = \sqrt{\frac{\Sigma(X_1-\bar{X}_1)^2 + \Sigma(X_2-\bar{X}_2)^2 + \ldots \Sigma(X_k-\bar{X}_k)^2}{(n_1-1)+(n_2-1)+\ldots(n_k-1)}} \tag{19}$$

in which

$k =$ number of operators;
$n_1 =$ number of determinations, X_1, by operator 1, whose average value is $\bar{X}_1$;
$n_2 =$ number of determinations, X_2, by operator 2, whose average value is $\bar{X}_2$;
$n_k =$ number of determinations, X_k, by operator k, whose average value is $\bar{X}_k$; and
$(n_1-1)+(n_2-1)+\ldots(n_k-1) =$ degrees of freedom of the repeatability data.

Similarly, for reproducibility:

$$S_R = \sqrt{\frac{(\bar{X}_1-\bar{\bar{X}})^2 + (\bar{X}_2-\bar{\bar{X}})^2 + \ldots (\bar{X}_k-\bar{\bar{X}})^2}{(k-1)}} \tag{20}$$

in which

$k =$ number of laboratories;
$\bar{X}_1 =$ average of results by laboratory 1;
$\bar{X}_2 =$ average of results by laboratory 2;
$\bar{X}_k =$ average of results of laboratory k;
$\bar{\bar{X}} =$ average of results over all laboratories; and
$(k-1) =$ degrees of freedom of the reproducibility array.

CONFIDENCE LIMITS

For an infinite number of tests the standard deviation, σ, is related to the difference between, or spread of, a pair of randomly selected test values. In this long run a range of 2.77σ should not be exceeded, because of the operation of random errors, 95 percent of the time. Thus, this magnitude or range sets the value for the system of the confidence level or confidence limit, of 95 percent. However, in practice only a finite number of experimental results are developed by the cooperative testing study of the developers of the method of test. From these results only the estimate of the standard deviation—not the standard deviation itself—may be evaluated, and this is the more susceptible to deviation from the standard deviation, σ, the fewer the available data (i.e., the fewer the degrees of freedom as

TABLE 17

ASTM D4 SPECIFICATIONS NOT REQUIRING A PRECISION STATEMENT

SPEC. NO.	JURISDICTION MAIN	SUB	TITLE	COMMENTS
D8–63	D4	1b	Definition of Terms Relating to Materials for Roads and Pavements	Unsuited for precision statement
D75–59	D4	3a	Sampling Stone, Slag, Gravel, Sand and Stone Block for Use as Highway Materials	Unsuited for precision statement
D98–59	D4	3b	Specifications for Calcium Chloride	For test operations uses D345–48
D140–55	D4/D8	3a	Sampling Bituminous Materials	Unsuited for precision statement
D241–43	D4	3d	Specifications for Asphalt Filler for Brick Pavements	For test operations uses D4–52, D5–61, D6–39T, D36–26, D92–57, D113–44, D140–55, D165–42
D242–57T	D4	5a	Specifications for Mineral Filler for Bituminous Paving Mixtures	For test operations uses D546–55
D244–61T	D4	4c	Test for Coating Ability and Water Resistance, etc.	Unsuited for precision statement; tests too subjective
D290–51	D4	2d	Recommended Practice for Bituminous Mixing Plant Inspection	Unsuited for precision statement
D448	D4	5a	Specifications for Standard Sizes of Coarse Aggregate for Highway Construction	Unsuited for precision statement
D490–47	D4	4d	Specifications for Tar	For test operations uses D4–52, D20–56, D36–26, D70–52, D95–58, D139–49, D872–48, D1665–61
D597–46	D4	4a	Specifications for Cut-Back Asphalt, Rapid Cure Type	For test operations uses D4–52, D5–61, D88–56, D113–44, D402–55, D1310–59T
D598–46	D4	4a	Specifications for Cut-Back Asphalt, Medium Cure Type	For test operations uses D4–52, D5–61, D88–56, D113–44, D402–55, D1310–59T
D632–58	D4	3b	Specification for Sodium Chloride	For test operations uses Official Methods of Analysis of Assoc. of Official Agricultural Chemists for Salt
D633–44	D4	4d	Standard Volume Correction Table for Tar and Coal Tar Pitch	Unsuited for precision statement
D692–63	D4	5a	Specifications for Coarse Aggregate for Bituminous Paving Mixtures	For test operations uses D75–59, C29–60, C88–63, C131–55, C136–61T
D693–54	D4	5a	Specifications for Crushed Stone and Crushed Slag for Bituminous Macadam Base and Surface Courses of Pavements	For test operations uses D75–59, C29–60, C131–55, C136–63
D694–62	D4	5a	Specifications for Crushed Stone, Crushed Slag, and Crushed Gravel for Dry-Bound or Water-Bound Macadam Base Courses	For test operations uses D75–59, D423–61T, D424–59, C29–60, C88–63, C131–55, C136–63
D946–63T	D4	4a	Specifications for Asphalt Cement for Use in Pavement Construction	For test operations uses D4–52, D5–61, D6–39T, D92–57, D113–44, D140–55, D271–58
D977–63T	D4	4b	Specifications for Emulsified Asphalt	For test procedures uses D244–60, for 7 special tests; uses D4–52, D5–61, D70–52, D113–44, D128–61
D979–51	D4	3a	Sampling Bituminous Paving Mixtures	Unsuited for precision statement
D995–61T	D4	2d	Specifications for Requirements for Mixing Plants for Hot Mixed, Hot Laid Bituminous Paving Mixtures	Unsuited for precision statement
D1073–63	D4	5a	Specifications for Fine Aggregate for Bituminous Paving Mixtures	For test operations uses D75–59, C88–63, C125–58, C136–63
D1139–61T	D4	5a	Specifications for Crushed Stone, Crushed Slag, and Gravel for Single or Multiple Bituminous Surface Treatments	For test operations uses D75–59, C29–60, C88–63, C123–57A, C131–55, C136–61T, C142–55T, C235–57T
D1190–52T	D4	3d	Specifications for Concrete Joint Sealer, Hot Poured Elastic Type	For test operations uses D1191–52T
D1191–52T	D4	3d	Tests for Concrete Joint Sealers	3 tests unsuited for precision statements; 1 test with partial precision coverage via D95–58; 1 test without precision coverage needed

TABLE 17—*Continued*

SPEC. NO.	JURISDICTION MAIN	SUB	TITLE	COMMENTS
D1369–58	D4	2e	Recommended Practice for Quantities of Materials for Bituminous Surface Treatments	Unsuited for precision statement
D1663–59T	D4	2d	Specifications for Hot Mixed, Hot Laid Asphalt Paving Mixtures	For test operations uses D75–59, D140–55, D979–51, D423–61T, D424–59, D546–55, D1097–58, C127–59, C128–59, C136–61T
D1664–59T	D4	2c	Test for Coating and Shipping of Bituminous Aggregate Mixtures	Unsuited for precision statement; too subjective on "go no-go" basis of visual appraisal
D1751–60T	D4	3d	Specifications for Expansion Joint Fillers for Concrete Paving and Structural Construction (Non-Extruding and Resilient Bituminous Types)	For test operations uses D545–49
D1752–60T	D4	3d	Specifications for Preformed Expansion Joint Filler for Concrete Paving and Structural Construction (Non-Extruding and Non-Resilient Bituminous Types)	For test operations uses D545–49
D1753–60T	D4	3d	Specifications for Hot Mixed, Hot Laid Tar Paving Mixtures	For test operations uses D75–59, D423–61T, D424–59, D979–51, D1097–58, C127–59, C128–59, C136–61T
D1850–61T	D4	3d	Specifications for Concrete Joint Sealer, Cold Application Type	For test operations uses D1851–61T, D1191–52T, D5–61 (with grease cone replacing needle)
D1852–61T	D4	3d	Testing Jet Fuel Resistant Concrete Joint Sealer, Cold Application Elastic Type	For test operations uses D5–61 (with grease cone replacing needle), D140–55, D1853–61T
D1854–61T	D4	3d	Specifications for Jet Fuel Resistant Concrete Joint Sealer, Hot Poured Elastic Type	For test operations uses D140–55, D1855–61T
D2026–63T	D4	4a	Specifications for Liquid Asphalt, Slow Curing Type	For test operations uses D4–52, D88–56, D92–62, D95–58, D113–44, D139–49, D140–55, D243–36, D402–55, D445–61
D2027–63T	D4	4a	Specifications for Liquid Asphalt, Medium Curing Type	For test operations uses D4–52, D5–61, D88–56, D95–58, D113–44, D140–55, D402–55, D445–61, D1310–59T
D2028–63T	D4	4a	Specifications for Liquid Asphalt, Rapid Curing Type	For test operations uses D4–52, D5–61, D88–56, D95–58, D113–44, D140–55, D402–55, D445–61, D1310–59T

previously defined). Thus, to meet any given confidence level, or for a specific probability to obtain, a larger multiplier than 2.77 is required in practice.

The multipliers of the estimates of standard deviations in repeatability or in reproducibility that are applicable for defining the range between any two selected values that should not be exceeded 95 percent of the pair selections are given in the previously cited subcommittee report.*

FORMAT OF PRECISION STATEMENTS

The authors of the same subcommittee report † summarized their precision statement recommendations as follows:

Precision:

The following data should be used for judging the acceptability of results (95 percent probability) according to the concept of precision as given in the ASTM Proposed Recommended Practice for Applying Precision Data Given in ASTM Methods of Test for Petroleum Products and Lubricants.

(a) Repeatability

Duplicate results by the same operator should be considered suspect if they differ by more than the following amounts:

Range or Sample Description	Repeatability
—————	—————
—————	—————
—————	—————
—————	—————

(b) Reproducibility

The result submitted by each of two laboratories should not be considered suspect unless they differ by more than the following amounts:

Range or Sample Description	Reproducibility
—————	—————
—————	—————
—————	—————
—————	—————

* *ASTM Proceedings* 53:382 (1953), Table 1.
† *Ibid.*, Section 9.

TABLE 18

ASTM D4 SPECIFICATIONS NEEDING BUT HAVING NO PRECISION STATEMENT

SPEC. NO.	JURISDICTION MAIN	JURISDICTION SUB	TITLE	NO. OF TESTS	PRECISION STATEMENT RANGE	PRECISION STATEMENT CONFIDENCE LEVEL	PRECISION STATEMENT DEGREES OF FREEDOM
D2–33	D4	5b	Test for Abrasion of Rock by Use of Deval Machine	1	X	X	X
D3–18	D4	5b	Test for Toughness of Rock	1	X	X	X
D4–52	D4	4h	Test for Bitumen (CS_2 Soluble)	1	X	X	X
D113–44	D4	4e	Test for Ductility of Bituminous Materials	1	X	X	X
D139–49	D4	4e	Float Test for Bituminous Materials	1	X	X	X
D165–42	D4	4h	Test for Bitumen Soluble in CCl_4	1	X	X	X
D289–63	D4	5b	Test for Abrasion of Graded Coarse Aggregate by Use of Deval Machine	1	X	X	X
D345–58	D4	3d	Sampling and Testing Calcium Chloride	3	X	X	X
D423–61T	D18	—	Test for Liquid Limit of Soils	1	X	X	X
D424–59	D18	—	Test for Plastic Limit and Plasticity of Soils	2	X	X	X
D517–50	D4	3d	Specifications for Asphalt Plant	4	X[a]	X[a]	X[a]
D545–49	D4	3d	Testing Preformed Expansion Joint Fillers for Concrete (Non-Extruding and Resilient Types)	8	X[b]	X[b]	X[b]
D546–55	D4	5b	Test for Sieve Analysis of Mineral Filler	1	X	X	X
D762–49	D4	2f	Test for Hot Extraction of Asphaltic Materials and Recovery of Bitumen by Modified Abson Procedure	1	X	X	X
D872–48	D4	4d	Test for Sulfonation Index of Road Tars	1	X	X	X
D915–61	D18	—	Testing Soil-Bituminous Mixtures	3	X	X	X
D916–47T	D18	—	Test for Shear Strength of Flexible Road Surfaces, Subgrades, and Fills by Burggraf Apparatus	1	X	X	X
D994–53	D4	3d	Specifications for Preformed Expansion Joints for Concrete (Bituminous Type)	4	X[a]	X[a]	X[a]
D1074–60	D4	2a	Test for Compressive Strength of Bituminous Mixtures	2	X	X	X
D1075–54	D4	2c	Test for Effect of Water on Cohesion of Compacted Bituminous Mixtures	2	X	X	X
D1097–58	D4	2f	Test for Bitumen Content of Paving Mixtures by Centrifuge	1	X	X	X
D1138–52	D4	2a	Test for Resistance to Plastic Flow of Fine Aggregate-Bituminous Mixtures by Hubbard-Field Apparatus	1	X	X	X
D1189–61	D4	4f	Test for Vacuum Distillation of Liquid and Semi-Solid Asphaltic Materials for Residue of Specified Penetration	1	X	X	X
D1461	D4	4f	Test for Moisture or Volatile Distillates in Bituminous Paving Mixtures	2	X[c]	X[c]	X[c]
D1159–62T	D4	2a	Test for Resistance to Plastic Flow of Bituminous Mixtures Using the Marshall Apparatus	1	X	X	X
D1560–63T	D4	2a	Test for Resistance to Deformation and Cohesion of Bituminous Mixtures by Hveem Apparatus	1	X	X	X
D1561–63T	D4	2a	Preparation of Test Specimens of Bituminous Mixtures by the Calif. Kneading Compactor	1	X	X	X
D1856–63	D4	2f	Test for Recovery of Asphalt from Solution by Abson Method	1	X	X	X

TABLE 18—*Continued*

SPEC. NO.	JURISDICTION MAIN	JURISDICTION SUB	TITLE	NO. OF TESTS	PRECISION STATEMENT RANGE	CONFIDENCE LEVEL	DEGREES OF FREEDOM
D2170–63T	D4	4e	Test for Kinematic Viscosity of Asphalts	1	X	X	X
D2172–63T	D4	2f	Test for Quantitative Extraction of Bitumen from Bituminous Paving Mixtures	5	X[d]	X[d]	X[d]
C88–63 [e]	C9	—	Test for Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate	2	X	X	X
C117–62T	C9/D4	5b	Test for Materials Finer than 200 Sieve in Aggregate by Washing	1	X	X	X
C123–63T	C9	—	Test for Light Weight Pieces in Aggregate	1	X	X	X
C131–55	C9/D4	5b	Test for Abrasion of Coarse Aggregate by Los Angeles Machine	1	X	X	X
C136–63	C9/D4	5b	Test for Sieve or Screen Analysis of Fine and Coarse Aggregate	1	X	X	X
C142–55T [f]	C9	—	Test for Clay Lumps in Natural Aggregates	1	X	X	X
C235–62T	C9/D4	5b	Test for Scratch Hardness of Coarse Aggregate Particles	1	X	X	X

[a] 3 tests; 1 unsuited for precision statement, too subjective.
[b] 5 tests; 1 by D5–61 and D402–55 with partial precision coverage; 2 unsuited for precision statement, too subjective.
[c] 1 test; 1 by D95–58 with partial precision coverage.
[d] 4 tests; 1 by D 95–62 with partial precision coverage.
[e] Reagents of C88–63 called for by D692, D694, D1073, D1139.
[f] Called for by D1139.

In considering this recommended format for the precision statement, several comments may be made, as follows:

1. The repeatability section uses positive phrasing (i.e., "should be considered suspect if . . ."), whereas the reproducibility section uses negative phrasing (i.e., "should not be considered suspect unless . . ."). Use of the positive form of phrasing in both sections is recommended as the firmer and more symmetrical.

2. In the range values that appear in the columns headed "Repeatability" and "Reproducibility" in the format, the individual values of the estimate of the standard deviation and the multiplying factor become lost. In the interest of preserving the full integrity (or lack of it) of the original cooperative development data, it is recommended that somewhere in each of the repeatability and reproducibility sections the values of the estimates of the standard deviations in repeatability and in reproducibility be posted as they were used in the cooperative committee development report.

3. In the format recommended by the D2 report the degrees of freedom of the development study data in repeatability and in reproducibility are lost in the range number actually shown. Because a factor of this range number varies with the degrees of freedom (i.e., the number of independent data), it is recommended that, somewhere in each of the sections of repeatability and of reproducibility, the degrees of freedom used in the original development work be posted.

4. Although degrees of freedom give a measure of the quantity of experimental data generated by the cooperative development committee, this factor still fails to adequately describe the balance of the data as between operators, laboratories, and number of replicates. Although X replicates by a single operator generate $(X-1)$ degrees of freedom, the authority of the work would be better supported were $(X-1)$ degrees of freedom to result from several replicate results of a plurality of operators.

The 1960-1962 Ad Hoc Committee of ASTM D4 recognized this weakness in precision statement data, and recommended that the precision statement of each method of test include a condensed table showing (a) number of operators, (b) number of laboratories, and (c) number of replicates per test. These data depict the balance in the development work and make possible an estimate of degrees of freedom, but fail to illuminate the estimates of standard deviations of repeatability and reproducibility. The tabulation recommended by this D2 Ad Hoc Committee should be reinforced by recommendations regarding the estimates of standard deviations and the degrees of freedom of items 2 and 3. The resulting precision statement will still be compact and precise and will then reveal all the essentials of the development work on which the precision statement is based.

A GUIDELINE FOR COOPERATIVE TESTING

The following guideline is advanced for consideration when implementing cooperative testing for development

TABLE 19

ASTM D4 SPECIFICATIONS WITH AMBIGUOUS OR PARTIAL PRECISION STATEMENTS

SPEC. NO.	JURISDICTION		TITLE	NO. OF TESTS	PRECISION STATEMENT					
					RANGE		CONFIDENCE LEVEL		DEGREES OF FREEDOM	
	MAIN	SUB			REPEAT-ABILITY	REPRODUC-IBILITY	REPEAT-ABILITY	REPRODUC-IBILITY	REPEAT-ABILITY	REPRODUC-IBILITY
D5–61	D4	4e	Test for Penetration of Bituminous Materials	1	X	X	X	X	X	X
D6–39T	D4	4g	Test for Loss on Heating of Oil and Asphaltic Compounds	1	—[a]	—[a]	X	X	X	X
D20–56	D4	4d	Test for Distillation of Tar and Tar Products	1	X	X	X	X	X	X
D61–38	D4	4d	Test for Softening Points of Tar Products (Cube-in-Water)	1	—[a]	—[a]	X	X	X	X
D70–52	D4	4h	Test for Sp. Gr. of Road Oils, Road Tars, Asphalt Cements and Soft Tar Pitches	1	—[a]	—[a]	X	X	X	X
D71–52	D4	4h	Test for Sp. Gr. of Asphalts and Tar Products Sufficiently Solid to be Handled in Fragments	1	—[a]	—[a]	X	X	X	X
D243–36	D4	4f	Test for Residue and Specified Penetration	1	X	X	X	X	X	X
D244–60	D4	4c	Tests for Emulsified Asphalts	3	Unsuited for precision statements; too subjective					
				8	X	X	X	X	X	X
				1	X	X	X	X	X	X
				1	—[a]	—[a]	X	X	X	X
				5	D4–52, D5–61, D70–52, D113–44, D128–61					
D402–55	D4	4f	Test for Distillation of Cut-Back Asphalts	1	—[a]	—[a]	X	X	X	X
D632–58	D4	3b	Specification for Sodium Chloride by Official Method of Analysis (for Salt) of the Assoc. of Official Agricultural Chemists	1	—[a]	—[a]	X	X	X	X
D1188–56	D4	2b	Test for Sp. Gr. of Compressed Bituminous Mixtures	1	—[a]	—[a]	X	X	X	X
D1665–61	D4	4d	Test for Engler Specific Viscosity of Tar Products	1	X	X	X	X	X	X
D1754–63T	D4	4g	Test for Effect of Heat and Air on Asphaltic Materials (Thin Film Oven Test)	2	X	X	X	X	X	X
D1851–61T	D4	3d	Testing Concrete Joint Sealers (Cold-Application Type)	2	X	X	X	X	X	X
				1	Unsuited for precision statement; too subjective					
D1853–61T	D4	3d	Testing Jet-Fuel-Resistant Joint Sealer for Concrete (Cold-Application Elastic Type)	4	X	X	X	X	X	X
				3	Unsuited for precision statement; too subjective					
D1855–61T	D4	3d	Testing Jet-Fuel-Resistant Concrete Joint Sealer (Hot Poured Elastic Type)	4	X	X	X	X	X	X
				2	Unsuited for precision statement; too subjective					
D2171–63T	D4	4e	Test for Absolute Viscosity of Asphalts	1	X	X	X	X	X	X

TABLE 19—*Continued*

SPEC. NO.	JURISDICTION MAIN	SUB	TITLE	NO. OF TESTS	PRECISION STATEMENT RANGE REPEAT-ABILITY	RANGE REPRODUC-IBILITY	CONFIDENCE LEVEL REPEAT-ABILITY	CONFIDENCE LEVEL REPRODUC-IBILITY	DEGREES OF FREEDOM REPEAT-ABILITY	DEGREES OF FREEDOM REPRODUC-IBILITY
D88–56	D2	—	Test for Saybolt Viscosity	1	X	X	X	X	X	X
D92–57	D2	—	Test for Flash and Fire by C.O.C.	2	X	X	X	X	X	X
D93–62	D2	—	Test for Flash by Pensky-Martens Closed Tester	1	X	X	X	X	X	X
D95–62	D2/D4	4f	Test for Water in Petroleum and Other Bituminous Products	1	X	X	X	X	X	X
D271–58	D5	—	Sampling and Analysis (Ash) of Coal and Coke	1	Sampling procedure unsuited for precision statement					
				1[b]	X	X	X	X	X	X
D445–61	D2	—	Test for Kinematic Viscosity	1	X	X	X	X	X	X
D1310–63	D1	—	Test for Flash Point of Volatile Flammable Materials by Tag Open Cup	1	X[c]	X[c]	X[c]	X[c]	X[c]	X[c]
C29–60	C9	—	Test for Unit Weight of Aggregate	1	—[a]	—[a]	X	X	X	X
C127–59	C9/D4	5b	Test for Sp. Gr. and Absorption of Coarse Aggregate	1	—[a]	—[a]	X	X	X	X
C128–59	C9/D4	5b	Test for Sp. Gr. and Absorption of Fine Aggregate	1	—[a]	—[a]	X	X	X	X

[a] Ambiguous.
[b] Ash.
[c] See *ASTM Proc.*, 56: Ann. III of D1.

TABLE 20

ASTM D4 SPECIFICATIONS NEEDING AND HAVING FULL PRECISION STATEMENT

SPEC. NO.	JURISDICTION MAIN	SUB	TITLE	NO. OF TESTS	PRECISION STATEMENT RANGE REPEAT-ABILITY	RANGE REPRODUC-IBILITY	CONFIDENCE LEVEL REPEAT-ABILITY	CONFIDENCE LEVEL REPRODUC-IBILITY	DEGREES OF FREEDOM REPEAT-ABILITY	DEGREES OF FREEDOM REPRODUC-IBILITY
D36–62T[a]	D4	4e	Test for Softening Point of Asphalts and Tar Pitches	1	X	X	X	X	X	X

[a] Lists number of samples, number of laboratories and replicates per test.

of methods of test. Ordinarily, in ASTM practice it is not too difficult to obtain several replicate tests from any given operator once that operator and his laboratory are induced to take part in the cooperative testing effort. Thus, sufficient data for repeatability evaluation are not too difficult to come by, but it frequently is quite difficult to enroll sufficient laboratories for an adequate evaluation of reproducibility variability. In this latter case, the degrees of freedom of the reproducibility system are one less than the number of laboratories and these cannot be increased, as in the case of repeatability, by having more replicate tests run by each laboratory. Something on the order of at least ten different laboratories should be enlisted for an adequate reproducibility evaluation. This may be realized by noting the rate of change of the range multiplying factor with change in degrees of freedom.*

If a sufficient number of qualified laboratories cannot be enlisted at the time of organization of the cooperative testing program, perhaps the lesser number of interested laboratories can be induced to conduct a second or a third series of tests at some interval (six months to a year) after

* *ASTM Proceedings* 53:382 1953), Table 1.

the first series. If different operators, and perhaps different assemblies of apparatus, are deliberately used in the second and third series, these repeat operations would fulfill most of the qualifications of "different" laboratories, and thus the effective degrees of freedom in reproducibility of the testing program can be built up.

SURVEY OF PRECISION STATEMENTS

All specifications under the individual or joint jurisdiction of ASTM Committee D4, and those under the individual jurisdiction of other ASTM committees but used by methods of test under the jurisdiction of ASTM Committee D4, have been analyzed with respect to their precision statements.

This analysis does not concern itself with whether or not the variabilities of the test results are sufficiently narrow for the purposes intended. It does concern itself with the following:

1. Whether or not the specification in question does or does not require a precision statement.
2. If it does, whether or not it distinguishes repeatability or reproducibility conditions.
3. In either case, whether or not it states a range within which test results by operators skilled in the art are to be regarded as statistically compatible.
4. In either case, whether or not the confidence level is defined within which this range or permissible variability is applicable.
5. In either case, whether or not the number and balance of the experimental data (with respect to operators, laboratories, and replicates of testing) on which the precision statement is based (i.e., on its degrees of freedom) are displayed.

It has been found that there are 102 specifications either (a) under ASTM Committee D4 jurisdiction directly or jointly with another ASTM committee, or (b) under other than D4 ASTM committees, whose methods of test have been adopted by ASTM Committee D4.

Not all of these 102 specifications require precision statements. Some (for example, D8-63, comprising the definition of terms) are by their inherent nature unsuited for precision statements. Others (for example, D241-43) consist of a listing of other specifications which describe methods of test and which may, and usually do, require precision statements. The specifications of this D241-43 type are not amenable to precision statements. The 37 specifications that deal with the definitions of terms or the testing of other specifications and therefore do not require precision statements are listed in Table 17. Those specifications given as operating methods under these main specifications have been classified with respect to precision statement coverage in Tables 18, 19, and 20.

Of the 65 specifications remaining after subtraction of the 37 of Table 17, another 37 (Table 18) fall into a classification in which precision statements are needed but are not present. This last group of 37 specifications includes 62 tests (gross) or, after elimination of what are essentially duplicates, some 48 different operating methods, none of which have precision statement coverage. Many of these are old and commonly used methods of test, and their lack of precision statement coverage is disconcerting.

Of the remaining 28 specifications dealing with test methods, 27 are in a classification in which some precision coverage is shown (Table 19), but on an ambiguous or partial coverage basis. Some 60 tests (gross) are required by these 27 specifications, but elimination of those which are essentially duplicate tests reduces this number to 48. In 11 of these test methods a precision range is given, but it is ambiguous as to whether conditions of repeatability or of reproducibility are under consideration. These 11 ambiguous cases are also lacking in exposition of the confidence level involved, and in data from which degrees of freedom of the data may be read or inferred. Statements regarding all the tests involved in these 27 specifications are lacking in information from which the adequacy of the development data and their degrees of freedom may be evaluated.

Table 20 should contain those specifications having full precision statement coverage with respect to range, confidence level, and degrees of freedom (and balance of experimental design) for both repeatability and reproducibility conditions. Unfortunately, the exhibit is limited to one specification, which involves only one test method.

CHAPTER ELEVEN

CURRENT STATUS AND FURTHER DEVELOPMENT OF PRACTICAL AND REALISTIC SPECIFICATIONS

DEFECTS OF CURRENT SPECIFICATIONS

Most highway agencies are rather slow to grasp newly developed techniques for preparing specifications. Because of political pressures, or perhaps the unwillingness to take a chance with that which has not already been proved, some agencies have been content to go along with the status quo. It has only been in recent months that certain specification items have taken on a "new look" by incorporating more realistic procedures for determining what characteristics to specify, what level should be specified, and how the specification should be enforced. Assumptions have prevailed in the industry that highway engineers in the past were:

1. Taking advantage of technological developments in preparing specifications.
2. Specifying the most efficient and up-to-date construction techniques.
3. Outlining requirements that could be met with a reasonable degree of assurance.
4. Giving proper tolerances that would allow for normal variations present in all good quality work and materials.

However, recent comprehensive engineering studies have disclosed that construction and materials specifications do not always fulfill these criteria and all segments of the highway industry have come to realize that more scientific and exacting techniques must be developed for preparing specifications. Otherwise the highway system can not keep a realistic pace with the increasing traffic demands.

THE STATISTICAL APPROACH

One of the most practical and significant approaches known at this time is the application of statistical concepts, as discussed in Chapter Three, in choosing numerical limits for measurable properties of specification items, as well as for formula tolerances within which measurements can reasonably be expected to fall a given percentage of the time.

Few highway engineers have had the necessary training to fully understand the proper application of complex statistical principles. However, the fundamentals can be acquired with a reasonable amount of study and effort, and once understood, the application of these basic principles to highway problems is not difficult. A lack of knowledge on this subject may be the reason for some degree of resistance to the statistical approach. It has been observed that various state highway officials across the country with even a little statistical knowledge are enthusiastic regarding the potentialities for improving specifications by the application of statistical methods.

A number of state highway organizations, as well as federal agencies, have established statistical sections of sorts, to investigate and evaluate the practical applications to highway problems. There have been a few pioneers in this field (Pennsylvania, California, Illinois Toll Road Commission) but the majority of the states and public agencies have taken a "wait and see" attitude. Those who have ventured into this untried area have had some rather surprising revelations when their test data were statistically analyzed and plotted in graph form. It then became apparent that many of the specification requirements were unrealistic and required revision to make proper legal and engineering enforcement possible.

Statistical methods provide a tool for calculating the probability that a given percentage of results will fall within a stated limit or limits and serve as a guide for assigning realistic numerical values to these limits. They are also a valuable aid to the engineer in determining those areas which require special studies for the purpose of decreasing variability. They are useful in the control of materials production, in construction control, in inspection and testing, in determining realistic tolerances, and a host of other purposes.

Although the full potential of this science has not yet been realized, there are many efforts under way throughout the highway industry to educate key personnel in the use of the more fundamental statistical calculations. Typical of these efforts is the one-week short course on statistical quality control which was held at the University of Virginia during the spring of 1964 and again in December 1964. Attendees at this course included representatives from state highway departments, the Bureau of Public Roads, the Corps of Engineers, consulting engineering firms, industrial organizations, and a number of people from the educational field interested in adapting statistical methods to their particular specialty. In this course an attempt was made to show specific applications of simple statistical principles to some of the more common on-the-job problems, such as base density control, moisture control, compressive strength of concrete cylinders, and similar indices of construction quality. A growing interest and hunger for knowledge in the statistical field was quite evident and most of the persons present reported using these concepts to some degree, even though such use was limited, in most cases, to investigating degree of compliance with current requirements or to the interpretation of test data.

Within the last two years several contractor schools, designed to acquaint supervisory construction personnel with some of the advanced techniques for design and control, have been available. Each of these schools has been of one-week duration, with a very intensive program of study that included several night problem sessions. All participants showed enthusiastic response and eagerness to continue in advanced studies beyond the scope of the schools.

RESEARCH EFFORTS

A number of research projects have been undertaken across the nation to determine the statistical parameters related to local needs. As an example, the West Virginia State Road Commission has recently begun a study of its historical test data, coupled with statistically designed experiments, to determine numerical limits for use in realistic specifications. Many other states have related projects under way such that the whole spectrum of highway materials and construction methods is receiving similar scrutiny. As the results of these efforts are translated into highway specifications, highway engineers are beginning to realize the full usefulness of these new-found statistical tools. Special statistical sections have been established in many highway organizations, including the Bureau of Public Roads. These sections vary in size from a single individual who spends only a portion of his time on these studies, to several individuals who devote full-time effort. One of the major decisions to be resolved in this area is whether to hire trained statisticians and then give them the necessary highway engineering training or to attempt to provide highway engineers with the necessary statistical training. As a matter of practicality, the latter course has been followed. As the application of these concepts grows, and as the more complex principles are employed, it is quite likely that the services of academically trained statisticians will be necessary.

The Office of Research and Development of the Bureau of Public Roads, recognizing the advantages to be gained through such an approach, awarded a research contract in early 1963 to develop a feasible plan for adapting statistical methods to highway construction problems. This study resulted in a report entitled "A Plan for Expediting the Use of Statistical Concepts in Highway Acceptance Specifications," which was completed in August 1963. Subsequently, the Bureau held a series of regional meetings throughout the country to implement certain recommendations in the report that would provide engineering data for future specifications. Approximately 30 states have undertaken statistical programs to varying degrees in an attempt to determine parameters required for defining practical and realistic tolerances on most highway materials and construction items. Full value of these studies cannot be assessed until all data have been assembled and evaluated, which may take from one to three more years. In any event, a movement has been undertaken which will have a significant effect on future specifications.

Another segment of public domain has made a study of variability among contractors performing similar work and has rated each contractor according to the magnitude of his variations. These ratings are published at periodic intervals. As a result, a competitive spirit has been created wherein contractors continually strive to decrease or eliminate those variables affecting their ratings.

In addition to the research activities previously cited, two projects included in the National Cooperative Highway Research Program, identified as HR 10-2 "Evaluation of Construction Control Procedures," and HR 10-3 "Effects of Different Methods of Stockpiling and Handling Aggregates" involve determination of statistical parameters.

Project 10-2 is primarily concerned with variations in aggregate gradation at different points in the production stream. The first phase of Project 10-3 has been completed and a report has been published (NCHRP Report 5, 1964). In this investigation ten stockpiling methods were studied, using crushed stone and various types of construction equipment. A numerical rating system was developed for comparing the efficiency of one stockpiling procedure with another. A continuation of the project has been approved and will involve the construction of test sections to determine the degradation effects on aggregate bases under various types of handling and compaction equipment. Additional types of aggregate will be used for further stockpiling studies.

SIGMA BANK

Throughout this report there has been frequent reference to normal variability of materials and construction items. The determination of what constitutes normal variability is neither an easy job nor one which can be accomplished overnight. Programs currently in being to collect such data have been previously described. Most of these studies are under the joint direction of the Bureau of Public Roads and various state highway departments.

How can the data be used to best advantage once they are collected? The answer to this question is perhaps the key to effective use of statistical parameters for preparing realistic specifications. As far as is known, no central coordinating agency has been established for collection, analysis, and dissemination of these data. Obviously, unless the data are made available to those who have a use for them they cannot serve their intended purpose. In addition to the special statistical projects under way, a wealth of historical data that could provide a preliminary estimate of sigma values is stored in the files of practically every highway agency.

In recognition of the need for some type of storage system, at least one agency* has started the development and operation of a sigma bank. To implement this system, data from many sources are analyzed and statistical parameters are calculated. These data, together with all other information regarding details of the test or construction item (type of material, source, temperature, forming and curing conditions, agency performing test, etc.) are entered on IBM cards for rapid recovery. The ultimate goal of such a sigma bank is to provide normal values of sigma (standard deviation) that might be expected under a given set of conditions. It should be realized that the value of sigma for each material or process is not a constant because the many variables affecting each measurement influence the magnitude of sigma. As long as this limitation is recognized, sigmas acquired from any such storage system can be a valuable aid to the specification writer.

A LOOK AT THE FUTURE

American Practice

The project investigators are not aware of the existence of any State Highway Standard Specifications Book that

* Miller-Warden Associates, Raleigh, N.C.

has been prepared on the basis of the concepts presented herein. There are, however, cases involving a limited number of materials or methods which are based on some portion of these guidelines.

Foreign Practice

A review of the literature indicates that the British Road Research Laboratory makes extensive use of the statistical approach in investigating highway problems. Attention is now being focused on methods of developing specifications for bituminous mixtures which will minimize arguments between engineers and contractors as to the degree of compliance attained. Investigations as to the quantity of testing required for quality control on large highway projects are also under way.

FUTURE IMPLEMENTATION OF THE DEVELOPMENT OF PRACTICAL AND REALISTIC CONSTRUCTION SPECIFICATIONS

This report presents several new ideas, new approaches, and new methods. Most of these are controversial matters and it is unlikely that any will be adopted in toto without further discussion and investigation. Before practical and realistic specifications are actually published and enforced, present attitudes may have to be changed. This change can be brought about only by better understanding in three broad areas, as described in the following.

Engineer-Contractor Relationships

This area includes recognition of the necessity for increased clarity of specifications, elimination of ambiguous phrases, definition of words and construction terms, and the definition of a legal and moral basis for decisions by the engineer, that will be acceptable by all parties concerned.

The contractors' potential for effecting economies in construction should be appreciated and every local contractor should be given frequent opportunity to challenge requirements that may be nonessential and which affect costs. At the same time, contractors must be made aware that they are responsible for quality control and that they must be prepared to assume the total load that is now shared with agency engineers.

Improved relationships in this area can be brought about by better communications. Highway departments that do not already have such a program should be encouraged to schedule formal engineer-contractor meetings twice yearly, before and after the construction season. Such meetings should be conducted on the basis of a prepared agenda to which all interested parties should be invited to contribute. The published minutes of such meetings should do much to convince the taxpayer that both the construction industry and the professional engineers have a sincere interest in providing better roads at lower cost.

Statistical Concepts

As discussed in Chapter Five, some engineers are reluctant to accept the concept that measurements on a lot will have some average value, but that there would be a wide range of values if measurements were made on all the small subdivisions. The idea persists that a test on any small portion, or on a so-called representative sample, shows the true quality of the lot, and that if any test result is not within arbitrary limits, there is something wrong with the lot, or with the sampling. The conversion of such skeptics will require not only an understanding of the rudiments of statistics, but also considerable evidence that statistical methods do apply to construction situations in the real world. This evidence may come from published papers by fellow engineers whom they know and respect, or from personal contact with programs concerning probability sampling of actual construction that they know is of acceptable quality. First, there must be available an easily-read manual that explains the basic concepts and methods of statistics in simple language. Secondly, there must be available a great deal of information on what variation of measurements can be expected in acceptable construction, and on the sources of this variation. In addition to the programs initiated by the Bureau of Public Roads, highway departments should be encouraged to set up combined training and research programs wherein the variance associated with materials, types of construction, sampling procedures, and test methods, can be measured and analyzed by properly designed experiments.

The exchange of information effected by the publishing of technical papers based on these programs will probably provide more impetus to the acceptance of statistical concepts than any other factor.

Essential Characteristics

Before really practical and realistic specifications for a material or item of construction can be written, the characteristics essential to performance, and the requirements for these characteristics, must be known. Preferably, the measurement value by which the characteristic is evaluated should be in such form that it can be expressed as a single number, adaptable to statistical treatment. Although it is commonly assumed that the characteristics currently controlled by specification requirements are those which are essential, this is not necessarily the case. Recent investigations have upset many entrenched ideas, and continued effort should be made to replace requirements based on theory or assumption by those that make a real difference in performance and longevity. A listing and publishing of requirements (by some agency recognized by the highway industry) suitable for a value engineering analysis would focus interest on this type of research.

A closely related field is the development of rapid test methods that will actually provide assurance of quality control. It is realized that there is a great deal of current activity and interest in such test methods, but those known to be under development have a limited application. Additional research based on designed experiment is needed to establish the relative value of rapid methods which make possible a large number of approximate measurements at a critical point in production or construction, in comparison with methods which yield one, or only a few, precise measurements after the opportunity for correction has passed.

APPENDIX A

GLOSSARY AND NOTATION

ACCEPTABLE QUALITY LEVEL — The maximum percent defective that can be considered satisfactory as a lot average.

ACCEPTANCE PLAN — An agreed upon method of taking and making measurements on a sample, for the purpose of determining the acceptability of a lot of material or construction.

ACCURACY — The agreement between a measured value and a true value.

AESTHETIC VALUE — The worth of an item of construction in terms of pleasing appearance or gratifying performance.

ANALYSIS OF VARIANCE (ANOV) — A mathematical method of isolating causes of variation.

ASSIGNABLE CAUSE — A relatively large factor, usually due to error or process change, which contributes to variation and whose effects are of such importance as to justify time and money required for its identification.

ATTRIBUTE — A characteristic which, by its presence or absence, classifies a unit or segment as being acceptable or defective.

AVERAGE ($\overline{X}$) — A measure of central value which usually refers to the arithmetic mean.

BIAS — An error, constant in direction, common to each of a set of values, which cannot be eliminated by any process of averaging.

BUYER'S RISK — The probability of accepting poor or unsuitable material or construction as a result of using a particular acceptance plan.

COST VALUE — The price of a collection of units of material or an item of construction, having specified characteristics, in terms of money, proportion of available manpower, or depletion of natural resources.

CRITICALITY — The classification of various factors of specifications as they affect safety, performance, or durability.

DATA — Measurements collected for a planned purpose and suitable for the inference of conclusions.

DEFECT — A fault or flaw that affects a material or item of construction with respect to specification requirements.

DEFECTIVE — Having one or more defects.

DENSE-GRADED — Continuously graded from a specified maximum size to dust, so as to have a low aggregate voidage.

DISTRIBUTION — An arrangement of data which shows the frequency of occurrence of each successive individual measurement or range of measurements.

DISTRIBUTION CURVE — The smooth curve that encloses an arrangement of data which shows the frequency of occurrence.

EXPERIMENTAL ERROR — The difference between measurements on two identically treated experimental units.

FINENESS MODULUS (FM) — The sum of the percentages in the sieve analysis of the aggregate divided by 100. The sieve analysis is reported as percentages by weight coarser than each of the U.S. Standard Sieves No. 100, 50, 30, 16, 8, 4, ⅜ in., ¾ in., 1½ in., and 3 in.

FINES — Usually mineral particles which are less than 74 microns in size (passing a No. 200 standard sieve).

HISTOGRAM — A type of bar chart which displays in terms of area the relative number of measurements of different classes. The width of the bar represents the class interval; the height represents the number of measurements.

HUDSON $\overline{A}$ — The term for a factor which expresses the relative coarseness of an aggregate gradation in a single number. It is found by summing the percentages passing the 1½ in., ¾ in., ⅜ in., No. 4, No. 8, No. 16, No. 30, No. 50, No. 100, and No. 200 standard sieves and dividing by 100.

INCREMENTS — Small portions of a material taken to form a sample.

INHERENT VARIANCE (σ^2_a) — The effect of random or inconsequential causes in a given process.

LOT — An isolated quantity of material from a single source.

A measured amount of construction assumed to be produced by the same process.

LOT ACCEPTANCE PLAN — See acceptance plan.

MEAN — Average of all possible measurements made on a lot; often used as the desired value.

MEAN SLOPE VARIANCE — The average of the slope variances for the inner and outer wheelpaths of a pavement.

NON-CENTRAL t DISTRIBUTION — A nonsymmetrical or skewed distribution of t values occurring when the true mean of a lot is not the desired (assumed) mean.

NORMAL CURVE — A curve, having a bell-shaped form, that is determined by values of $\overline{X}'$ and σ' and is often used to describe the distribution of individual measurements.

NORMAL DISTRIBUTION CURVE — See normal curve.

OPEN-GRADED — A well-graded aggregate containing little or no fines, with a high percentage of aggregate voids.

OPERATING CHARACTERISTICS — A graphical presentation showing the buyer's and seller's risks associated with lots having stated mean values.

OPERATING CHARACTERISTICS (OC) CURVE — A graphical presentation of a sampling plan which shows the relationship between the quality of a lot and the probability of its acceptance or rejection.

PARAMETER — A constant or coefficient that describes some characteristic of the distribution of a series of measurements.

POORLY-GRADED — Containing a disproportionate quantity of particles of some sizes.

PRECISE — See precision.

PRECISION — The degree of agreement among a series of measurements.

PRESENT SERVICEABILITY INDEX (PSI) — A mathematical combination of values obtained from certain physical measurements of a large number of pavements, so formulated as to predict a serviceability rating for those pavements within prescribed limits.

PROBABILITY SAMPLE — One in which every increment in the lot has a known chance of inclusion.

PROBABILITY SAMPLING — A method of making use of the laws of chance for the purpose of selecting increments on which measurements are to be made.

RANDOM — Without aim or reason, depending entirely on chance.

RANDOM DISTRIBUTION — A distribution of values resulting from chance alone.

RANDOM NUMBER — A number selected entirely by chance as from a table of random sampling numbers.

RANDOM SAMPLE — A sample in which each increment in the lot has an equal probability of being chosen.

RANGE — The difference between the largest and smallest measurements in a set of data.

REPEATABILITY — The range within which repeated measurements are made by the same operator on the same apparatus. Essentially, the precision of the test.

REPRESENTATIVE SAMPLE — In highway terminology, a nonrandom sample taken on a judgment basis and which, in the opinion of the sampler, represents an average condition of a material or an item of construction.

SAMPLE — A small part of a lot which represents the whole.

A sample may be made up of one or more increments or test portions.

SEGMENTS — Arbitrary divisions of a lot, which may be either real or imaginary.

SEGREGATE — SEGREGATION — Separation of portions of a mixture from the mass. In a stockpile consisting of a mixture of large and small particles of aggregate, the large particles tend to segregate by separating from the combination. In concrete, segregation occurs when the coarse aggregate separates from the combination of coarse aggregate, fine aggregate, cement, and water.

SELLER'S RISK — The probability of having acceptable material or construction rejected as a result of using a particular acceptance plan.

SIGMA BANK — A system of collecting, storing, and retrieving information pertaining to the variance of measurements on samples of materials or items of construction.

SIGMA PRIME (σ') — The true value of the standard deviation when all possible measurements on a lot are considered.

SKIP-GRADED — Lacking one or more fractional particle sizes.

SLOPE VARIANCE (SV) — A measure of the variations from the mean in a single wheelpath of a pavement; an indication of the smoothness of that pavement.

STANDARD DEVIATION (σ) — A term indicating the value calculated from the differences between the individual measurements in a group and their average.

STANDARD SIEVES — Those screens used in aggregate gradation analysis in which the size of the openings is successively halved as the sizes decrease. Included are: 1½ in., ¾ in., ⅜ in., No. 4, No. 8, No. 16, No. 30, No. 50, No. 100, No. 200.

STATISTICS — The science which deals with the treatment and analysis of numerical data. Also a collection of numerical data.

STRUCTURAL NUMBER (SN) — A linear combination of (flexible) pavement components that expresses pavement design as a single number.

TABLE OF RANDOM NUMBERS — A table arranged so that every digit has an equal chance of occurrence.

TEST PORTION — The part of a sample actually tested. Usually obtained by reducing the sample by quartering, riffling, or taking an aliquot quantity.

TYPE I ERROR — A decision, made on the basis of sampling, to reject a lot of acceptable quality.

TYPE II ERROR — A decision, made on the basis of sampling, to accept a lot of unacceptable quality.

UNIFORMITY COEFFICIENT (C_u) — The ratio of the diameter at the 60 percent finer point to that at the 10 percent finer point on the gradation curve.

USE VALUE — The obtained characteristics and qualities of a material, product, or item of construction, associated with accomplishment of functional performance.

VALUE ENGINEERING — An organized effort directed at analyzing the function of highway components with the purpose of achieving the required function at the lowest possible cost.

VARIABLE — A measurement that can have a series of different values.

VARIANCE — A measure of dispersion found by adding the squares of individual deviations from their average and dividing by the number of them less one.

VARIATION — Differences in measured values of a characteristic within a stable pattern due to chance, or outside this normal pattern due to assignable cause.

WELL-GRADED — Having a frequency of occurrence of particle sizes approximating a normal distribution.

$\bar{A}$ — See Hudson $\bar{A}$.

ANOV — See analysis of variance.

AQL — See acceptable quality level.

α — The statistical risk of making a type I error.

β — The statistical risk of making a type II error.

C — The amount of cracking per 1,000 sq ft of pavement, measured in linear feet for rigid (PC concrete) pavement and in square feet for flexible (bituminous concrete) pavement.

C_u — Uniformity coefficient, the ratio of the diameter at the 60 percent finer point to that at the 10 percent finer point on the gradation curve.

Δ — Degree of accuracy, or the tolerance which is the maximum allowable difference between results to be obtained from the measurements and the true value.

$\overline{d}$ — The average size of particles passing a sieve having opening of size d_1 but retained on a sieve having openings of size d_2.

FM — See fineness modulus.

$\overline{g}$ — The average particle weight, in grams, of the grains of aggregate within a range of sizes.

k — The modulus of subgrade reaction.

K_p — The number of standard deviation units between the average values of the measured characteristic in acceptable and unacceptable construction or material $\left(= \dfrac{\overline{X}'_g - \overline{X}'_p}{\sigma}\right)$.

L — Lower specification limit.

M — A factor used to convert the sample standard deviation (s) to the range (R); $s = M\,R$.

n — The number of measurements in a set of data.

P — percent by weight passing a designated sieve.

P — bituminous patching (in PC concrete pavement), in sq ft per 1,000 sq ft of pavement area.

P_g — The approximate probability of rejecting acceptable material or construction having the desired mean value ($\overline{X}'_g$) of the measured characteristic.

P_L — The percentage of the total possible measurements on a lot whose values are equal to or greater than the lower tolerance value (L).

P_p — The probability of rejecting unacceptable material or construction having a mean value ($\overline{X}'_p$) of the measured characteristic which denotes the material or construction as poor or undesirable.

P_U — The percentage of a lot whose values are equal to or less than the upper tolerance value (U).

$P_{U,L}$ — The percentage of a lot lying between the L and U tolerance limits ($= P_U + P_L - 100$).

PSI — See present serviceability index.

Q_L — Quality index, determined by subtracting the lower tolerance limit (L) from the average value ($\overline{X}$) and dividing this result by R (or by $\overline{R}$, where $n \geq 10$).

Q_U — The quality index determined by subtracting the average value ($\overline{X}$) from the upper tolerance limit (U) and dividing the result by R (or by $\overline{R}$, where $n \geq 10$).

R — The range, which is the difference between the largest and smallest measurement in a set of data.

$\overline{R}$ — The average of a number of ranges.

R — Ratio of percentage passing a standard sieve to percentage passing the next smaller standard sieve.

$\overline{RD}$ — Mean depth of rutting in both wheelpaths, in in. under a 4-ft straightedge.

s — An estimate of the true standard deviation (σ').

S_b — The percentage of asphalt by volume in a mixture of asphalt and aggregate.

SN — See structural number.

SV — See slope variance.

$\overline{SV}$ — Mean slope variance.

σ — Standard deviation, which is a measure of the dispersion of measurements from their average and is an estimate of the true value (σ'); the square root of the sum of the squares of the deviations from their average, divided by their number less one.

σ' — The true value of σ.

σ_a — The standard deviation due to inherent variance.

σ_o — The overall standard deviation of measurements.

$\sigma_{\bar{x}}$ — The standard deviation of sample average values.

$\sigma^2{}_a$ — The inherent or actual variation in a material or product despite the closest practical control of variables.

$\sigma^2{}_b$ — Within-batch variance, where a batch is some segment of a lot such as a mixer-truck load of concrete or a load of subbase material. The value depends largely on the method of collecting the sample and on the tools used.

$\sigma^2{}_l$ — Within-lot variation due to long-term segregation.

$\sigma^2{}_o$ — Overall variance.

$\sigma^2{}_s$ — Within-segment (batch) variation due to local segregation.

$\sigma^2{}_t$ — Variation due to testing error.

t — A distribution slightly more spread out than a normal distribution; used when the true standard deviation (σ') can not be assumed to be known.

T — A test criterion for outliers, expressed in standard deviation units.

T_a — The allowable tolerance, which is the difference between the desired mean ($\overline{X}'_g$) and the mean of a lot of poor or unacceptable material ($\overline{X}'_p$).

T_s — The specification tolerance, which is the difference between the average value of a lot of poor or unacceptable material ($\overline{X}'_p$) and the nearest specification limit (either U or L).

U — Upper specification limit.

VMA — The percentage of voids, in a compacted mixture of asphalt and aggregate, not filled with asphalt.

$\overline{w}$ — Average particle weight (in same units as test-portion weight) of the grains of aggregate within a range of sizes.

W — Total sample (test portion) weight, which is the weight of all particles placed on the sieves.

$\overline{X}$ — The average, or arithmetical mean, found by dividing the sum of n measurements by n.

$\overline{X}'$ — The mean of a distribution.

$\overline{X}'_g$ — The mean of a distribution of measurements on a lot of acceptable material or construction.

$\overline{X}'_p$ — The mean of a distribution of measurements on a lot of poor or unacceptable material or construction.

X_i — An individual measurement from a series of such measurements.

z — Distance from the centerline to a point on the base of the normal distribution curve, expressed in standard deviation units.

APPENDIX B

SUMMARY OF STATE HIGHWAY DEPARTMENT CONCRETE PAVEMENT AGGREGATE STANDARDS

The following two tables, representing summaries of state highway department standards for fine and coarse aggregates used in concrete pavements, are from pages 4 and 6 of a copyrighted publication of the Portland Cement Association entitled "A Charted Summary of Concrete Road Pavement Standards Used by State Highway Departments —1963," and are reprinted here by permission of the Association.

The introductory statement of the "Summary" contains the following:

> "This publication tabulates in convenient form for reference a summary of the major items of the standards for concrete pavements in use by the highway departments of 47 states and the District of Columbia. The summary represents the specifications of each state highway department in effect for the 1963 construction season.
>
> "Thickness, crowns, widths, etc., are features of design for a particular project and are specified in the plans for the improvement. Therefore, there are no standards for these items in any state and they cannot be presented in summarized form within the limits of this tabulation. . . .
>
> "Wherever possible, an effort has been made to distinguish between specifications for the Interstate System, the Primary System and the Secondary System.
>
> * * *
>
> "While all possible care has been taken to ensure the accuracy of this summary, no responsibility can be assumed by the compilers for errors or omissions."

State	FINE AGGREGATE										
		Grading: per cent by weight passing each sieve (Numbers)								Maximum per cent silt allowed by weight	Notes
	3/8"	4	8	16	20	30	50	100	200		
Col. No.	27	28	29	30	31	32	33	34	35	36	37
ALA.	100	95-100	80-100	60-90	N	N	12-30	2-10	N	2	Must pass sodium sulfate test
ARIZ.	100	95-100	N	45-80	N	N	10-30	2-10	0-4	N	Mortar test AASHO T-71
ARK.	100	95-100	70-95	45-80	N	20-60	5-30	0-5	N	2	
CAL.	100	90-100	65-95	45-70	N	25-45	10-20	2-8	0-4	N	Sand equivalent 70% minimum Natural sand 50% minimum
COLO.	100	95-100	N	45-80	N	N	10-30	2-10	N	3	AASHO T-104 loss @ 5 cycles <10% or 5-year satisfactory service record
CONN.	100	95-100	N	45-80	N	20-55	10-30	2-10	N	3	
DEL.	100	95-100	N	N	N	5-30	N	1-7	N	4	Color test—AASHO T21—plate 3—if less than 1% past #100 add 24# inert filler per CY or A/E agent
D. of C.	100	95-100	N	45-80	N	N	10-30	2-10	N	3	
FLA.	100	95-100 (0-5)	85-100 (0-15)	65-97 (3-35)	N	25-70 (30-75)	5-35 (65-95)	0-5 (95-100)	N	3	FA specified in "% retained on"—(lower numbers)
GA.	100	95-100	N	45-95	N	N	8-30	1-8	N	3*	*When evenly distributed
HAW.	100	95-100	50-85	32-60	N	N	15-30	2.5-12.5	N	N	Combination of crusher screenings & calcareous beach sand. Sand equivalent 70% minimum. Sodium sulfate 5 cycles less than 10% loss. Mortar Test AASHO T-71
IDAHO	100	95-100	N	45-80	N	N	10-30	2-10	0-1	N	Total of all deleterious substances not to exceed 1% by weight
ILL.	100	95-100	N	45-80	N	N	5-25 SP15-30	0-10	N	3	
IND.	100 100	95-100 100	80-95 75-95	— 50-75	N	20-50 —	5-20 8-25	0-5 1-17	— 0-5	≯2 ≯3	#14 sand #1 #14 sand #2 } OC
IOWA	100	95-100	75-100	N	N	N	N	N	0-1½	1½	Not more than 40% retained between any two sieve sizes—4, 8, 16, 30, 50, 100
KAN.	100 100	95-100 —	— 70-97	60-80 45-75	N	— 25-50	10-20 —	0-5 2-15	N	2 4	FA—1 FA—2 Being revised
KY.	100	85-100	N	40-80	N	N	5-25	0-5	N	3	Clay, coal and other deleterious substances ≯1%
LA.	100	95-100	N	65-90	N	N	7-30	0-7	N	3	Coal or lignite <0.25% Maximum clay lumps <0.50%
ME.	100	95-100	N	50-85	N	N	10-30	2-8	N	N	
MD.	100	95-100	N	45-80	N	20-60	10-30	1-8	N	3	All deleterious material ≯5%
MASS.	100	95-100	N	55-80	N	N	10-25	2-8	N	2	≯3% loss by washing
MICH.	100	95-100	65-95	35-75	N	20-55	10-30	0-10	N	N	≯3% loss by washing
MINN.	100	95-100	75-100—CA15 85-100—Others	55-85	N	30-60	5-30	0-10	0-2	2	
MISS.	100	95-100	80-100	50-90	N	30-70	3-30	0-5	0-1	1	
MO.	100	95-100	N	N	40-75	N	5-30	0-10	N	2	Natural sand
MONT.	100	95-100	65-95	35-80	N	N	5-30	0-10	N	3	Coal or lignite <0.25%, max. clay lumps <0.5% Shale & light particles <1%, other <1%, sum <4%
NEB.	N	90-100 75-95	N	N	30-50 20-40	20-40 15-30	N	0-5 0-5	0-3 0-3	N	47A, 47C 47B #10 55-75 45-65 clay lumps ≯0.5% by weight
N.J.	95-100	80-100	N	N	N	20-50	12-25	N	0-5	N	Maximum 4% elutriable material % passing #10 sieve 20-60
N.M.	100	95-100	N	45-80	N	N	10-30	2-10	0-3	N	Clay, coal & other deleterious substances ≯1.0% magnesium sulfate soundness (AASHO T-104) ≯12.0
N.Y.	100	100	N	55-75	N	N	10-30	1-8	2*	N	
N.C.	100	95-100	80-100	45-95	N	25-75	8-30	0.5-6	0-3	3	
N.D.	100	95-100	N	45-80	N	N	10-30	0-10	≯3	N	Clay lumps ≯0.5% by wt., coal & lignite ≯1.0% Other deleterious materials ≯2% by wt.
OHIO	100	95-100	70-95	45-80	N	25-60	10-30	1-10	N	4	Manufactured sand not permitted, AASHO T102, max. loss 10% in 5 cycles
OKLA.	100	95-100	N	45-85	N	N	5-30	0-7	N	3	Clay lumps (wet on #4) ≯0.5%, coal & lignite ≯1.0% Lightweight particles (sp. gr. <1.95) ≯1.5%
ORE.	100	90-100	N	45-75	N	25-50	5-30	0-5	N	3	
PENN.	100	90-100	70-92	50-80	N	30-65	10-30	1-8	N	3	Soundness $NaSO_4$—10% loss in 5 cycles
R.I.	N	100	N	N	30-60	N	7-30	3-8	N	3	
S.C.	100	96-100	75-100	55-98	N	25-75	8-30	0-7	0-4	4	
S.D.	100	95-100	N	45-80	N	N	10-30	2-10	N	N	≯1.5% minus #200 by wt. allowed in combined CA & FA ≯2% by wt. of combined CA & FA shall be deleterious
TENN.	100	95-100	N	#14 60-92	N	N	#48 10-30	0-10	N	3	SP on mfg. sand
TEX.	100	95-100	N	N	50-85	N	N	0-15	N	4	Plus 2% if of same quality as FA or mineral filler
UTAH	100	95-100	N	45-80	N	N	10-30	2-10	N	3	Claylumps ≯0.5% by wt., coal & lignite ≯0.25% by wt. Other deleterious materials ≯5.0% by wt.
VT.	100	95-100	N	55-80	N	30-50	12-30	3-8	N	3	Must be free from clay and deleterious mat'l
VA.	100 —	95-100 100	80-95 95-100	65-85 60-85	N	30-60 30-60	8-25 10-30	0-10 5-15	0-5 0-5	0.25—clay lumps 1.0—deleterious	Grading A natural Grading A mfg.
WASH.	100	95-100	68-86	47-65	N	27-42	9-20	0-7	0-2	2 Wet sieve	82-98 passing #6
W. VA.	100	95-100	80-95	50-85	N	N	5-25	0-9	N	3	Removed by decantation
WIS.	100	95-100	N	45-80	N	N	5-30	0-10	N	3.5	
WYO.	100	90-100	N	N	N	N	10-30	2-10	0-3	3	

*Wet weight

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APPENDIX C

BIBLIOGRAPHY

This bibliography contains the major part of the literature items consulted in connection with the preparation of this report. To show areas of interest, the items have been classified as:

- I. Generic
- II. Statistics
- IIa. Sampling and Acceptance Plans
- IIb. Process Control
- IIc. Analysis of Variance
- IId. Regression Analysis
- IIe. Statistics and Specifications
- IIf. Statistical Methods—General
- III. Cost-Benefit-Tolerances—General
- IIIa. Surface Smoothness—Bases, Pavements and Subgrade
- IIIb. Thickness Requirements—Pavements and Bases
- IIIc. Aggregate Gradations
- IIId. Process Tolerances
- IV. Current Practice
- IVa. Application of Statistical Methods
- IVb. Record Samplings
- IVc. Precision Statements
- IVd. Equipment Specifications
- V. Definitions

To aid in information retrieval the following code, indicating specific areas of reference, has been used to further classify particular items:

- A. Generic
- B. Statistical
- C. Benefit
- D. Current Practice
- E. Glossary
- F. General Interest

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State	Separate sizes	COARSE AGGREGATE Grading: per cent by weight passing each sieve Sizes	3	2½	2	1½	1¼	1	¾	½	⅜	¼ or #4	Notes
Col. No.	53	54	55	56	57	58	59	60	61	62	63	64	65
ALA.	N	A2 A3 A4	N	100 — —	90-100 100 —	— 95-100 100	N	35-70 40-90 90-100	— 35-70 —	10-30 — 25-60	— 10-30 —	0-5 0-5 0-10	≯2% soft fragments, ≯0.25% coal & lignite, ≯0.25% clay lumps, ≯5% passing #200, ≯10% thin or elongated
ARIZ.	2R	1 2 1 + 2	N	— 100 100	100 95-100 95-100	100 35-70 —	N	95-100 0-15 35-70	N	25-60 0-5 10-30	N	0-10 — 0-5	#8 0-5 / — { Soundness AASHO T-104 loss ≯10% Wear ≯40 by AASHO T-96
ARK.	OC 1 or 2	1½ 1 & 2½	N	— 100	N	100 35-70 100	N	— 0-15 95-100	35-75 — —	— 0-5 25-60	10-30 — —	0-5 — 0-5	When furnished in two sizes the amount of each size shall be ≮ 25% of the total
CAL.	3 2 1	2½" 1½" ¾"	100 — —	95-100 — —	80-95 100 —	65-87 90-100 —	N	50-75 50-86 100	45-66 45-75 90-100	N	38-55 38-55 60-80	30-45 30-45 40-60	OC OC E { Combined grading including fine aggregate
COLO.	2R*	—	N	100	95-100	N	N	35-70	95-100	10-30	N	0-5	AASHO T-104 loss @ 5 cycles <12% or 5 year satisfactory service record—AASHO T-96—max. 45%
CONN.	2R	50% ea. or E	N	— 100	— 95-100	— 35-70	— 0-25	100 0-10	90-100 —	20-50 —	0-20 —	0-5 —	Grading of 2" & ¾" shown, 1¼" & ½" may be used
DEL.	2R	Sp-3 Sp-57	N	100 —	95-100 —	35-70 100	N	0-15 95-100	N	— 25-60	N	— 0-10	#8 — / 0-5 (Sp—simplified practice)
D. of C.	2R	Sp-4 Sp-67	N	N	100 —	90-100 —	N	20-55 100	0-15 90-100	N	0-5 20-55	— 0-10	#8 — / 0-5
FLA.	N	Gr. 3 Gr. 6	100 —	N	97-100 100	N	40-75 97-100	— 75-95	N	N	N	0-5 0-5	
GA.	2R	2½" 1½"	N	100 —	95-100 —	35-70 100	N	0-15 90-100	N	0-5 25-60	N	— 0-10	#8 — 40% 0-5 60%
HAW.	N	1½"-#4	N	N	100	95-100	N	N	35-70	N	10-30	0-5	See note p. 16
IDAHO	2R	2-1 1-#4	N	100 —	95-100 —	35-70 100	N	0-15 95-100	N	0-5 25-60	N	— 0-10	LA Machine—35% loss
ILL.	2R	LA SM B	N	100 — —	85-100 — —	30-70 95-100 100	N	0-15 0-65 90-100	N	0-5 0-10 25-60	N	— 0-5 0-10	LA + SM (optional) + B
IND.	2R	#2U #3 #5L	N	100 100 —	95-100 90-100 —	— 35-70 100	N	0-20 0-15 85-98	0-5 — 60-85	0-2 0-5 30-60	N	— — 0-10	35-40% #2U or #3 } Freeze-thaw test used when ≯60% 5L } aggregate fails sodium silicate test
IOWA	N	1 2 3	N	N	N	100 100 100	N	60-90 50-95 50-100	N	N	15-35 10-40 5-50	0-5 0-5 0-5	1—FA 35%-40%, 2—FA 45%-50%, 3—FA 50%-70%
KAN.	N	CA 1 CA 2 MA 3	N	N	N	100 — 100	N	90-100 95-100 90-100	35-70 — 60-90	N	7-30 — —	— 25-45 40-70	#8—0-5 #8—0-10 CA-1 gravel, crushed stone or flint, CA-2 chat #30—16-22, #50—5-8 30% sweetened sand-gravel
KY.	OC	#36 #47	N	100 —	85-95 100	— 85-95	N	35-70 —	— 35-70	10-30 —	— 10-30	0-5 0-5	Limestone, slag, gravel Gravel only
LA.	N	A B D	N	— — 100	— 100 90-100	100 85-100 —	N	90-100 — 40-80	40-85 40-85 —	N	N	0-5 0-5 0-5	A is normally used
ME.	2R	2"-¾" ¾"-#4	N	N	100	95-100	N	N	30-60	N	5-25	0-5	
MD.	2R	#2 #6	N	100 —	90-100 —	35-70 100	N	0-15 90-100	N	0-5 25-60	N	— 0-10	#8 — / 0-5 } 50% ea. ± 10%
MASS.	2R	1½" ¾"	N	N	N	90-100	N	N	35-50	N	10-25	0-5	Approximately 50% each size
MICH.	2R	4A 6A	N	100 —	95-100 —	65-90 100	N	10-40 95-100	N	0-20 30-60	0-5 —	— 0-8	50% of each size ±10%, air-cooled blast furnace slag permitted when tested & approved, unit wt. 75#/cu.ft.
MINN.	2R	CA 15 CA 25 CA 35 CA 45	N	N	100 100 — —	90-100 95-100 100 —	— — 95-100 100	— — — 95-100	35-65 50-80 55-85 65-95	N	5-25 20-40 20-45 25-55	0-7 0-7 0-7 0-7	
MISS.	N	A B C	N	100 — —	97-100 100 —	95-100 95-100 100	N	70-95 80-100 80-100	40-60 55-90 —	— 30-60 30-60	N	0-5 0-6 0-6	Three sizes—OC
MO.	2R	+ ¾" — ¾"	N	N	100	95-100	N	N	35-70	N	10-30	0-5	Approximately 50% each size
MONT.	2R	+ ¾" — ¾"	N	N	100	95-100	70-95	—	35-70	—	10-30	0-5	C.A. furnished in 2 separate sizes, separation is at ¾" sieve
NEB.	N	47A, 47C 47B	N	N	N	95-100 100	N	— 95-100	40-80 70-100	N	— 20-50	0-5 0-10	#20 — / 0-5
N.J.	2R	1½ ¾	N	N	2¼"-100 —	N	0-30 100	N	0-5 45-75	— 25-45	N	0-2 0-10	Trap rock, granite, gneiss, or washed gravel. 1½" & ¾" may be used with % determined by workability & min. void content
N.M.	2R	A B	N	100 —	95-100 100	— 95-100	N	35-70 —	— 35-70	10-30 —	— 10-30	0-5 0-5	Passing #200, A—0-1, B—0-1.0 A & B require two stockpiles, split on ¾" screen
N.Y.	2R	1 & 2 1 & 2 + 3	N	— 100	— 95-100	100 68-88	N	93-100 47-66	N	27-58 14-35	N	0-8 0-5	In blend, 30-50% shall be No. 1 size In blend, 40-50% shall be No. 3 size
N.C.	N	1	N	N	N	100	N	85-97	N	25-45	N	0-10	—
N.D.	2R	1½"-¾" ¾"-#8	N	N	100	95-100	N	N	35-70	N	10-30	0-5	C.A. gradation based on combined classification clay lumps ≯0.5% by wt., coal and lignite ≯1% by wt. passing #200 ≯3% by wt., other ≯2% by wt.
OHIO	2R	#3 #4	N	N	100 —	80-100 —	N	20-60 100	0-20 80-100	— 20-60	0-5 5-30	— 0-5	#4 size varied between 35 to 50% of total to secure most desirable gradation
OKLA.	R	—	N	100	95-100	70-95	N	50-85	N	15-40	N	0-5	Combined C.A. grading when batched separately
ORE.	3R 2R 2R	2½"-¼" 2" -¼" 1½"-¼"	2½-1½, 1½-¾, ¾-#4 2-1, 1-#4 1½-¾, ¾-#4 See gradings page 16										
PENN.	2R	2B 3A	N	— 100	— 90-100	100 35-70	N	90-100 0-15	N	25-60 0-5	N	0-10 —	#8—0-5, max. thin and elongated particles (¼:1 ratio) ≯10% by wt.
R.I.	2R	2½-1¼" 1¼"-#4	N	100	2⅛" 85-100	N	N	40-75	N	⅝" 20-50	N	0-10	—
S.C.	2R	—	N	100	90-100	35-70	N	0-15	N	25-60	N	8-24	50% each size —
S.D.	2	1½"-¾" ¾"-#4	N	N	100 —	90-100 —	N	20-55 100	0-10 90-100	N	— 20-55	— 0-10	Usually 2 sizes, 60%—1½" to ¾", 40%—¾" to #4 % of each size, A
TENN.	N	6 or 7 OC	N	N	100 100	85-100 90-100	N	50-80 75-90	25-40 40-70	N	5-20 5-25	0-5 0-5	Combined
TEX.	R	N	100	100	80-100	N	N	N	N	30-75	N	0-5	Decantation loss—1%, max. clay lumps 0.25%, shale—1% max., laminated or friable—5% max.
UTAH	2R	2½"-1" 1½"-#4	N	100 —	90-100 —	35-75 100	N	0-15 90-100	N	— 25-60	N	— 0-10	Soft fragments ≯5% by wt. clay lumps ≯0.25% by wt., material passing #200 ≯0.5% by wt., other deleterious material ≯5.0% by wt.
VT.	2R	1¾-1½ ¾-#4	N	N	1¾" 100	95-100	N	N	90-100	N	N	0-5	Aggregate must meet separate and combined requirements
VA.	2R	3 57	N	N	100 —	45-80 100	N	— 95-100	0-20 —	0-5 25-60	N	— 0-10	#8 — 3, 50-60% / 0-5 57, 50-40% } Subject to wear, soundness and freeze-thaw tests
WASH.	R	#2 #3 #4 #5	— — — —	95-100 — — —	75-100 — — —	100 30-60 100 —	95-100 0-15 95-100 —	— — — 100	40-70 0-1 0-20 95-100	N	5-20 — 0-2 10-40	0-2 — — 0-4	0.5% silt allowed, wet sieve— mix with 2½" max.—two parts #2, one part #3 mix with 1½" max.—one part #4, one part #5 contractor option to supply either
W.VA.	2R	#26 #37	N	100 —	90-100 100	— 95-100	N	35-70 —	— 35-70	10-30 —	— 10-30	0-5 0-5	
WIS.	2R	Series I 1 Series I 2 Series II 1 Series II 2	N	— — — 100	— 100 — 95-100	— 90-100 100 35-70	N	100 20-55 95-100 0-15	90-100 0-15 — —	— — 25-60 0-5	20-55 0-5 — —	0-10 — 0-10 —	#8 0-5 1.—35-45% of total — 0-5 2.—55-65% of total —
WYO.	N	1" max. 1½" max.	N	N	N	— 100	N	100 —	— 35-70	N	15-35 10-30	0-10 0-5	—

*Except when ¾" max. allowed (OC— 7 sk/cu.yd.)

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V. DEFINITIONS

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