STATE-OF-THE-ART IN ASPHALT PAVEMENT SPECIFICATIONS

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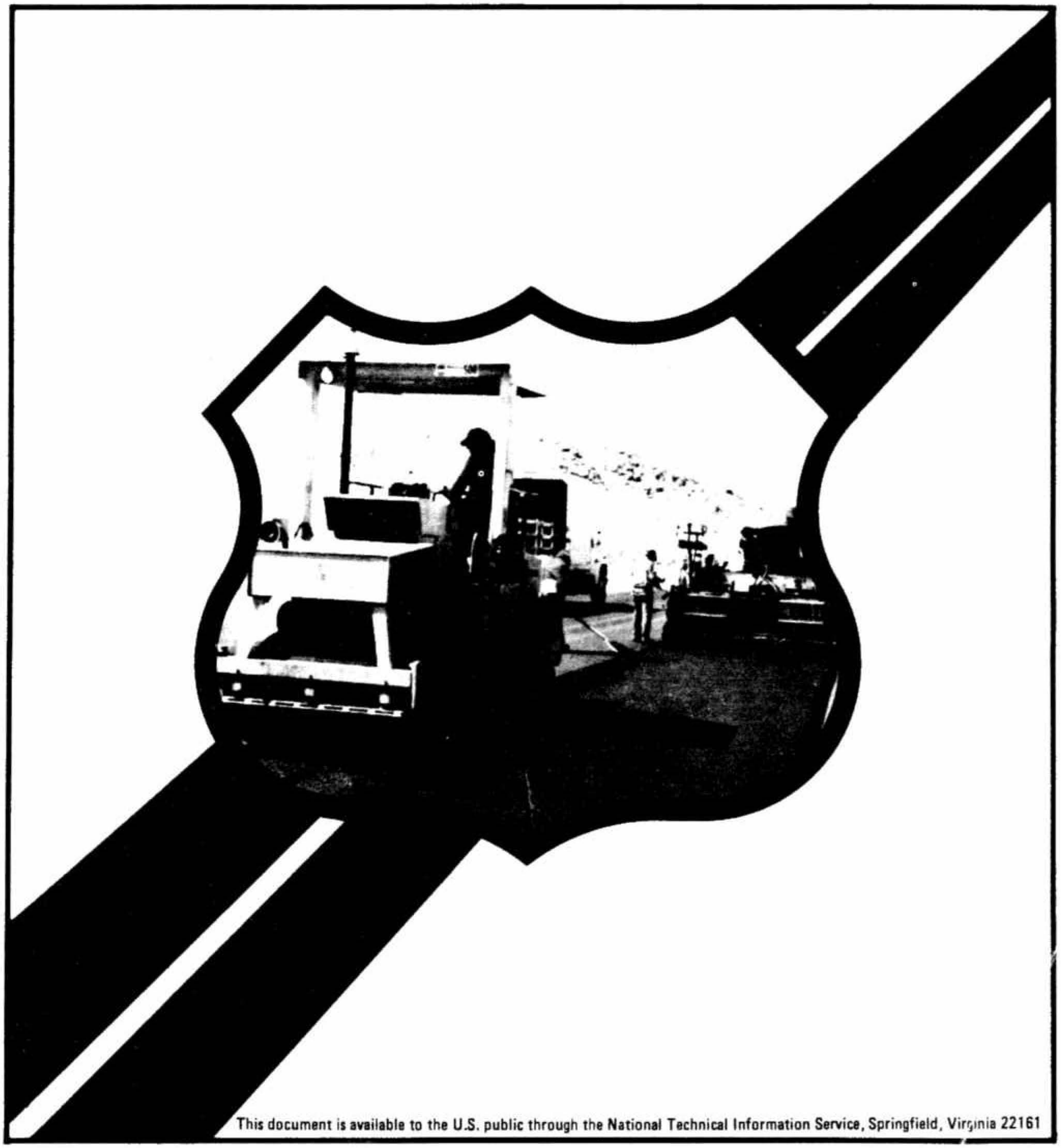

FOREWORD

This report is a first step in the development of asphalt pavement specifications built around quality criteria that are truly related to pavement performance. The report provides a history of materials and construction specifications and summarizes current knowledge in quality assurance. It also describes a recommended framework for a system of performance-related specifications. This framework includes both new and existing test methods needed to control the properties of materials. Construction methods to support the system are likewise identified.

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16. Abstract

The great increase in highway construction beginning in the 1950's made evident the need for better control of materials and construction. A comprehensive research and development program was begun to use statistical methods for quality assurance in highway construction. The effort since has resulted in quality control and acceptance plans which are used in specifications to some degree by more than 30 states. The quality assurance specifications usually assign the responsibility for control of materials and construction to the contractor. Acceptance and method for pay adjustment for non-compliance are highway agency responsibilities; surveys show a wide disparity in pay adjustment factors. Performance-related specifications based on distress modes and contributing factors are also described. Studies indicate that the most predominant forms of distress are cracking (load and non-load), distortion, disintegration, roughness and reduced skid resistance. Contributing material factors and evaluation methods are outlined for each of the performance-related distress modes. The report also summarizes the problem of reflection cracking, its contributing factors, and methods of overlay design and special treatments to prevent or minimize this form of distress condition. Recommendations are to encourage the effort to continue development of quality assurance specifications based on sound engineering judgment and to develop detailed performance-related specifications with optimum mix-design requirements to meet the need for structural capacity, rideability and skid resistance.

17. Key Words

Asphalt pavements, specifications, quality assurance, performance-related, distress modes, acceptance plans, pay adjustment factors

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INTRODUCTION

The first standard test methods for bituminous materials were published in 1911, and the first American Society for Testing and Materials (ASTM) specifications for materials were adopted in 1921. There are now about 78 standards that cover specifications, methods of sampling and methods for testing materials and processes for use in asphalt pavement construction.

Since 1962, there has been an increased emphasis on quality assurance programs for highway materials and pavement construction. The programs have made significant progress and a number of agencies have adopted or are evaluating quality control and acceptance plans for asphalt pavement construction. In conjunction with quality assurance programs, there is a continuing effort to develop better methods and criteria for bituminous mix designs and for controlling material properties and construction processes that will result in more durable and higher quality asphalt pavements.

The overall objectives of this study are to trace the development of a state-of-the-art in specifications for materials and construction methods for asphalt pavements, identify and evaluate requirements that are performance-related, and provide a framework of a system of specifications that will assure higher quality and longer life pavements. The work was divided into the following objectives:

1. Define distress modes for asphalt pavements that are due to construction methods and material properties.

2. Evaluate existing specifications to identify those elements that relate directly to distress modes.

3. Develop a framework of a system of performance-related specifications for asphalt pavements.

4. Identify test procedures that are required to support the performance-related specifications.

5. Examine scenarios to implement performance-related specifications and identify the most cost-effective method.

To accomplish the objectives, the report is divided into the following six sections:

I. EARLY DEVELOPMENT OF SPECIFICATIONS FOR MATERIALS AND CONSTRUCTION

Section I of the report covers the early history and current status of the development of standard specifications, and sampling and testing methods that are used to measure and control material properties, mixture design and construction methods of asphalt pavements.

The report includes up-to-date listings of all standard specifications, methods of sampling and methods of testing that were developed by the ASTM and the American Association of State Highway and Transportation Officials (AASHTO).

II. QUALITY ASSURANCE

Section II of the report covers the development and application of quality assurance and statistical methods for plant control and acceptance of materials and construction. Section II also shows the growth of the use of quality assurance programs from 1962 to 1983. The report includes the advantages and disadvantages of the use of quality assurance programs in asphalt pavement constructions.

III. SURVEY OF ASPHALT PAVEMENT SPECIFICATIONS

Section III reports the results of a survey of specifications to show:

(a) responsibilities of agency and contractor;

(b) material and construction requirements;

(c) quality requirements;

(d) quality assurance.

IV. PERFORMANCE-RELATED SPECIFICATIONS

Section IV includes the following information:

(a) review of the distress modes and identification of the properties of materials and mixtures and the construction methods that contribute to the distresses;

(b) development of a framework for performance-related specifications, identification of existing and new test methods needed to control the properties of materials, and the identification of construction methods that would support the specifications.

V. REFLECTION CRACKING AND OVERLAYS

Summary of various treatments to prevent reflection cracking and the design methods of overlays.

VI. REHABILITATION

Road roughness and skid resistance are two of the major requirements considered in asphalt pavement rehabilitation. Some of the contributing factors and methods of measuring roughness and skid resistance are summarized in Section VI.

To accomplish the objectives of Section I through Section VI, the author relied on information from the literature. The author also relied on an Advisory Panel to provide assistance and direction to the report.

The report concludes with a summary of conclusions and recommendations.

I. EARLY DEVELOPMENT OF SPECIFICATIONS FOR MATERIALS AND CONSTRUCTION

One of the first successful asphalt pavements was constructed in 1876 in Washington, D.C. The paving mixture was composed of sand, mineral filler (dust) and natural asphalt. The mixture came to be known as sheet asphalt. Up to that time heavy duty pavements were built with cobblestone, wood block, stone block, brick or stone macadam. One of the earliest references concerning asphalt quality was published in 1892 (1). The report stated:

> "The durability of asphalt pavements depends wholly on the suitability of the asphalt for the purpose. It must be of such a nature as to permanently and thoroughly cement together the sand and limestone powder forming the body of the pavement. It must be elastic, independent of the residuum oil required on making the paving cement and in no degree brittle."

SOURCES OF ASPHALT

Up to 1900, the major source of asphalt was from a deposit, a natural pitch (asphalt) lake at LaBrea, Trinidad, and became known as Trinidad Lake Asphalt. The asphalt was surface mined from the lake and transported by tramway to a processing plant where extraneous water and organic matter were removed and to a dock where the asphalt was loaded onto ships for overseas shipment.

One other source of asphalt that came into limited use for pavement construction was called "iron asphalt" or "land pitch". The material was found in overflow areas from the lake. The asphalt material was extremely hard and brittle and gray to black in color in contrast to the uniformly glossy and uniformly black color of the natural lake asphalt. Large deposits were found in the village of LaBrea, Trinidad. In some areas houses and streets, and in one case a cemetery, were built on the deposits.

The lake and land asphalts were very hard, usually less than 10 penetration by our present standards. A flux oil had to be added to make the asphalt cement soft enough for use as a binder in pavement construction.

During the 1880's and 1890's, much contention developed over the superiority of lake and land asphalts. The literature contains numerous accounts of hearings, court actions and investigations. Reports were prepared by Public Works Departments of cities and by consultants, asphalt suppliers and contractors. Based on numerous studies conducted by cities and asphalt suppliers, the final consensus was that lake asphalt resulted in better performance and was more durable than land asphalt.

TESTS AND CONSTRUCTION CONTROL

An evaluation of pavement performance in 1894 showed that the production of paving mixtures up to that time was entirely a matter of rule of thumb (1). It was also determined that a large part of the success of asphalt pavements was due to the use of proper sands and correct gradings. Thus, simple specifications and relatively crude test methods came into being in the early 1890's. Information became apparent that the time of mixing was important, as well as proper scales to measure the amount of asphalt in a mixture. A percolation (extraction) test was devised for the determination of bitumen in mixtures. The penetration test for use in determining the proper amount of flux was added to the scheme of asphalt analysis adopted by laboratories. A method for forming cylinders and determination of the specific gravity were added to the routine analysis of paving mixtures during the late 1890's. The establishment of field or "sub" laboratories to provide a means for the careful examination of paving materials was initiated during that period. The field laboratories were usually established by the companies that produced materials and paving mixtures, and provided a means for correcting the composition by making immediate and constant tests during plant operation. One report stated:

"The sub-laboratory dignifies the yard and puts the whole yard force on a more exact, careful and scientific basis." Kettlemen, sandmen, and mixermen were found to be more careful in their work. Thus, quality control was present long before modern laboratories and standard test methods were established.

Specifications developed for asphalt pavement construction in Washington, D.C. required that the asphalt be from Trinidad Lake or from another source of equal quality. Specifications included requirements for the amount of matter soluble in carbon disulphide, a melting point, amount of oils lost on heating to 400°F (204°C), and a visual examination of the mineral matter recovered from the natural asphalt.

Requirements on the mixture were that the pavements constructed with the asphalt be solid, durable and capable of withstanding the constant strain of the heaviest and most crowded wagon traffic. Another problem that received considerable attention was that asphalt pavements were slippery under horses' hoofs. Experience showed that the sharp sand in sheet asphalt mixture made with Trinidad asphalt gave a better foothold for horses than a rock asphalt imported from Sicily. The Sicilian rock was a limestone aggregate and became very smooth and slippery under traffic conditions common at that time. Thus, pavements having high friction properties were recognized before the development of high speed vehicles.

For residential streets, asphalt pavements were found to be smoother and cleaner and to generate less noise than granite block pavements used in commercial areas. Asphalt pavements were also found to be superior to wood block in all respects. Up to 1906, a very small amount of asphalt was used to construct pavements in rural areas.

The almost exclusive use of Trinidad Lake asphalt lasted until about 1900, when a natural asphaltic material from Bermudez and asphalts refined from domestic crudes came into the market in competition with Trinidad asphalt (2)(3). The promoters of Trinidad asphalt fought to prevent the introduction of domestic asphalt. At one point, the heated argument even reached the U.S. Senate Committee on District of Columbia Affairs. The

Committee decided in favor of the natural (Trinidad) asphalt. Later, a favorable court decision permitted the specifications to be broadened to allow the use of domestic or petroleum asphalts. Thus, the monopoly by the promoters of natural asphalt for the exclusive use of Trinidad Lake Asphalt was broken.

Laboratories to control the properties of materials for use in road construction came into more general use during the late 1890's. Beginning about then and later, test methods and test equipment were developed to measure the properties of asphaltic materials, paving mixtures and aggregates. Up to 1900, however, the literature shows that there was little recognition of standard specifications or methods of test for controlling hot asphalt plant mixtures. In many cities, the standard practice was to construct heavy duty pavements comprised of a portland cement concrete base, 1-1/2 inches (38 mm) of open asphalt binder mix and 1 to 1-1/2 inches (25 to 38 mm) of sheet asphalt surface. This practice has been continued in recent years in some large cities. According to the Barber Asphalt Paving Company, the largest supplier of Trinidad asphalt, 24 million square yards (20 million m^2) of sheet asphalt had been laid up to 1899 in over 100 cities in the United States and Canada. During the period 1900 - 1910, mixing plants and practices were developed to produce and compact sheet asphalt mix. Laydown was performed by hand spreading and using ironing tools and hand compactor techniques (4). Using present technology, most pavements constructed at that time would not be considered as flexible pavements.

ASPHALT-CONCRETE SURFACES

The first dense graded asphalt-concrete pavements were constructed under patents issued by Warren, trademarked as "Bitulithic", in 1901. The patented pavement was a two-inch thick course of dense-graded asphalt mix placed in a single lift. The thickness was increased to three inches if needed. The pavements constructed under the Warren patents would be considered as flexible pavements.

Patented asphalt plants also came into use in 1901. The process included equipment for grading hot aggregate by a multi-bin procedure. In contrast to sheet asphalt plants, which used sand and one bin, multi-bin plants with up to six bin separation were specified. Asphalt cement was added either on a weight or volume basis. The aggregate dryers were of the external fired type. Cold feed aggregates were proportioned to the cold elevator by manual use of a shovel. Production of plant mix was about 25 tons (23 Mg) per hour (4).

THE ROLE OF THE BUREAU OF PUBLIC ROADS

As stated earlier, prior to 1900 little effort had been given to standardizing test methods and specifications for materials and construction processes. During 1901, the Federal Government established the Office of Public Roads in the Department of Agriculture (2). Dr. Logan Walter Page of Harvard University was appointed to be in charge of a mechanical and chemical laboratory to receive samples of road materials from all parts of the country, and to test them "FREE". By 1911, the Office of Public Roads consisted of eleven employees, many of whom are recognized today as pioneers in the development of standard methods for testing of road materials and for the development of specifications.

In addition to the establishment of a laboratory in 1901 to secure scientific facts in reference to the value of road building materials, the Director of the Office of Public Roads and Road Inquiry increased federal support to develop a program for the construction of object-lesson roads. The purpose of these short field test sections was to enlighten the people in all of the states of scientific facts for road construction at a cost no greater than would be required by individual states. The belief was that no laboratory test was equal to the actual application of the material. Although the object-lesson roads were constructed on a limited basis during the late 1890's, their support by the federal government increased after 1901. Excellent cooperation was obtained by the states, local interests, equipment manufacturers and material suppliers. The object-lesson roads were found to be very beneficial, not only in showing the scientific side of the question, but the economical side as well (5).

Through the initiative and support of the Office of Public Roads, later called the Bureau of Public Roads (BPR) and now the Federal Highway Administration (FHWA), Committee D4 on Road and Paving Materials was formed by the American Society for Testing and Materials (ASTM). Dr. Page was appointed Acting Chairman and later Chairman, where he served until 1919.

Later, the American Association of State and Transportation Officials (AASHTO) also played an important part in the development and standardization program. Credit also must be given to universities, industry and other federal agencies for their continuing active participation and leadership.

Up to 1910, much of the road construction in rural and city street areas consisted of the application of bituminous dust preservatives to combat dusting. The roads treated were narrow and the applications were thin, but they were adequate to carry automobiles and farm vehicles. In general, the treatments solved the dust problem. In the spring of 1918, however, the adequacy of the treatments was seriously challenged by the increasing failure of all types of roads due to increased heavy truck traffic. The disaster was described by Prevost Hubbard, the Chief Chemist of the OPR, as follows (6):

"Hundreds of miles of roads failed under this heavy motor-truck traffic within a comparatively few weeks or months. Roads with bituminous surfaces, bituminous macadam roads and bituminous concrete roads all failed alike, together with other types used in state and county work. These failures were not only sudden, but complete, and almost overnight an excellent surface might become impassible...a very large portion of the failures have been characterized by an almost simultaneous destruction of the entire structure, and not merely the disintegration of the wearing course or pavement proper."

Some of the reasons for the failures were considered to be overloading of frost-softened subgrade, and internal failure of macadam due to aggregate crushing, soil types and drainage. The most significant observation was that hundreds of pavement failures were due to moisture-softened clay soils. Investigators agreed that pavements built on sandy, well drained soils had given better service. Studies also determined that the failure of pavements was closely associated with truck traffic. Extensive research studies were conducted to show the relationship of materials and traffic on road performance. Failures such as described above spurred the research effort to develop improved and standard test methods and specifications for asphalt pavement materials and construction. A significant development reported in 1929 was the soil classification system using soil constants to evaluate the performance of soils in foundations. Another development was a method for controlling moisture-density relationships for use in soil compaction. Compaction specifications for subgrades and soil-aggregates base courses required that the material have the proper moisture when compacted to reach the target density.

The early development towards standardization are reported in a series of Department of Agriculture bulletins. The most important ones are presented below:

Bulletin No. 38, "Methods for the Examination of Bituminous Road Materials" (7), described methods for testing bituminous materials in use at that time. The need for the development of standard methods was considered imperative.

Bulletin No. 555, "Standard Forms for Specifications, Tests, Reports and Methods of Sampling for Road Materials" (8), included recommendations or actions taken at a conference of representatives from 21 states and the Office of Public Roads and Rural Engineering to encourage the establishment of well equipped state laboratories and to adopt standard methods of testing and reporting results.

Bulletin No. 691, "Typical Specifications for Bituminous Materials" (9), provided engineers with information to (a) secure a suitable grade of material, (b) insure a uniform supply, and (c) sufficiently identify the material by type.

Bulletin No. 704, "Typical Specifications for Non-Bituminous Road Materials" (10), included specifications for aggregates for use in surface treatment and penetration macadams, and in asphalt concrete and sheet asphalt plant mixtures.

Bulletin No. 949, "Standard and Tentative Methods for Sampling and Testing Highway Materials" (11), is the first publication of recommended standards endorsed by the AASHTO.

Bulletin No. 1216, "Tentative Standard Methods for Testing Highway Materials" (12), included test methods adopted as standards by AASHTO and remained as standard until 1931, when the first edition of "Tentative Standard Specifications for Highway Materials and Methods of Sampling and Testing" was published.

SPECIFICATIONS FOR ASPHALT CEMENT

The promulgation of various specifications for asphalt cement was often spontaneous, with a lack of agreement as to what grades and what requirements were needed for various types of construction and environment. In 1923, a conference of producers, distributors, users and others developed a simplified practice recommendation to reduce 88 different specifications of asphalt cement and 14 grades of joint filler to nine and four grades, respectively. These grades were adopted by AASHTO in 1926, nine grades by ASTM in 1947, and nine grades by the General Services Administration in 1948. AASHTO added the 70-85 grade in 1936. In 1959, AASHTO dropped the 50-60, 70-85 and 100-120 grades, leaving the 40-50, 60-70, 85-100, 120-150 and 200-300 penetration grades in use today.

Specification requirements for asphalt cements for use in asphalt pavement construction did not change significantly from the early 1920's to the 1930's. During that period, methods relied on for measuring the properties of asphalt cement included penetration, ductility, softening point, oven loss test and penetration of the residue, and flash point and solubility in one or more types of solvent.

In 1933, the Abson Recovery Test was developed to provide a valuable tool to determine the properties of asphalt cements after being subjected to plant mixing and after service in pavements. Also in 1933, Olensis developed the Spot Test that was useful in determining whether asphalt materials had been overheated or cracked during the refining process. Because some cracked asphalts were subject to early hardening during plant mixing or in service, the Spot Test was adopted by a majority of agencies. However, the test has found little use during the past 30 years because high temperature refining methods have been replaced with more efficient processes.

A major accomplishment that affected specifications was the development of the Thin-Film Oven Test by the BPR during 1936-1940 for use in predicting asphalt hardening during plant mixing. The test was adopted as a standard in 1959 by AASHTO and in 1969 by ASTM. The hardening was evaluated by penetration and ductility tests on the residue. A rolling thin-film oven test was adopted by a few western states, AASHTO and ASTM in the 1970's.

During the 1960's, fundamental viscosity tests came into common use as an additional requirement, or as a means for grading asphalt cements by viscosity in place of grading by penetration. Some specifications now require viscosity at two temperatures in an attempt to measure temperature susceptibility.

New specifications for asphalt cement based on viscosity grading were adopted by AASHTO and many states during the 1970's. The penetration grade specifications were retained by AASHTO and ASTM as an alternate. Recently, a few states, AASHTO and ASTM have added an AC-30 grade which partially overlaps the range of the AC-40 grade.

SPECIFICATIONS FOR AGGREGATES

Aggregates play a major role in the design, construction and performance of asphalt pavements. A major effort to standardize specifications was initiated in 1948, when the Bureau of Standards approved and issued a Simplified Practice Recommendation (SPR), R 163-48, for coarse aggregate, including crushed stone, gravel and slag. The practice provides for the following standard procedures:

Standard Sieves - Employs a simple and convenient series of sieve sizes based on a logarithmic principle. The basic series for aggregates for use in hot-mixed, hot-laid, bituminous paving mixtures is 1-1/2-inch (38 mm), 3/4-inch (19 mm), 3/8-inch (9.5 mm), No. 4 (4.75 mm), No. 8 (2.36 mm), No. 16 (1.18 mm), No. 30 (600 μm), No. 50 (300 μm), No. 100 (150 μm) and No. 200 (75 μm).

Standard Aggregate Size - Provides standard grading requirements for the production of coarse and fine aggregates for use in bituminous paving mixtures. The composition of dense and open bituminous paving mixtures using the standard sizes and the bitumen contents are given in ASTM Standard Specification for Hot-Mixed, Hot-Laid Bituminous Paving Mixtures, D-3515-83. The specification provides that under certain aggregate availability conditions, other gradations are used for coarse and fine aggregates and filler, provided they meet the total grading prescribed in ASTM D-3515.

Standard Method of Reporting - To compare different aggregate gradings, bands with upper and lower control limits for each sieve size are usually reported on a cumulative basis. Systems of grading bands for combined coarse, fine aggregate and filler have been developed, as shown in ASTM D 3515. Graphical methods are often used to assist in the selection of aggregate gradings that are desirable from the standpoint of stability, and resistance to moisture and weathering of the binder in bituminous paving mixtures. In 1962, the Bureau of Public Roads (BFR) devised a gradation chart based on earlier work by Nijboer of the Netherlands. Up to this time, gradation charts usually used an arithmetical vertical scale for percent passing the various sieves and a horizontal scale of logarithms of the sieve openings. The plots of gradings usually were curved. Nijboer's chart was based on a double logarithmic scale (percent passing) and resulted in gradations represented by straight lines. The BPR chart based the horizontal scale on the sieve openings (inches or millimeters) raised to the 0.45 power, which converts the grading curve to a straight line from the maximum particle size to a zero-size opening on the horizontal scale shown in Figures 1 and 2. The straight line approximates the maximum density grading. The 0.45 power gradation chart has been very useful in evaluating the performance of bituminous paving mixtures. An example is the mixtures that were hard to compact and remained tender for some time after rolling. In nearly all cases, the gradings had a hump in the grading curve in the finer sand fractions (No. 30 to No. 50 size).

The adoption of the production of standard size aggregates and method of reporting by all agencies would provide an economic advantage to both the producer and consumer.

In 1962, the Bureau of Public Roads pointed out that, in view of the magnitude of the nationwide construction program and the enormous amount of public funds needed to finance it, every effort should be made to develop and apply ways to reduce construction costs and at the same time assure the production of quality work (14). A survey showed that there was a wide diversity of requirements pertaining to aggregate gradations then in use by

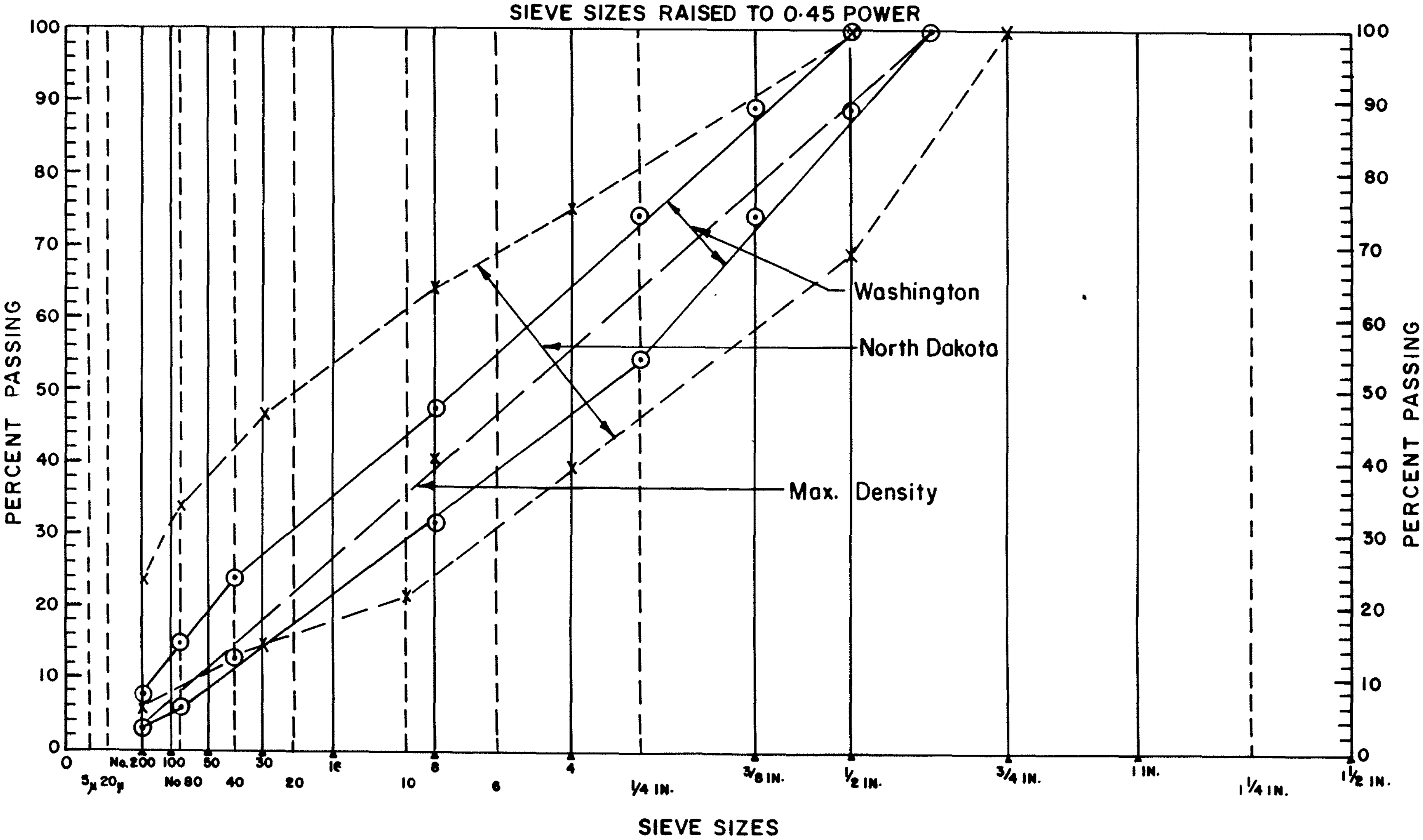


FIGURE 1 RANGE IN MASTER GRADING BANDS FOR WASHINGTON AND NORTH DAKOTA

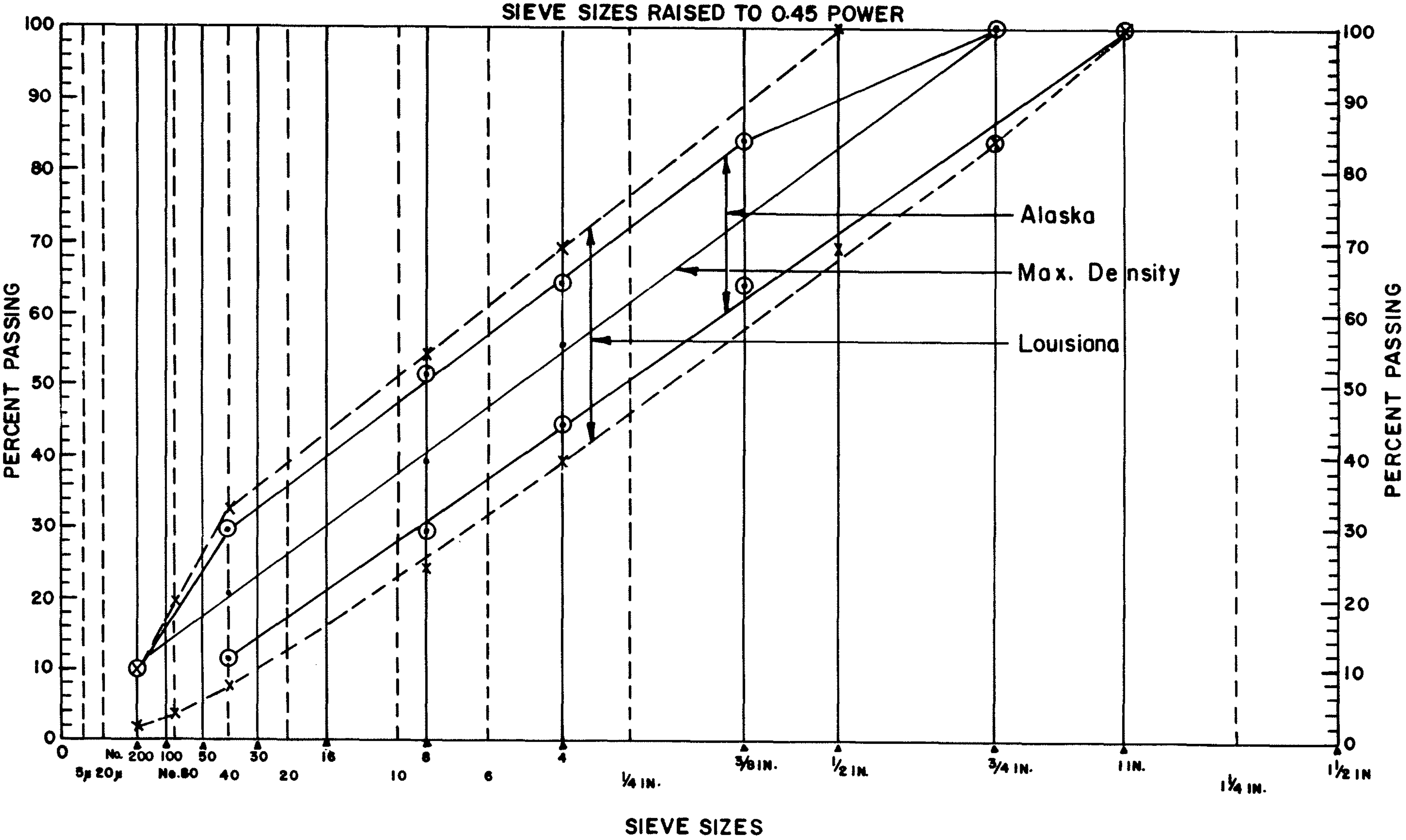


FIGURE 2 RANGE IN MASTER GRADING BANDS FOR ALASKA AND LOUISIANA

the 50 state highway departments, the District of Columbia, and Puerto Rico.

Present standards include specifications for fine and coarse aggregates and mineral filler. Quality requirements include tests to measure and control plastic fines, coating and stripping tests, amount of crushed particles, and flat or elongated pieces. Test methods include unit weight, sieve analysis, specific gravity, absorption, soundness, abrasion, polishing resistance, liquid limit, plasticity index and durability.

AASHTO Specification M283 contains 7 supplementary quality requirements, some of which may improve the performance of bituminous mixtures if adequately controlled. The properties and requirements are:

S-1 Coating and stripping of bituminous aggregate mixtures--minimum retained coating 75 percent.

S-2 Plasticity index for aggregate passing the No. 4 sieve--maximum of 6 percent.

S-3 Adherent coating on aggregate after dry sieving--not more than 0.5 percent.

S-4 Crushed gravel shall consist of particles with not less than 75 percent of the portions retained on the 4.75 mm (No. 4) sieve at least two fractured faces.

S-5 Crushed gravel shall consist of particles with not less than 50 percent of the portions retained on the 4.75mm (No. 4) sieve at least two fractured faces.

S-6 Sand equivalent--not less than 35.

S-7 Flat or elongated particles--not more than 15 percent.

DESIGN METHODS FOR MIXTURES

The development of standard specifications and test methods for bituminous mixtures did not begin in earnest until after 1955. Currently, there are six ASTM standard methods for use in mix designs: Compressive Strength, Marshall, Hveem, Gyratory and Dynamic Modulus and a method, recently published by ASTM, based on the resilient modulus of compacted bituminous paving mixtures. The Compressive Strength, Marshall and Hveem Methods have been adopted by AASHTO.

AASHTO AND ASTM STANDARDS FOR ASPHALT PAVEMENT MATERIALS

The first ASTM Standard method of test was published in 1911 and was adopted in 1921. AASHTO endorsed the publication of the Standard and Tentative Methods of Sampling and Testing in 1921 and adopted them as Tentative Standards in 1924.

The 13th Edition of AASHTO Material Specifications, Part I, and Methods of Sampling and Testing, Part II, were published in 1982. The standards cover almost all of the materials used in highway construction. Table 1 shows the number of standard specifications, and the sampling and testing methods that are used to specify and control the properties of materials used in asphalt pavement construction (15).

AASHTO continues to adopt ASTM Standards when they conform to the needs of AASHTO Subcommittees. When the two standards are identical, the ASTM designation is shown with the AASHTO designation. When AASHTO adopts some revision of the ASTM standard, a footnote indicates that the standard is similar, but not technically identical, or indicates the exception in the footnote.

The AASHTO 1982 Books of Standards show that, altogether, there are eight specifications, four sampling methods and 44 test methods for aggregates, bituminous materials and bituminous mixtures. There are 22 ASTM

Standard methods of sampling and for specifications and test methods that have not been adopted by AASHTO. There also are 10 AASHTO standards that have no counterpart in ASTM. Tables 1 to 5 list the standard AASHTO and ASTM specifications, sampling and test methods.

The Association continues the policy of indicating, for naturally occuring materials, test limits which may be considered the most liberal that safety allows. This has been done with the understanding that where higher grade materials are locally available, more rigid requirements should be inserted. The policy has been followed in recognition of the necessity of adjusting requirements to meet local demands. Recommended test limits covering manufactured products such as cement, steel, asphalt, etc., may be considered as definite requirements for the materials for specific uses and under specific conditions and not subject to modification in the same sense that modifications in specifications for naturally occurring materials is justified.

TABLE 1
AASHTO & ASTM STANDARDS RELATED TO ASPHALT PAVEMENT CONSTRUCTION

MATERIAL	SPECIFICATIONS			SAMPLING METHODS			TEST METHODS		
	AASHTO ASTM	AASHTO ONLY	OTHER ASTM	AASHTO ASTM	AASHTO ONLY	OTHER ASTM	AASHTO ASTM	AASHTO ONLY	OTHER ASTM
Aggregates	3	1	2	2	-	-	7	6	5
Bituminous Materials	3	-	-	1	-	-	14	1	0
Bituminous Mixtures	1	-	1	1	-	-	14	2	12
General	-	-	-	-	-	2	-	-	-

TABLE 2
STANDARD METHODS OF SAMPLING AGGREGATES, BITUMINOUS MATERIALS AND MIXTURES FOR USE IN ASPHALT PAVEMENT CONSTRUCTION

AASHTO	ASTM	
T2	D75	Sampling Aggregates
T40	D140	Sampling Bituminous Materials
T168	D979	Sampling Bituminous Paving Materials
T248	C702	Reduce Field Samples of Aggregates to Testing Size
-	E105	Practice for Probability Sampling of Materials
-	D3665	Practice for Random Sampling of Paving Materials

TABLE 3
STANDARD SPECIFICATIONS AND METHODS OF TESTING FOR AGGREGATES
FOR USE IN ASPHALT PAVEMENT CONSTRUCTION

AASHTO	ASTM	AGGREGATE - SPECIFICATIONS
M17	D242	Mineral Filler for Bituminous Paving Mixtures
M29	D1073	Fine Aggregate for Bituminous Paving Mixtures
M43	D448	Standard Sizes of Coarse Aggregate for Highway Construction
M283	-	Coarse Aggregate for Highway & Airport Construction Supplementary Requirements for Use in Specifications
S1	-	Coating & Stripping of Bitumen-Aggregate Mixture; Minimum Retained Coating - 95%
S2	-	Plasticitiy Index for Aggregate Passing No. 4 not more than 6
S3	-	Adherent Coating on Aggregate After Dry Sieving not more than 0.5
S4	-	Crushed Gravel not less than 75% two crushed faces, Aggregate Retained on No. 4 (4.75 mm)
S5	-	Crushed Gravel not less than 50% two crushed faces, Aggregate Retained on No. 4 (4.75 mm)
S6	-	Sand Equivalent not less than 35
S7	-	Flat or Elongated Particles, not more than 15%
	D692	Coarse Aggregate for Bituminous Paving Mixtures
	D2940	Graded Aggregate Material for Bases and Subbases for Highways or Airports.

AASHTO	ASTM	AGGREGATE - METHODS OF TESTING
T11	C117	Amount of Material Finer than 0.075 mm, Sieve in Aggregate
T19	-	Unit Weight of Aggregate
T27	-	Sieve Analysis of Fine & Coarse Aggregate
T30	-	Mechanical Analysis of Extracted Aggregate
T37	D546	Sieve Analysis of Mineral Filler
T84	C128	Specific Gravity & Absorption of Fine Aggregate
T89	-	Determining the Liquid Limit of Soils
T90	-	Determining the Plastic Limit & Plasticity Index of Soils
T104	C88	Soundness of Aggregate by use of Sodium Sulfate or Magnesium Sulfate
T96	C131	Resistance to Abrasion of Small Size Coarse Aggregate by use of the Los Angeles Machine
T176	D2419	Plastic Fines in Graded Aggregates & Soils by use of the Sand Equivalent Test
-	D3319	Accelerated Polishing of Aggregates by using British Wheel
-	E303	Measuring Surface Frictional Properties using the British Pendulum Tester 1/
-	D3744	Aggregate Durability Index
-	D3398	Index of Aggregate Particle Shape & Texture
T112	C142	Clay Lumps and Friable Particles in Aggregates
T210	-	Production of Plastic Fines in Aggregates
-	E660	Accelerated Polishing of Aggregates or Pavement Surfaces using Small Wheel Circular Track

1/ May apply to any surface.

TABLE 4
STANDARD SPECIFICATIONS AND METHODS OF TESTING
BITUMINOUS MATERIALS FOR USE IN ASPHALT PAVEMENT CONSTRUCTION

AASHTO	ASTM	BITUMINOUS MATERIAL - SPECIFICATIONS
M20	D946	Penetration Graded Asphalt Cement
M52	D490	Tar for Use in Road Construction
M226	D3381	Viscosity Graded Asphalt Cement

AASHTO	ASTM	BITUMINOUS MATERIAL - METHODS OF TESTING
T44	D2042	Solubility of Bituminous Materials in Organic Solvents
T47	D6	Loss on Heating Oil and Asphaltic Compounds
T48	D92	Flash & Fire Points by Cleveland Open Cup
T49	D5	Penetration of Bituminous Materials
T50	D139	Float Test for Bituminous Materials
T51	D113	Ductility of Bituminous Materials
T52	D20	Distillation of Road Tars
T53	D2398	Softening Point of Asphalt & Tar in Ethylene Glycol Ring & Ball
T102	-	Spot Test of Asphaltic Materials
T164	D2172	Quantitative Extraction of Bitumen from Bituminous Paving Mixtures
T179	D1754	Effect of Heat & Air on Asphaltic Materials (Thin-Film Oven Test)
T201	D2170	Kinematic Viscosity of Asphalts
T202	D2171	Viscosity of Asphalts by Vacuum Capilarity Viscometer
T228	D70	Specific Gravity of Semi-Solid Bituminous Materials
T240	D2872	Effect of Heat & Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test)

TABLE 5
STANDARD SPECIFICATIONS AND METHODS OF TESTING BITUMINOUS MIXTURES FOR USE IN ASPHALT PAVEMENT CONSTRUCTION

AASHTO	ASTM	BITUMINOUS MIXTURES - SPECIFICATIONS
M156	D995	Requirements for Mixing Plants for Hot-Mixed Hot-Laid Bituminous Paving Mixtures
-	D3515	Hot-Mixed, Hot-Laid Bituminous Mixtures

AASHTO	ASTM	BITUMINOUS MIXTURES - METHODS OF TESTING
T110	D1461	Moisture & Volatile Distillates in Bituminous Paving Mixtures
T164	D2172	Quantitative Extraction of Bitumen from Bituminous Paving Mixture
T165	D1075	Effect of Water on Cohesion of Compacted Bituminous Mixtures
T166	D1188	Bulk Specific Gravity of Compacted Bituminous Mixtures using Paraffin Coated Specimens
T167	D1074	Compressive Strength of Bituminous Mixtures
T170	D1856	Recovery of Asphalt from Solution by Abson Method
T172	D290	Bituminous Mixing Plant Inspection
T182	D1664	Coating & Stripping of Bitumen-Aggregate Mixtures
T195	D2489	Determining Degree of Particle Coating of Bituminous-Aggregate
T209	D2041	Maximum Specific Gravity of Bituminous Paving Mixtures
T230	-	Determining Degree of Pavement Compaction of Bituminous Aggregate Mixtures
T245	D1559	Resistance to Plastic Flow of Bituminous Mixtures using Marshall Apparatus
T246	D1560	Resistance to Deformation and Cohesion of Bituminous Mixtures by Measurement of Hveem Appartus
T247	D1561	Preparation of Bituminous Mixture Test Specimens by means of California kneading compactor
T270	-	Centrifuge Kerosene Equivalent & Approximate Bitumen Ratio
-	D3387	Compaction & Shear Properties of Bituminous Mixtures by means of U.S. Corps of Engineers Gyratory Testing Machine
T269	D3203	Percent of Air Voids in Compacted Dense and Open Bituminous Paving Mixtures
-	D3496	Preparation of Bituminous Mixture Specimens for Dynamic Modulus of Asphalt Mixtures
-	D3497	Dynamic Modulus of Asphalt Mixtures
-	D3549	Thickness or Height of Compacted Bituminous Mixture Specimens
-	D3625	Effect of Water on Bituminous Coated Aggregate - Quick Field Test
-	D3637	Permeability of Bituminous Mixtures
-	D3666	Practice for Evaluation of Inspection & Testing Agencies for Bituminous Paving Materials
-	D4013	Practice for Preparation of Test Specimens of Bituminous Mixtures by Means of Gyratory Shear Compactor
-	D2950	Density of Bituminous Concrete in Place by Nuclear Method
-	E451	Testing Pavement Polishing in the Laboratory (Full Scale Wheel Method)
-	E510	Determining Pavement Surface Frictional & Polishing Characteristics using Small Torque Device
-	D2726	Bulk Specific Gravity of Compacted Bituminous Mixtures using Saturated Surface-Dry Specimens

II. QUALITY ASSURANCE

RESEARCH AND DEVELOPMENT PROGRAMS

The following summaries show the development in quality assurance from 1962 to the present.

In 1962, the Federal Highway Administration (FHWA) launched a comprehensive research and development program on the use of statistical methods for the control of quality assurance in highway construction (16). This program was necessitated by the tremendous highway construction program underway and the need to provide functional methods of quality control and acceptance of construction.

The program included the following objectives:

1. Awaken the industry's interest to the utility of the statistical approach to quality control and acceptance testing.

2. Develop guidelines for research to establish the statistical parameters needed for writing specifications.

3. Plan and coordinate a nationwide program of research in statisical methods.

4. Gather and analyze research data and disseminate research findings.

5. Design and implement experimental projects to evaluate the findings of the research program.

In 1965, the Bureau of Public Roads sponsored a conference on the state-of-the-art in quality control and acceptance specifications, materials and construction (16). The conference attracted representatives from the highway construction equipment industry, material producers, state highway departments, federal government agencies, consulting firms, universities and local governments. The conference focused on:

- Quality control in highway construction and maintenance
- Basic properties of materials
- Development of rapid non-destructive tests for acceptance.

Papers were presented on the need for quality assurance in the highway construction industry, material characteristics and processing factors in quality control, rapid and non-destructive test methods, statistical approach to quality control and acceptance specifications, materials testing variability and the development of statistical specifications.

By 1965, 28 states had been or were engaged in research to measure the quality of present construction. It was essential that information be established to show variability due to materials, sampling and testing so that realistic statistical specifications for acceptable construction could be written.

In 1969, the Office of Research and Development, FHWA, recommended that statistical concepts be incorporated in highway specifications to improve communications between contractors, engineers, lawyers and auditors (17). To implement the recommendations, the concepts should include the materials and material properties, the construction operations to be measured and controlled, the methods to be used for determining compliance and conditions under which either full or partial payment will be made.

The proper use of statistical concepts provides the following requisites:

- Statement of precise quality requirements
- Development of valid tolerances based on capabilities of process control and acceptance
- Delineation of responsibilities for process control to the seller and acceptance of the completed construction to the buyer
- Development of valid sampling plans as a basis for decision-making
- Establishment of precise decision criteria
- Development of valid proportional-payment schedules.

PROGRESS IN QUALITY ASSURANCE PROGRAMS

A substantial amount of the needed information was developed and published in the form of guidelines that were distributed to the states for use in planning research projects. Based on data received from the states prior to 1969, 50 percent or more of the overall variance from materials, processes, sampling and testing could be attributed to methods of sampling and testing. A statistical analysis of the data showed that a considerable portion of the construction was outside the limits as defined by the specifications. This variation, in part, reflected the errors in sampling and testing and did not reflect valid allowances for variable materials. The results of studies showed the magnitude of the sampling and testing error and indicated the need for a comprehensive effort to train inspectors and laboratory technicians.

Based on the results of studies and conferences conducted prior to 1969, it became evident that to fully implement a statistical approach to end-result requirements, adequate test methods to measure quality and trained manpower must be available to control the processing of materials and inspect the final product.

The importance of the contractor's role in the development of quality control and acceptance specifications using statistical concepts became evident in that each contractor would be completely responsible for providing quality materials and construction. To accomplish this, each contractor should develop his own quality control program so he would be assured of meeting the acceptance requirements of the state.

The state could elect to use the results from the suppliers' or contractors' quality control program for acceptance of materials and construction operations. The buyer could establish an independent plan for each material or construction requirement. The acceptance plan would include the lot size, the number of random samples per lot, method of test and the quality requirement. The procedure for making the decision would be based on the results of tests that would be compatible with the number of samples and the risk possibilities.

In 1971, the Transportation Research Board published Special Report No. 118 on the state-of-the-art and the needs of a highway department in the area of quality assurance and acceptance procedures (18). In that report, C. S. Hughes of the Virginia Highway Research Council reviewed the status of statistically-oriented specifications in bituminous construction, and pointed out that it was not evident that the highway departments were ready to change to statistically-oriented specifications. The particular concern was that the highway industry was reluctant to abandon the traditional methods and specifications that were in use for many years. There also was little evidence that contractors saw a need to introduce quality control procedures, mainly because the necessary incentive had not been provided.

Hughes showed that there are generally four steps in fully implementing statistical specifications:

- Step one is to establish realistic variability by making statistical analyses of historical data or by developing a sampling and testing system under controlled procedures. The first procedure is time-saving but the data probably are not based on random samples. The latter provides data collected by random sampling methods. At that time, there were about 25 highway agencies that were either working on step one or had proceeded further.

- Step two is to use variability to establish tolerances. This can be done by (a) merely inserting new tolerances in conventional specifications, or (b) changing the specifications entirely by adopting complete acceptance plans. There were about 12 agencies that had established tolerances for asphalt content and sieve analysis based on their data or those of others.

- Step three is to use new statistically-oriented specifications in simulated construction projects where the project is actually governed by the agency's conventional specification. Up to 1971, there were about 10 agencies that had or were using simulation procedures.

- Step four is to use statistically-oriented specifications as the basis of acceptance in a contract. There were eight states that had or were considering using this concept in some form.

Hughes enumerated the components more or less inherent in all of the statistical specifications either in simulation stage or actually in use. The specifications included all or part of the following components:

1. Lot size - generally considered a days production, for example, 2000 tons (1800 Mg). In setting the lot size, the consequences of

having a rejection or pay adjustment and number of tests should be considered.

2. Number of samples - number of samples per lot ranged from two to five with most states using four or five.

3. Acceptance of central tendency - the sample average is used and then compared to the process tolerance around the job mix to determine acceptance. Some states used a moving average with compatible limits. They found this procedure to be a more continuous function than simple averages.

4. Acceptance of variability - three methods often used are:

   (a) Limit the amount any one sample may vary from the central tendency.

   (b) Limit the size of the standard deviation.

   (c) Use the range to estimate variability.

5. Other acceptance criteria - percent defective product, quality index and limits based on sequential analysis - are also used.

6. Adjustment of bid price - this form of specification is based on acceptance, and leaves quality control up to the contractor or producer. When the product does not comply with the acceptance criteria, an adjustment is often required - either by removal or reduction in bid price. The latter is usually used because of the cost and difficulty of removal.

7. Control charts - used widely to control the contractor's process. The plotted data may be used for acceptance or, in most cases, to indicate a needed change in control.

8. Retesting and referee procedures - the limits established are completely dependent on the number of samples used for acceptance. If a retest is necessary and additional samples are necessary, the tolerances must be adjusted to agree with the number of samples.

Hughes summarized the pros and cons of statistically-oriented specifications as follows:

Statistically-oriented specifications do not solve all of the engineering or material problems but can solve many of the problems that arbitrary and indefinite specifications have caused in the past. Statistical specifications are being and will continue to be increasingly used because of their clarity and defensibility. The most serious problem is lack of statistical and other training of manpower that faces the contractor as he assumes more control of his process.

In 1976, NCHRP published Synthesis 38, Statistically-Oriented End-Result Specifications (19). The purpose of the report was to extend and amplify the concepts and findings of HRB Special Report No. 118, published in 1971 (18), with respect to specifications for highway materials and construction, and to show the advantages and disadvantages of statistical acceptance plans. It also was intended to provide contractors with a better understanding of their responsibilities in end-result specifications and the advantages of such a program to them.

The results of the NCHRP survey reported in Synthesis 38 showed that 33 states were using, planning to use or had tried some form of statistically-oriented end-result specification. Seventeen states were not using and were not planning to use this type of specification. Table 6 shows the number of states that had implemented or were considering the use of statistically-oriented specifications for the features and properties

TABLE 6
NUMBER OF STATES THAT HAVE IMPLEMENTED OR CONSIDERED THE USE OF STATISTICALLY-ORIENTED SPECIFICATIONS

FEATURE PROPERTY	CONTRACTOR OR PRODUCER QUALITY CONTROL	AGENCY QUALITY CONTROL	RANDOM SAMPLING	LOT-BY-LOT ACCEPTANCE	ACCEPTANCE BASED ON		OTHER STATISTICAL ACCEPTANCE CRITERIA	COMPACTION REFERENCED TO CONTROL STRIP	RAPID TEST METHODS	GRADUATED UNIT PRICE REDUCTION	NOT CONSIDERING ERS
					AVERAGE VALUES	QUALITY INDEX					
ASPHALT CONTENT	9	10	21	19	15	3	5	0	0	19	17
COMPACTION	5	7	21	24	12	5	7	12	14	19	17
GRADATION	11	9	22	19	19	1	5	0	0	21	17
SMOOTHNESS	1	0	4	5	1	1	0	0	0	7	17
THICKNESS	1	0	3	6	3	3	0	0	0	0	17

From NCHRP Synthesis Number 38 (19).

shown. Random sampling and lot-by-lot acceptance for asphalt content, aggregate gradation and compaction were being used by the largest number of agencies. Acceptance plans based on average values were used by a large number of of agencies.

QUALITY CONTROL SYSTEMS

Synthesis No. 38 reviewed the specification requirements to establish a quality control system by the contractor or producer. The requirements may be a simple statement that the contractor or producer shall install a quality control system or it may be a detailed list of requirements.

Some of the contractor's responsibilities in a quality control system are:

- Responsible for the complete supervision, performance and completion of all work in accordance with the original approved or revised drawings, specifications, special requirements and contract.
- Provide and maintain an inspection system for the quality control of all materials and construction.
- Perform inspections and tests required to show compliance.
- Provide and maintain test equipment.
- Correct conditions which result or could result in materials, processes or construction that do not conform to the requirements of the specification.

In addition to the above, a quality control system may include requirements for certification to determine whether:

- The processing plant is capable of producing a uniform product meeting specification requirements. The inspection usually includes testing equipment and facilities for the contractor's quality control.
- Personnel are capable of performing the required tests, computations and documenting results. Up-to-date maintenance of control charts may be specifically required.

NAPA Quality Control Manual

In 1982, the National Asphalt Pavement Association (NAPA) published a detailed manual on Quality Control for Hot Mix Plant and Paving Operations (20). The purpose of the manual is to assist engineers, contractors and producers in setting up a quality control system for sampling, testing and analyzing the test results which will assure a high probability of compliance with specifications.

The manual presents a detailed discussion with supporting data illustrations. The following is a brief review of the contents:

1. Developing a Contractor Quality Control Organization:

   Objectives, elements of quality control and quality control techniques, quality control personnel and relationship between the buyer and seller.

2. Quality Control Operations and Procedures:

   Plant control of materials, contractor's duties and responsibilities, mix design, acceptance sampling and testing, field control of placement.

3. <u>Quality Control Sampling and Evaluation Procedures</u>:

   Sampling techniques for quality control, random sampling, frequency of sampling and testing and process control charts.

4. <u>End-Result and Acceptance Plans and Specifications</u>:

   Inspection, acceptance plans, requirements and acceptance tests.

5. <u>Personnel Requirements</u>:

   Quality control organization, quality control training certification and qualification tests.

6. <u>Laboratory Requirements</u>:

   Field and laboratory tests required, laboratory equipment and layout.

7. <u>Problem-Solving Guidelines</u>:

   Failing tests - gradation, hot mix, field density and smoothness.

THE COST OF QUALITY CONTROL

Recently, Darrell Manning, Director of the Idaho Department of Transportation, reviewed the aspects of quality control of highway construction in relation to costs and higher quality pavements (21). He based his comments on information developed from the 1976 and 1979 surveys conducted by the FHWA on "Highway Condition and Quality of Highway Construction." Many states have improved their quality control methods but the high number of early distresses indicate that further improvements in quality control procedures are necessary. Manning identified the following areas that should be considered in developing a quality assurance program:

1. Frequency of sampling and testing needed for quality control of materials during construction.

2. Frequency of sampling needed to properly document the quality of the completed construction for acceptance.

3. Cost of sampling and testing in relation to the total construction cost of the project.

4. Availability of results of quality control tests that can be utilized to take early corrective action.

5. Use of engineering judgement in place of or in addition to sampling and testing programs.

6. Improved specifications for asphalt pavement construction written to properly identify and specify the number of tests and observation snecessary for good construction.

7. Specifying allowable tolerances for material properties and construction processes that are just and reasonable.

Manning enumerated the following programs that should be implemented:

1. Develop and implement performance requirements in specifications that will assure adequate structural capacity, durability, frictional properties and rideability of asphalt pavements.

2. Develop functional quality control and acceptance procedures for materials and construction that will result in improved performance.

3. Initiate training programs to develop certified technicians for inspection, testing and quality control of materials and construction.

4. Encourage the use of currently available rapid methods and the development of new methods for the control and acceptance of materials and processes used in asphalt pavement construction.

5. Encourage the collection of pavement performance data to show their relation to the properties of materials and construction.

6. Develop information on the variability of test data for properties of materials and construction and their relation to pavement performance.

PRICE ADJUSTMENT SYSTEMS

In 1977, Willenbrock and Kopac (22)(23)(24) presented a methodology to develop price adjustment systems suited for statistically-based highway construction specifications. The following is a brief outline of the suggested methodology of such a system:

1. Acceptance characteristics should be chosen so as to ensure that the desirable properties of the material are evaluated. The combination of acceptance characteristics and required process control characteristics should be comprehensive enough to provide adequate protection to the highway agency.

2. Individual price adjustment schedules should be devised by considering each acceptance characteristic separately.

3. The ideal schedule is probably one which assigns a payment reduction equal to the economic consequences of reduced quality. If the acceptance characteristic correlates strongly with pavement serviceability or performance, then such a schedule can be developed. If not, the highway agency should consider the cost of production approach.

4. If the schedule is developed on the basis of serviceability, a schedule based on the cost of production method should also be developed, if possible. Comparing the results of both methods may be beneficial to the agency so it can choose to use the cost of production method whenever it results in a larger price reduction.

5. Operating characteristic curves (o.c. curves) and curves of expected payment should be developed in step 4 as a check to assure that the proposed schedule is reasonable and meets the needs of the agency.

6. If neither the serviceability method nor the cost of production method applies to the acceptance characteristic in question, then the trial and error o.c. curve approach should be used.

7. The overall effect created by combining each individual schedule should be considered. Adjustments should be made to the individual schedules if necessary. Where adjustments are made, o.c. curves and curves of expected payment should be drawn.

8. The entire system should be carefully monitored under contract conditions. Data related to cost, serviceability, and quality should be gathered continuously to check on the design assumptions of the price adjustment system. The effects on the highway agency-contractor-material supplier relationship should also be examined.

ACCEPTANCE PLANS

In 1981, AASHTO published a Standard Recommended Practice for Acceptance Sampling Plans for Highway Construction, AASHTO Designation R9-81 (15). AASHTO also published a Standard Recommended Practice for Definitions of Terms for Specifications and Procedures, AASHTO R10-81.

These recommended practices were prepared to provide guidance in the use and application of acceptance plans and procedures for highway construction materials and items of work. Certain prerequisites were listed for realistic and practical acceptance plans. The most important are:

- A direct correlation between the criticality of the specification requirement as defined by the engineer and the estimated risk must be determined.
- The buyer's and seller's risk must be determined and must correspond with the criticality of the specification requirement.
- The number of sample increments required must be practical.
- The tolerance limits must be reasonable and acceptable to the engineer and reflect successful past construction experience.
- The statistical procedures and calculations must be simple and straight-forward.
- The specification requirement must be explicit and subject to only one interpretation by all concerned.
- The plan must be suitable for use by the highway industry and be applicable to various materials and construction on large or small jobs.

Statistical acceptance plans are of two types, those requiring inspection by attributes and those requiring inspection by variables.

An attribute sampling plan may be used when a characteristic can not be measured or does not have to be measured. The unit can be classified as acceptable or defective by visual examination. The most common use of this plan is a go or no-go situation such as aggregate particles that either have or do not have fractured faces.

A variables sampling plan applies to all cases where a characteristic is measured, such as viscosity of the asphalt or the resilient modulus of an asphalt concrete mix. There are two general cases, one where the standard deviation is known and the other where it is not known. Many of the acceptance plans in use today are based on variables.

Details of acceptance plans using the variables method where the standard deviation is known or unknown, the procedure for substituting range for sample standard deviation, and acceptance plans for estimating percent within tolerance (PWT) are given in Synthesis 38 but will only be referenced here.

The following factors should be considered when acceptance plans are being developed:

- <u>Random Sampling</u> - To insure that samples are not biased, random sampling points and times must be used. To spread out sampling points, random numbers are usually used in a stratified random sample plan.

- <u>Rapid Test Methods</u> - The use of rapid test methods has increased quickly. By 1976, 39 states were using nuclear methods to control the density and moisture in soils and aggregates. Twenty-nine states were using nuclear equipment to control the density of asphalt concrete.

- <u>Personnel</u> - The transfer of quality control to the contractor has placed more technical responsibilities with the contractor and material producer and, in some cases, has created a shortage of qualified technicians. With proper training and reliability, the agency and contractor testing personnel could be reduced.

In 1978, Hughes (25) made a survey questionnaire to determine current practices on the use of quality assurance techniques for bituminous concrete. All 50 states replied, but many indicated their specifications were in a state of change. The responses showed that 25 states had a statistical quality assurance specification for accepting production, which encompassed asphalt content and gradation. Twenty-five states were employing the program in acceptance of construction which encompassed density, thickness and roughness. The states estimated they were saving from $100,000 to $1,000,000 annually by using quality assurance programs.

The responses indicated that many of the states were very well satisfied with their quality assurance specifications. Some of the comments were:

- "Construction is better."
- "Less administrative costs."
- "Overall success very good...in time it should be excellent."
- "We consider this is a much more efficient and logical method than was used previously."
- "We are convinced that (the system) has not caused an increase in cost."
- "Several hundred thousand dollars savings based on reduction in legal suits and claims."

Responses from some agencies indicated a misunderstanding and mistrust of quality assurance procedures. The following are some of the pertinent comments concerning the question of whether the agency used a quality assurance program:

- "Not by your definition."

- "We have not seen an improvement in the product and, in fact, could see unnecessary manipulation by contractors giving us a less uniform product."

- "We do not employ formal statistically-oriented sampling and testing programs using rigidly defined lot sizes and sampling locations. However, most of our specifications, sampling frequencies, etc., are statistically sound, but flexible enough to accommodate unique situations."

- "May be forced into this by FHWA."

Table 7 shows the number of states using quality assurance specifications in 1978, the requirements for production and construction being used and those indicating interest in future use.

In 1979, Oregon State Highway Division and Oregon State University initiated a research project to study what effect materials properties outside specification limits had on pavement life. The effect of non-compliance on pavement serviceability had been questioned and resulted in frequent controversy with contractors. This study was aimed at developing a rational approach to assess the effects of variations from specification limits so that a firm basis could be established for the development of pay factors (26).

A questionnaire to state highway agencies, the District of Columbia and the Federal Highway Administration (FHWA) was employed to determine current methods being used for acceptance or rejection of asphalt concrete paving materials. Questionnaire items included were:

1. Acceptance of out-of-specification materials.

2. Properties tested for acceptance and methods of testing.

TABLE 7
SURVEY OF QUALITY ASSURANCE SPECIFICATIONS FOR THE PRODUCTION OF BITUMINOUS CONCRETE

ITEM	NO. OF AGENCIES	
	YES	NO
1) Agencies having quality assurance specification	25	25
Does your agency perform acceptance testing?	23	2
Does the contractor do control testing?	12	10
Is it required?	7	5
2) Are the following items specified?		
Point of acceptance sampling:		
Plant	13	--
Road (paver)	9	--
Lot size:		
2000 Tons (1800 Mg.)	5	--
2500 Tons (2250 Mg.)	4	--
Days production, tons	8	--
Number of tests:		
3	4	--
4	6	--
5	13	--
Are tolerances applied to:		
Average	18	--
Standard deviation	1	--
Range	7	--
Quality index	3	--
Price adjustments made	25	--
Control charts used	14	--
Agencies having quality assurance specification for bituminous concrete construction	25	25
Agencies having tolerances on:		
Roughness	14	--
Thickness	11	--
Density	25	--
Control strips used	13	--
Success of quality assurance program		
Excellent	6	--
Good	14	--
Fair	4	--
Poor	0	--
Is the quality assurance program cost beneficial	10	6*
Estimated annual dollar savings $100,000-$1,000,00		
If quality assurance specification is not used now, are you considering the use of one in the future?		
Production	14	
Roughness	15	
Thickness	7	
Density	16	
Other	0	

* Six (6) "No" and six (6) undecided.

3. Pay adjustment factors used.

4. Basis for establishing pay factors.

5. Relationship of pay factors to pavement serviceability.

6. Effectiveness of pay factors.

7. Summary opinions regarding pay adjustments.

Of the 51 questionnaires sent out, 47 were returned. Brief evaluations of the above items are as follows:

Forty one of forty five agencies indicated that they will accept some aspects of work or materials when they are out-of-specifications. The properties evaluated for acceptance were: thickness, smoothness, compaction, asphalt content, asphalt properties, aggregate quality, mix moisture content and mix gradation. The basis of applying pay factors were identified as follows:

- Statistical: the concepts of random sampling were used in collecting test data.

- Guide in specification: agency made use of pay factor guide, usually in tabular form as part of specifications. Statistical methods not used.

- Schedule: the agency established guidelines for use in applying pay factors, but they were not part of specifications.

- None: materials below specifications were not accepted.

- Negotiated: agency accepted out-of-specifications work. Negotiated with contractor and applied pay adjustments.

Many agencies which make use of pay-adjustment factors still retain a process of decision-making by the Project Engineer. The pay factors apply only if the out-of-specifications work or material is accepted.

The report shows the methods used for measuring the eight properties given above and the different bases used for the pay factors. The predominant method for establishing pay factors and the percent of agencies using the method are:

o Laboratory results	17%
o Field studies	23%
o Experience	60%

The authors considered the question of whether pay adjustment is proportional to the value of reduced pavement serviceability resulting from specification non-compliance. Because the reply to this question may depend on who in the agency responds to the question, the answers may not be considered the agency policy, but are considered here as valuable indicators of current trends in the development of pay factors. Only 26 percent of the agencies indicated that they believed their pay adjustments are proportional to reduced pavement serviceability.

The questionnaire obtained opinions regarding the need for pay adjustments and the success of the agencies' methods for acceptance of materials. A range of positive and negative comments illustrates the controversial nature of this topic. The authors reported on the advantages and disadvantages of using pay adjustments. The more important of these are as follows:

Advantages

o Improves contractor's quality control

- Creates a uniform procedure for accepting non-compliance
- Reduces problems of contract administration
- Reduces litigation
- Requires fewer state personnel

Disadvantages

- Needs to be based on sound engineering approaches
- Contractors resist change
- Contractors may increase estimates on bids
- Results in poor quality work
- Can't measure reduced serviceability
- Administrative problems

Summary of Findings

1. Ninety-one percent of the agencies indicated that they would accept some aspects of work or materials outside specification tolerances.

2. The specific properties accepted outside of specification tolerances by a large majority of the agencies were compaction, asphalt content, asphalt properties, aggregate quality and mix gradation. Approximately 50 percent of the agencies would accept smoothness and thickness requirements outside of the specification tolerances.

3. Most of the agencies which accept construction and materials outside of the tolerances applied a pay adjustment in reducing compensation to the contractor.
4. Background experience was predominantly used to establish pay factors.
5. There was a wide disparity in the pay adjustment factors used by different state agencies.

Recommendations

1. Continue research and testing to assess effects of variations from specification limits of construction and material properties.
2. Use current research results and data available from past projects to identify the design characteristics or properties which are critical to pavement serviceability and life.
3. Develop a uniformly accepted, equitable pay adjustment format based on sound engineering judgment. The use of layered elastic analysis and appropriate failure criteria analysis should be considered in preference to current practice using standard design procedures such as used in AASHTO asphalt pavement design method.
4. Evaluate the applicability of including bonus payments for construction and materials which are above specification tolerances and provide increased pavement serviceability or life.

Moore, et al, reported on a further analysis of the information obtained in the 1979 questionnaire to state agencies and FHWA (27). The emphasis of this study was to evaluate current practices and to present a rational approach to developing pay factors. Data were presented to show the pay adjustment factors used by agencies for thickness, smoothness, compaction, asphalt content, asphalt properties, aggregate quality, mix moisture content, and aggregate gradation. Table 8 shows the number of agencies that included each of the above properties, the methods used and the predominant basis for establishing pay adjustment factors. Detailed information on current pay for all properties was not complete. Thus, compaction, asphalt content and gradation were selected for detailed pay factor information:

Compaction - The tendency for wide divergence of approaches used by state agencies to determine pay adjustment for non-compliance with compaction requirements is shown in Table 9. There were ten approaches used by 23 states. Eleven of the agencies used pay factors based on target or control strip densities. Three used a reduction in contract price computed by a formula based on statistics. One or two agencies used each of the other approaches.

The divergence of approaches used by the agencies makes it almost impossible to make a logical comparison of the pay factors. Some indications of the variation can be obtained for six states using compaction pay factors for percent of target density. For 100 percent pay, the minimum percent of target density ranges from 94 to 97. At 85 percent pay, the minimum target density ranges from 87 to 94. The large difference in the minimum percent of target density is shown by Mississippi with 92.8 percent target density with zero pay, compared to Connecticut with 87 percent density and 85 percent pay.

The Oregon study points out the possible cause for confusion and dissatisfaction among paving contractors who undertake work in several states. This can be illustrated by comparing Mississippi with other states. For less than 92.8 percent density, Mississippi pays nothing. At 92 percent minimum density, South Dakota pays 70-80 percent and Utah pays 50 percent.

TABLE 8
NUMBER OF AGENCIES THAT TEST PROPERTIES, METHODS USED AND BASIS FOR PAY FACTORS

PROPERTY	AGENCIES THAT TEST PROPERTY	PREDOMINANT TEST METHOD USED AND NUMBER OF AGENCIES	PREDOMINANT BASIS FOR PAY FACTOR USED AND NUMBER OF AGENCIES
Thickness	31	Cores 23	Statistical 5 Guide in Spec. 7 None [1] 14
Smoothness	37	Straight-edge 26	Statistical 6 Guide in Spec. 6 None [1] 18
Compaction	43	Nuclear Gage 26	Statistical 11 Guide in Spec. 11 None [2] 16
Asphalt Content	43	Extraction 32	Statistical 17 Guide in Spec. 6 None [2] 15
Asphalt Properties	44	Agency Tests 31	Statistical 8 Guide in Spec. 13 None [2] [3] 16
Aggregate Quality	39	Approved Source 9 AASHTO Spec. 28	Statistical 3 Guide in Spec. 2 None [2] [3] 27
Mix Moisture Content	21	Standard or Modified Tests 18	None [2] [3] 15
Mix Gradation	45	AASHTO 35	Statistical 18 Guide in Spec. 8 None [2] [3] 14

From "Overview of Pay Adjustment Factors for Asphalt Concrete Mixtures"--Moore et al.

[1] Do not accept work below specification tolerance. Most agencies require overlay to correct deficiency at contractor's expense.
[2] Do not accept work below specification.
[3] Usually a requirement is not necessary.

TABLE 9
APPROACHES USED BY STATE AGENCIES TO DETERMINE PAY ADJUSTMENTS FOR NON-COMPLIANCE WITH COMPACTION REQUIREMENTS

APPROACH	NUMBER OF AGENCIES
Percentage reduction in contract price computed by formula based on statistics	3
Pay factors for percentage of target density	7
Pay factors for percentage of control strip density	4
Pay factors for percentage of voidless density	1
Pay factors for daily mean air void content	1
Pay factors based on deviation of air void content	1
Price adjustment for percentage of deficiency	1
Pay factors based on computed quality level	2
Pay factors based on computed quality index	1
Pay factors for percentage within limits	2

Asphalt Content - Twenty-four state agencies submitted detailed information on pay adjustment factors for asphalt content. The various approaches are shown in Table 10. Eight approaches were used by the 24 agencies.

As for compaction, the pay factors for asphalt content showed a wide disparity among state agencies. Pay adjustment factors determined by computing the average deviation of the asphalt content from the job-mix criteria were used by 13 states, the most common practice. The pay adjustment is applied either above or below the job-mix target value.

For 100 percent pay, the maximum deviation was 0.18 in one state and 0.55 in another state. The authors pointed out that, in terms of asphalt content, the same material supplied in two different states could be rejected by one state and be full payment in another state.

Mix Gradation - Twenty-five agencies reported detailed information on pay adjustment factors for non-compliance with mix gradation requirements. The seven different approaches used are given in Table 11. The most common approach is the pay factor based on the deviation of the mean from the job-mix formula, and was used by 14 agencies. There was a large disparity in pay adjustment factors for the No. 8 (2.36 mm) or No. 10 (2 mm) and the No. 200 (75 μm) sieves. For 100 percent pay for the No. 8 (10) material, the maximum deviation was zero for one state and 4.3 for another state. The maximum deviations for the No. 200 sieve material ranged from 0.0 to 2.0. For 90 percent pay, the maximum deviations ranged from 2.4 to 5.8 and from 1.2 to 4.0 for the No. 8 and No. 200 materials, respectively.

Based on the Oregon report, there was a wide disparity in pay adjustment factors. The range in deviations from target values and job-mix formulas indicates that for compaction, asphalt content and aggregate gradations, there is a definite need to clarify and rationalize the application of pay factors to acceptance specifications.

TABLE 10
APPROACHES USED BY STATE AGENCIES TO DETERMINE PAY ADJUSTMENT FOR NON-COMPLIANCE WITH ASPHALT CONTENT REQUIREMENTS

APPROACH	NUMBER OF AGENCIES
Percentage reduction in contract price computed by formula based on statistics	3
Pay reduction for percent out-of-tolerance	3
Pay factors for average deviation from job mix	13
Pay factors for deviation of sample average as percentage	1
Pay reduction for sample average as percentage	1
Pay factors based on deviation of mean above or below mix tolerances	1
Price adjustment computed by specific procedure based on percentage of asphalt above or below mix-design tolerance	1
Pay factors for degree of non-conformance of moving average	1

TABLE 11

APPROACHES USED BY STATE AGENCIES TO DETERMINE PAY ADJUSTMENT FOR NON-COMPLIANCE WITH MIX GRADATION REQUIREMENTS

APPROACH	NUMBER OF AGENCIES
Percent of reduction in contract price computed by formula based on statistics	4
Pay factors for deviation of the mean from job-mix formula	14
Pay reduction for percent within limits	1
Pay reduction for deviation of the sample average as a percent of mix tolerance	1
Pay reduction for the percent out-of-tolerance	3
Pay factors for the degree of non-conformance	1
Pay adjustment computed by a detailed procedure in the specification	1

OREGON ASPHALT CONCRETE PERFORMANCE STUDIES

Three in-depth studies were initiated by Oregon during the period between 1978 and 1980 to evaluate the performance of asphalt concrete base and surface courses (28)(29)(30). The overall intent of the studies was to obtain a better understanding of the causes of pavement distress problems and to develop the relationship between pavement performance and the different mix variables. The information was used as a basis to develop pay adjustment factors for materials and construction not complying fully with specifications. The mix variables and range of values studied were:

(1) Asphalt content: 5%, 6%, 7%

(2) Percent passing No. 200 (75 μm) sieve 2%, 6%, 10%

(3) Percent passing No. 10 (2 mm) sieve (for two projects only)

(4) Mix density 100%, 97%, 92%, 90%

Laboratory test specimens were prepared using materials from the three paving projects. The specimens were tested in the diametral mode for elastic modulus, fatigue life, permanent deformation and conventional tests (stability, void content and retained strength). To identify stripping, the elastic modulus, fatigue and permanent deformation were performed before and after vacuum saturation followed by a freeze-thaw cycle.

The authors made the following conclusions, which were essentially the same for the three paving projects:

1. The mix level of compaction was the controlling factor for all mix dynamic properties. Increasing mix density increased the mix stiffness, fatigue life and resistance to permanent deformation. For one project, high density substantially reduced the damage action of water.

2. One percent change in asphalt content from the design optimum did not significantly change the fatigue life of the mix.

3. The percent passing the No. 200 (75 μm) sieve was the second important factor for both fatigue life and the mix deformation. Decreasing the amount of fines decreased fatigue life and permanent deformation.

Using the range in mix variables, the authors evaluated the reduction in pavement life based on the mix properties not fulfilling the design specifications. Based on fatigue data, pay factors were developed to show variations in mix performance resulting from changes in mix density, asphalt content and percent passing the No. 200 (75 μm) sieve.

The data from the Oregon studies on the impact of variation in material properties on asphalt pavement life was analyzed further to show the development of rational pay-adjustment factors for asphalt concrete. Asphalt concrete mixture specimens were prepared with the same materials previously used. The specimens were subjected to diametral and conventional tests to determine the resilient modulus, fatigue life and permanent deformation characteristics of the mixtures. All tests were run using mix tensile strains ranging between 50 and 150 microstrain.

The mix properties evaluated were air voids, asphalt content, aggregate gradation and type of aggregate used. The influence of the various properties on performance was studied and the following relationships were found:

- Effect of density - Mix density (or air voids) was the most dominant factor for all mix properties. Fatigue life was primarily affected by the level of compaction (increased with decrease in percent voids).

- Effect of asphalt content - As asphalt content increased, fatigue life increased up to an optimum level. As the asphalt content increased, the voids were overfilled, aggregate friction decreased and the binder took over the loads. The fatigue life varied with type of aggregate and asphalt and level of traffic load.

- Effect of aggregate gradation - The amount of voids in the mineral aggregate (VMA) and voids filled with asphalt (VFA) greatly affected stiffness and fatigue life of an asphalt concrete mix.

- Effect of aggregate type - Aggregates used on the three field projects showed high statistical significance in their influence on fatigue life. The crushed stone mixtures showed better fatigue resistance than mixtures composed of gravel.

Using the material variables, pay-adjustment factors were developed based on fatigue and permanent deformation distress. The pay-adjustment factor was defined as the ratio of the fatigue life of the constructed pavement to the fatigue life of standard proposed pavement.

$$\text{Pay-Adjustment Factor} = \frac{N_f \text{ (of constructed)}}{N_f \text{ (of design standard)}} \times 100$$

N_f = number of load applications to failure

Pay-adjustment factors were developed for each mix variable and all three variables (asphalt content, voids and percent passing the No. 200 sieve). Aggregate type showed some influence on pay adjustment but the authors did not believe it was practical to include it in developing pay factors for general use.

THE CONTRACTOR AND QUALITY CONTROL

In 1978, Tunnicliff reported on the experiences of the Warren Brothers Company operating in seven states that were using statistically-oriented end-result specifications (31).

The control systems developed by the contractors to comply with the state specifications were explained. Problems and their solution were discussed, and contractor costs and benefits were tallied. However, overall company experiences were favorable and showed that end-result specifications are workable for contractors. Improvements that would be beneficial to both contractors and agencies were suggested.

Acceptance Requirements

Agencies in the seven states used seven different end-result specifications for acceptance. The different requirements specified and the number of agencies using each of the requirements included:

- Aggregate gradation - seven agencies. The number of sieve sizes varied from three to eight
- Asphalt content - seven agencies
- Mix temperature - seven agencies
- Marshall stability - four agencies
- Marshall flow - two agencies
- Roadway density - five agencies
- Air voids - one agency

- Smoothness - four agencies
- Thickness - two agencies
- Using one sieve size, the number of samples per lot varied from two to five and the tolerance for average results varied from ±2.2 to ±6.0. Lot size was based on day's production in three cases, on amount of material produced in three cases, and on unspecified amount produced in one case.
- The contractor was required to submit a job-mix formula for approval. In some cases, duplicate testing was required.

Control Systems

The control systems used by different states also varied, some of which were:

- The contractor furnished an agency-certified technician to perform all acceptance testing. Facilities and equipment for sampling and testing were specified. Acceptance tests were the basis for control.
- One agency performed its own acceptance testing and recommended a control system for the contractor.
- No control requirements were specified. The contractor was free to do whatever was necessary to ensure that the process was under control. Evidence of control through documentation, control charts and plant recordation were valuable to the contractor and agency.

Contractor Costs

In every case where the responsibility for quality control was passed to the contractor from the agency, there was an increase in the contractor's cost.

The costs varied with the circumstances of the agencies, but included some or all of the following:

- Maintaining qualified technicians at each plant
- Training costs for new technicians
- Laboratory facilities
- Penalties for out-of-specification materials or construction. Tunnicliff indicated that the costs usually amounted to a small fraction of one percent of contractor price.

Contractor Benefits

- More economical contractor mix designs more beneficial
- More effective use of quality control personnel
- Improved cooperation between contractor and agency
- Intangibles not readily determined but, in most cases, contractor's quality control appeared to be worth additional cost.

Future Implementation

Company experience with end-result specifications and contractor control of quality has been favorable. Major difficulties have been corrected and further implementation can be expected in the future. Areas for improvement include:

- More realistic tolerances
- Number of requirements
- Reproducibility of test methods
- Penalties - replace with incentives
- Development and use of just one standard end-result specification

MATERIAL SUPPLIERS AND QUALITY ASSURANCE

In 1975, the Georgia Department of Highways and the Georgia Crushed Stone Association initiated a quality assurance program for highway construction aggregates. Initially the program was voluntary, but by 1978 all stone producers elected to participate. The following items were identified as contributing to a good, functional quality control system:

1. Qualified personnel
2. A well planned, written system approved by management
3. Good housekeeping and preventive maintenance practices
4. Correct sampling and testing procedures
5. Proper data analysis

Vulcan Materials Company, a major aggregate producer, developed a quality acceptance program to support the state program (32). According to R.H. Brown, Vulcan's statistical control system has been a very effective aid in controlling quality and knowing what is being produced. The program is a valuable management tool which provides the following advantages:

- It documents the quality of products and satisfies the product certification programs of state highway departments.
- It reduces the amount of material shipped that does not meet specifications.
- It is simple to administer.
- It can be an effective cost-control activity.

The Standard Slag Company (33) developed a quality control system using a controlled sampling and testing program and the use of control charts for documentation. A moving average of five test results is used on the charts. To upgrade the quality control program, training sessions for technicians are required. They can become certified with attendance at the seminars.

To expedite sampling and testing, automatic sampling devices are used. A sample can be sliced from the conveyer, be split, sieved, the separate fractions weighed, and a printout prepared in less than 10 minutes. Fine aggregate samples are dried in microwave ovens, reducing the drying time to about one third of the time required in conventional ovens. A pycnometer method is used for determining the amount of material finer than No. 200 sieve (75 μm).

The cost of the process control plan has been determined to be from \$0.02 and \$0.03 per Mg (\$0.018 and \$0.027 per ton). To replace rejected material, the costs of production, transportation, placement and removal could well exceed the selling price by four or five times.

ECONOMIC ANALYSIS OF GRADATION CONTROL

In 1982, the Federal Highway Administration (FHWA) reported on a study of the economic analysis of aggregate gradation control. The study was conducted to evaluate the relative costs of aggregate gradation control programs by state highway agencies (34).

Three actual state programs were chosen as being representative of the different aproaches. The programs are described below.

State "A" Program

The aggregate gradation control program is a QA-QC type program. The producer has the primary responsibility for the gradation testing of aggregates for process control, while the state is responsible for assuring the reliability of the producer's test results. Producers are required to employ technicians certified by the state to perform process control gradation testing.

The resident engineer is responsible for sampling the hot mix at the project level and delivering the samples to the district laboratory for testing. The gradation tests on the extracted aggregate are used for acceptance by the engineer. Due to the lag in testing, the engineer's staff makes tests on the cold feed. These test results are considered advisory and are not used for acceptance.

Testing Frequency - Producers perform one gradation test for each 1,500 tons (1350 Mg) on each class of aggregate.

Verification tests are performed by the district laboratory for each 6,000 tons (5400 Mg) for each class of aggregate.

A minimum of one gradation test is performed by district laboratory per project for less than 6,000 tons (5,400 Mg).

District laboratory performs extraction and gradation tests on hot mix samples. Three samples are taken per day; usually only one random sample is tested. If it fails, the other two are tested and results averaged.

State "B" Program

The program is a QA-QC program that places emphasis on the construction contractor for quality control of aggregates. The program emphasizes "point-of-use" testing, whereby aggregates are sampled at the last point before being incorporated into their intended use product. This point is the project site for base and subbase materials and the mixing plant for bituminous mixes.

The program incorporates statistically-oriented end-result specifications for the acceptance of products in which the aggregates are used. The program requires that the contractor use certified technicians for gradation testing.

Testing Frequency - Quality control sampling and testing by the contractor's certified technicians is required at the rate of two samples of bituminous mix for extraction, asphalt content and gradation testing. One sample is taken in the morning and one in the afternoon.

Samples taken for verification testing by the state are obtained by splitting the samples taken by the contractor's certified technician at a frequency of one per day.

The state has established a comprehensive technician certification program which is available to contractor, state and independent testing laboratories.

State "C" Program

This program is a traditional program of aggregate gradation testing in which the state personnel perform nearly all sampling and testing. There are no state requirements for in-house quality control by the producers; however, many of the producers in the urban area perform a certain amount of aggregate gradation control for their own benefit. The program differs in the rural and urban areas, and the following covers the main differences:

Rural Areas - Samples of aggregates for gradation testing are collected by the resident engineer and tested by the engineer's staff. The actual samples are obtained by the contractor's employees under the supervision of the state inspector. The samples are often tested at the project site, but also may be tested at the engineer's office or district laboratory.

Urban Areas - A branch of the materials laboratory is located in the urban area and assists in testing and handling the increased work load. The engineer's technicians collect and test all samples of aggregate to be used in base and subbase construction. The district laboratory technician collects and tests all hot mix samples. Testing of verification samples is divided between the staff of the district and the staff of the materials section, jointly using the facilities of the district laboratory.

Testing Frequency - Project Control Tests. One sample per 4,000 tons (3,600 Mg) for subbase aggregate; one sample per 2,000 tons (1,800 Mg) at source plus one pe 5,000 tons (4,500 Mg) at project site for base aggregate; one sample per 2,000 tons (1,800 Mg) at the plant, plus one per 2,000 tons (1,800 Mg) at the project site for plant mix aggregate.

Verification Tests - One per project for subbase aggregate; one each at source and job site per 40,000 tons (36,000 Mg) for base course aggregate; one per 4,000 tons (3600 Mg) at the plant, plus one per 10,000 tons (9,000 Mg) at job site for plant mix aggregate.

Record Samples - One per 50,000 tons (45,000 Mg) for subbase aggregate; one each at source and project site per 25,000 tons (22,500 Mg) for base aggregate; one each at the plant and project site per 25,000 tons (22,500 Mg) for hot-plant mix aggregate.

Technician Certification - The state conducts a strong training program for technicians at different levels and various categories.

Economic Analysis

The only significant differences among the three state programs were in labor costs for gradation control.

The authors pointed out that the programs of the three states offered a unique combination of sources, producers, contractors and state highway agencies and should only be taken in the context of the three programs examined. The following are some of the noteworthy points made for this particular study:

- The large variation in state manpower devoted to aggregate testing
- The total producer effort is fairly low, even in State "A" where the gradation control program places considerable testing requirements on the producers. Less verification and acceptance testing by State "A" probably would suffice for adequate gradation control.
- All three states reported good aggregate quality as a result of their aggregate control programs. Thus, the most economical program should be favored in the future.

The quantities in the following table show the differences in manpower devoted to aggregate gradation control among the three states.

COMPARISON OF MANPOWER FOR STATES "A", "B", AND "C"			
State Program	Man-hours Per 1000 tons		Total Man-hours by SHA
	SHA	Producers	
State A	15.4	2.3	196,560
State B	2.8	0.8	56,160
State C	50.2	0.3	85,384

1 Ton = 0.9 Mg; 1 Man-hour per 1000 Tons = 1.1 Man-hour per 1000 Mg.

Model Aggregate Gradation Control Program (34)

The report describes in detail a model aggregate gradation control program. The model was formulated by extracting and combining the most favorable and economic features of various state programs.

The following is a summary of the various elements of the program:

- o Objective - Promote and maintain aggregate quality with respect to gradation.
- o Point of Use Testing - The agency avoids any involvement in disagreements between the contractor and his aggregate supplier by accepting aggregate at the point of use only.
- o Personnel Qualifications - Proper qualifications of individuals involved in quality control are essential. Certification requirements should be the same for state and outside personnel.
- o Laboratory Equipment - All equipment used to provide gradation control testing should meet the requirements of all applicable AASHTO and/or ASTM specifications and test methods.

- Contractor Quality Control - Process control testing is the responsibility of the contractor. The contractor may elect to perform the process control functions with his own forces, through those of his contractors and/or suppliers, or through the services of an independent testing laboratory.

- State Highway Agency's Quality Assurance - Test results generated by the contractor's quality control program are used directly for acceptance; the validity of those results is substantiated by a concurrent program of quality assurance which includes verification testing.

- Acceptance Criteria - Acceptance criteria allows for variance resulting from sampling and testing error. A more detailed discussion of acceptance criteria is given in the full report.

The structure of the model gradation program is summarized in the following paragraphs:

Place and Method of Sampling - Samples shall be taken at the last identifiable point where sampling is feasible prior to mixing with other ingredients.

Sampling and Testing Frequency - Sampling and testing frequency shall be determined by the particular utilization of the aggregate. In the case of aggregate for bituminous concrete, three sets of samples are taken each day (a set being defined as three samples taken consecutively within a short time interval).

Sampling and QC/Acceptance Testing by the Contractor - All sampling shall be performed by the contractor or his authorized representative. All samples shall be split by an approved splitting device. One half shall be delivered to the SHA representative at the project site. The other half shall be tested as soon as possible. Written test reports shall be delivered to the SHA no later than noon of the day following completion of the test.

Retesting by Contractor - If results indicate non-compliance with respect to any sieve size, the other two samples at the same set shall be tested immediately and the results of the three tests shall be averaged. Compliance is based on averages and total outside limit (TOL).

QA Testing by the State Highway Agency - SHA shall test, on a random basis, one sample out of every ten sets of samples submitted by the contractor. One sample out of each set where results were averaged by the contractor also shall be tested.

Sample Control and Documentation - A designated representative of the SHA shall maintain a log book containing identification of each sample and the time it was received. This log shall provide the primary documentation for verification of compliance with the sampling and testing frequency.

Acceptance Criteria - Acceptance shall be based only on the contractor's test results, with the SHA test results used only to establish the reliability of the contractor's results. Details are given in full report.

Payment Criteria - Monetary penalties apply not only to non-conforming aggregate accepted subject to price reductions, but also to aggregate delivered during periods when the contractor's test results show poor reliability. A price reduction of 10% shall be applied to all aggregate delivered during periods time that the contractor shows poor reliability.

SUMMARY OF SECTION II - QUALITY CONTROL

Section II shows that substantial progress has been made during the past 20 years in the effort to develop asphalt pavement specifications.

The prerequisites for the proper use of statistical concepts that were essential when the quality assurance programs were first undertaken have been resolved to various degrees. Included are:

- Proper allocation of responsibilities of the contractor and agency
- Effective and realistic quality control by the contractor
- Lot by lot acceptance of construction
- Use of random sampling methods
- Selection of end-result requirements
- Statistically-oriented acceptance plans
- Use of pay adjustments for non-conforming materials and construction

Because of the wide divergence in quality assurance and acceptance plans now being used by states and other agencies, more realistic and uniform tolerances for measured characteristics should be determined.

III. SURVEY OF CURRENT ASPHALT PAVEMENT SPECIFICATIONS

One of the tasks in this study was to review existing specifications for dense and open-graded bituminous concrete surfaces and bituminous base courses. The features were to be organized so that the advantages and disadvantages of the requirements could be compared. To accomplish this, requirements of specifications in use by 15 states, AASHTO and FHWA were tabulated in Tables 12-22.

The specifications reviewed were selected by FHWA and were considered to represent good geographical distribution, as well as a range in variability and type of requirements. The specifications used by nine states and FHWA included quality assurance requirements (QA) and were of end-result specification ERS type. The specifications of six states and AASHTO were considered conventional or "recipe" type. The author is aware that there are requirements in other state specifications that differ from those used by the 15 states. Where possible, the features of the QA will be compared with the features of the conventional or recipe specifications.

Representative specifications were reviewed to show:

1. Responsibilities of the agency (engineer) and contractor for materials and construction.
2. Job-mix formula, requirements for aggregate gradation and bitumen content.
3. Quality requirements for density, thickness and smoothness.
4. Construction requirements and limitations.
5. Quality assurance plans for control and acceptance and for pay adjustment.

In developing the information in tabular form, it was necessary, in some cases, to abbreviate or abstract the information as printed in the official book of specifications. The author suggests that if detailed information is desired the reader refer to the printed specification books.

A discussion of the principal items in Tables 12 to 22 follows.

Responsibilities of the Agency and Contractor - Quality Assurance (QA) Type Specifications - Table 12

Table 12 shows the responsibilities of the agency and contractor for nine states and FHWA, who are using specifications containing QA requirements for quality control and acceptance of materials and processes used in asphalt pavement construction. For convenience, the term agency(ies) will be used collectively for states, AASHTO and FHWA.

The more important items in the specifications and the responsibility for their conduct are:

Job-mix formula - In nine of ten specifications, the contractor prepares and submits the job-mix to the agency. Usually the job-mix includes a single percentage of aggregate passing each designated sieve size, a single amount of binder, and a single temperature of the mixture during production. The job-mix formula with the specified tolerances must be within the master range of the specification.

Job-mix approval - In all specifications, the job-mix formula is approved by the engineer.

Furnish samples - For seven agencies, the contractor furnishes the required samples. Three agencies obtain their own samples.

Certification of technicians - Six of the agencies require the contractor to have technicians certified by the State present during plant mixing and construction.

Approve material certification - Seven agencies approve materials by certification.

Construction control - Plant mixing, spreading and compacting are the responsibility of the contractor.

Mixing plant - Eight agencies approve the contractor's mixing plant.

Quality control testing - Five agencies and five contractors perform quality control testing. Tolerances allowed for aggregate grading, binder content, and density by nearly all agencies. Smoothness and thickness were used by two and three agencies, respectively.

Acceptance - All agencies make final acceptance. One or more of the following characteristics are used by one or more agencies: aggregate grading, binder content, density, smoothness and thickness.

TABLE 12 RESPONSIBILITIES OF AGENCY (ENGINEER) AND CONTRACTOR - QUALITY ASSURANCE (QA) TYPE SPECIFICATIONS

	ALASKA Sec. 106-401	CONN. Sec. 1.06-4.06 M04.01	GEORGIA Sec. 106-400	KENTUCKY	LOUISIANA	NORTH DAKOTA	UTAH	VIRGINIA	W. VIRGINIA	FHWA
Responsibility:										
Mix Design	Engineer	Engineer	Contractor	Engineer	Contractor	Engineer	Engineer	Engineer	Engineer	Contractor
Job mix formula	Engineer	Contractor	Contractor	Contractor	Contractor	Contractor	Contractor: Grading. Engineer: Bitumen Contractor	Contractor	Contractor	Contractor
Job mix approval	Engineer	Engineer	Engineer	Engineer	Engineer	Engineer	Engineer	Engineer	Engineer	Engineer
Furnish samples	Contractor	Engineer	Engineer	Contractor or Engineer	Contractor	Engineer	Contractor	Contractor	Contractor	Contractor
Quality Control testing	Engineer	Engineer 1/	Contractor	Contractor or Materials	Contractor	Engineer	Engineer	Contractor	Contractor	Engineer
Other Testing (Retesting)	Engineer	Engineer	Engineer	Contractor	Contractor		Engineer	Contractor	Contractor	Contractor
Certified Technician			Contractor	Contractor	Contractor			Contractor	Contractor	Contractor (Adequate)
Approve Material Certification	Engineer	Engineer	Engineer	Engineer	Engineer		Engineer			Engineer
Mixing Plant Control	Contractor	Contractor	Contractor	Contractor	Contractor	Contractor	Contractor	Contractor	Contractor	Contractor
Approved by:	Engineer	Engineer	Engineer	Engineer		Engineer		Engineer	Engineer	Engineer
Spreading Control	Contractor	Contractor	Contractor	Contractor	Contractor	Contractor	Contractor	Contractor	Contractor	Contractor
Compacting Control	Contractor	Contractor	Contractor	Contractor	Contractor	Contractor	Contractor	Contractor	Contractor	Contractor

1/ Chief Materials Testing Section

TABLE 12 (Cont'd) RESPONSIBILITIES OF AGENCY ENGINEER AND CONTRACTOR - QUALITY ASSURANCE (QA) TYPE SPECIFICATIONS

	ALASKA Sec. 106-401	CONN. Sec. 1.06-4.06 M04.01	GEORGIA Sec. 106-400	KENTUCKY	LOUISIANA	NORTH DAKOTA	UTAH	VIRGINIA	W. VIRGINIA	FHWA
<u>Quality Control by:</u> Based on allowable Tolerances for:	Contractor Aggregate grading Asphalt content Density Thickness Surface smoothness	Deviation and range Asphalt content Aggregate grading Density Surface smoothness Thickness	Aggregate grading Asphalt content Density	Aggregate grading Asphalt content Density Thickness	Aggregate grading Asphalt content Marshall Stability	Aggregate grading Asphalt content	Aggregate grading Asphalt content	Deviation from job Aggregate grading Asphalt content Density	Deviation from job Aggregate grading Asphalt content	Deviation from job Mix: grading Asphalt content
Acceptance by: Based on Tolerances for:	Engineer Lot 2500 tons 5 samples Aggregate grading Asphalt content density	Engineer Days run (Lot) Minimum 3 tests Pay factor for: Asphalt Aggregate grading	Engineer Lot (days run) Marshall Stability Roadway density Surface tolerance Thickness	Engineer None stated	Engineer Lot (days) Marshall Stabilityi Roadway density Surface tol- Thickness Aggregate grading	Engineer Lot (days) Aggregate grading Asphalt content density Surface tolerance Thickness	Engineer Lot (days run) 1 to 5 Tests based on quantity Aggregate Asphalt content density	Engineer Lots 1 to 4 tests to 4000 tons Standard deviation over Aggregate gradation Asphalt content	Engineer grading Bitumen content Surface tolerance	Engineer grading Asphalt content density Surface tolerance
Sampling Method:	Random	Random	Random samples	As directed by engineer	Random samples	Random samples	Random	Random samples	Random	Random samples

1 Ton = 0.907 Mg

Responsibilities of Agency and Contractor - Conventional Specifications - Table 13

Job-mix formula - Five contractors prepare and submit the job-mix formula to the agency. Two agencies prepare the job-mix formula.

Job-mix approved - Five agencies approve the job-mix.

Samples - Six contractors furnish samples.

Testing - Seven agencies perform tests.

Conformity - Seven agencies determine conformity with job-mix formula for asphalt content and gradation.

Acceptance - Seven agencies accept final work.

Conformity - Five agencies determine conformity with the job-mix: one agency, density; three agencies, smoothness; one agency, thickness.

Equipment and processes for mixing, placing and compacting - Seven contractors.

TABLE 13 RESPONSIBILITIES OF AGENCY AND CONTRACTOR - CONVENTIONAL SPECIFICATIONS

	CALIFORNIA Sec. 6-39	INDIANA	KANSAS	MICHIGAN	NEW YORK	WASHINGTON	AASHTO
			Item 603 Flexible Pavement	Item 7.10 Plant Mix	Item 401	Item 5.04-9.03	Guide Specifications
Mix design or type	Contractor	Engineer	Engineer	As specified	-	As specified by	Suggested values
Job mix formula	Contractor	Contractor	Contractor*	Engineer	Contractor	Engineer	Contractor
Job mix approved by	Engineer	Engineer	Engineer	-	Engineer	-	Engineer
Samples furnished by	Engineer	Contractor	Contractor	Contractor	Contractor	Contractor or Agency	Contractor
Testing performed by	Engineer	Engineer	Engineer	Engineer	Engineer	Engineer	Engineer
Conformity determined by		Job mix tolerance aggregate Asphalt content	Job mix Tolerance Gradation asphalt content	Job mix Tolerance Gradation asphalt content	Job mix Tolerance for Aggregate grading Asphalt content	Job mix Tolerance for Aggregate grading Asphalt content Compaction	
Acceptance by:		Engineer	Engineer	Engineer	Engineer	Engineer	Engineer
Based on Conformity with:		Job mix Mix uniformity Mix workability	Job Aggregate Surface tolerance Density	Properties of recovered asphalt Surface smoothness	Reasonable conformity with Job Mix Aggregate grading Asphalt content Surface smoothness Thickness	Conformity with Job Mix Aggregate grading Asphalt content	Job mix tolerance Temp. mix
Equipment and process for Mixing Placing Compaction	Contractor	Contractor	Contractor	Contractor	Contractor	Contractor	Contractor

*Asphalt content determined by engineer.

Requirements for Job-Mix Formulas - QA and Conventional Specifications - Tables 14 and 15

All agencies have master ranges for asphalt contents and gradations. Tolerances are to be applied to each sieve size and asphalt content in the job-mix formula. The values shown in Tables 14 and 15 are for dense-graded mixtures having a maximum nominal size aggregate of 3/4-inch (19 mm). Most agencies also specify aggregate gradations and asphalt contents for other nominal maximum size aggregates. The gradations for Kansas' job-mix aggregate are on a retained basis, but were transposed to a passing basis in this report. Utah specifies the gradation for an ideal mix and the allowed tolerances for each sieve size within that gradation.

Most agencies have provisions for changing the job-mix during construction with a provision that the new job-mix is subject to approval by the engineer. A subjective evaluation of the requirements in the job-mix formulas for the agencies using either QA or conventional specifications indicates significant differences in the master ranges for aggregate grading and asphalt contents. Some of the differences in the master grading ranges are illustrated in Figures 1 and 2 for four of the agencies. In addition to the master range, the Washington specification requires that the job-mix shall approach a maximum density grading.

Tolerances for plant mixing temperatures are usually included in the job-mix formula. The tolerances range from ±15 to ±25°F (±9.4 to ±3.9°C). Temperature requirements for master ranges during construction are included in Tables 19 and 20.

TABLE 14 JOB-MIX FORMULA - QA TYPE SPECIFICATIONS

	ALASKA		CONNECTICUT		GEORGIA		KENTUCKY		LOUISIANA		NORTH DAKOTA		UTAH		VIRGINIA		WEST VIRGINIA		FHWA	
	Sec. 401		Sec. 406		Sec. 400		Sec. 401 & 402		Sec. 501		Sec. 406 & 412		Sec. 402		Sec. 320		Sec. 401		Sec. 401	
Job-Mix Formula	Master Range	Tolerance	Master Range	Tolerance	Master Range	Tolerance	Master Range	Tolerance	Master Range	Tolerance	Master Range	Tolerance	Ideal Mix	Tolerance	Master Range	Tolerance	Master Range	Tolerance	Master Range	Tolerance
Aggregate Passing Sieve																				
1 inch	100		100						100	±6					100	±3.0			100	±7
3/4 "	85-100	±8	90-100	±8	100	±7			85-100	±6	100	-1	100	0	80-100	±5.0	100	±7	95-100	±7
1/2 "			70-100	±7	85-100	±6.1	100	±6	70-100	±9	85±15		80	±11	86-100	±5.0	85-100	±5	68-86	±7
3/8 "	65-85	±7	60-82	±7	70-85	±5.6	80-100	±5											56-78	±7
1/4 "																				
1/8 "																				
No. 4	45-65	±7	40-65	±7			55-80	± 5	40-70	±7	58±18	±5	50	±8	81-95	±5.0	50-70	±5	38-60	±7
No. 8	30-50*	±6	28-50	±6	44-48	±4.6	35-60	± 5	25-55*	±6	48±17				84-82	±4.5	30-55	±5	27-47	±6
or 10*													24	±7						
No. 16							22-46	± 5			38±16						20-40	±5	18-37	±6
No. 20																				
No. 30											31±16	±5			39-47	±4.0			13-28	±5
No. 40	12-30	±4							8-33	±5										
No. 50			6-26	±4	10-25	±3.8	5-21	±4											9-20	±4
No. 80 or 100*							3-14*	±2	4-20	±4	22±12		15	±6	20-28	±2.5	5-20	±4		
No. 200	3-10	±3	2-8	±2	2-10	±2.0	2-7	±1.5	2-10	±2	15±9	±2	6	±2	4-8	±1.5	1-10	±3	4-8	±2.5
Asphalt content		±0.5	5-8	±0.5	5.25-7.0		4-8	±0.3	4.5-7.0	±0.4	9±5	±0.55		1/	5.0-7.5	0.29	4-10			
Mix Temperature	250-325°F			±15°F		±20°F		± 15°F		±25°F		±20°F	220-260°F		210-280°F			±20°F	225	±30°F

1/Set by Engineer

1 in = 25.4 mm

To convert Fahrenheit temperature to Celsius temperature, use C = 5/9(F-32)

TABLE 15 JOB-MIX FORMULA - CONVENTIONAL SPECIFICATIONS

	CALIFORNIA		INDIANA Suggested Values		KANSAS BM2		MICHIGAN No. 12-WCM		NEW YORK Type 6-6F & 7-F		WASHINGTON Class B		AASHTO Suggested Values	
Job-Mix Formula	Master Range	Tolerance	Master Range	Tolerance	Master Range	Tolerance	Master Range	Tolerance	Master Range	Tolerance	Master Range	Tolerance	Master Range	Tolerance
Aggregate Passing Sieve		1/						2/				2/ 5/	2/	3/
1 inch	100				100				100				grad-	
3/4 "	95-100						100				100		ation	±7
1/2 "							95-100		90-100		90-100			±7
3/8 "	65-80		100		60-90		65-90				75-90			±7
1/4 "			90-100						36-65	±6	55-75	±10		
1/8 "			49-77								No. 10		Supp-	
No. 4	44-59	X ±5	88-61		No. 8	±6							lied	±7
No. 8 or No. 10	31-45	X ±5			28-58	±6	45-70				32-48	±8		±4
No. 16													by	±4
No. 20									15-39	±7				
No. 30	13-26	X ±5	24-47		12-36	±5	20-45		8-27		11-24		State	±4
No. 40			16-20											
No. 50						±5			3-6					
No. 80 or 100						±4			4-16	±4	6-15			±4
No. 200	3-8	4-10	6-26			±3	3-10			±2	3.0-7.0			±2
Asphalt Content	2/		2-17 0-7 0-4		2/		5-7		5.8-7.0	±0.4	4/ 4.0-7.5			±0.4
Mix Temperature					275°F -325°F	6/		±20°F		±25°F		±25°F		±20°F

1/ X = Job-Mix value.
2/ Designated by engineer.
3/ Suggested values.
4/ Percent of mix.
5/ Grading approaching straight line and meeting design requirement.
6/ Temperature based on furol viscosity of 75-150 sec.

1 in = 25.4 mm

To convert Fahrenheit temperature to Celsius temperature, use C= 5/9 (F-32)

Job-Mix Formula - Open-Graded Plant Mixtures (Friction Courses) - Table 16

Table 16 shows the master range for gradation, asphalt content, mixing temperature, and allowable tolerances for the job-mix for open-graded plant mix friction courses (OGFC) used in 10 states, FHWA and AASHTO specifications.

For all agencies, the maximum nominal size aggregate is either 1/2 in. (12.5 mm) or 3/8 in. (9.5 mm). In most cases, the smaller sizes are controlled by the No. 4 (4.75 mm), No. 8 (2.36 mm) and No. 200 (75 μ m) sieves. Two states specify No. 16 (1.18 mm) and two specify No. 50 (300 μ m) sieve sizes. The amount passing the No. 200 (75 μ m) sieve varies from 0 to 6 percent. The asphalt contents range from 5 to 7 up to 6 to 12 per cent.

The aggregate gradings vary as illustrated below:

% passing 1/2 in. (12.5 mm) sieve, 88-100 to 100
% passing 3/8 in. (9.5 mm) sieve, 22-43 to 100
% passing No.4 (4.75 mm) sieve, 5-15 to 30-50
% passing No.8 (2.36 mm) sieve, 0-7 to 10-30
% passing No.16 (1.18 mm) sieve, 5-15 to 18-24
% passing No.50 (300 μ m) sieve, 3-7
% passing No.200 (75 μ m) sieve, 0-6

TABLE 16 JOB-MIX FORMULA - OPEN GRADED PLANT MIXTURES (FRICTION COURSES)

	ALASKA		CALIFORNIA		GEORGIA				KENTUCKY			LOUISIANA			NEW YORK		UTAH (TYPE A)	
Aggregate	Range	Tolerance	Range	Tolerance	Range		Tolerance		Range		Tolerance	Range	Tolerance		Range	Tolerance	Range	Tolerance
Total Passing	Type II				D-I	D-II	D-I	D-II	Type I	Type II			1 Test	2 Test				
3/4 inch			100			100	±7										Ideal Mix	
1/2 "			88-100		100	90-100			100			100			95-100		100	0
3/8 "	100	±7	22-43	±7	85-100	40-75	±6.1	±6.1	90-100	100		90-100	±10	±7			97	±2
1/4 "															48-64	±5		
No. 4	30-50	±7			10-40	5-25	±5.7	±5.7	25-50	50-100	±6	20-50	±10	±7	8-18		40	±4
No. 8			2-3	±5	0-10	0-10	±4.6	±4.6	5-15	10-30	±4	0-15					30	±3
No. 10											(Type 2 only)		± 9	±6				
No. 16	5-15	±6															21	±3
No. 40																		
No. 50																	13	±2
No. 80																		
No. 100																		
No. 200					0-4	0-4	±2	±2				0-6	±3	±2	2-5		4	±1
Asphalt Cement					6.0-7.25	5.5-7.0							±.6	±.4	5-7.0		By Engineer	
Mixing Temp.													±25	±25°F	225-250°F			
Aggregate Temp.			Max. 275°F		Mix Temp. Delivered ±20°F from Job-Mix													

To convert Fahrenheit temperature to Celsius temperature, use C = 5/9(F-32)

TABLE 16 (Cont'd) JOB-MIX FORMULA - OPEN GRADED PLANT MIXTURES (FRICTION COURSES)

Aggregate	VIRGINIA (TYPE S-8)			WASHINGTON (CLASS D)		WEST VIRGINIA		FHWA		AASHTO	
	Range	Tolerance		Range	Tolerance	Range	Tolerance	Range	Tolerance	Range	Tolerance
Total Passing		1 Test	3 Tests[1]	% Mix						[3]	
3/4 inch											
1/2 "	100	±10	±5.6			100	±7.0	100	±7		
3/8 "	85-100	±10	±5.6	100		85-100	±5.0	85-100	±7		
1/4 "	15-32	±10	±5.6	30-50	±10						
No. 4		±9.0	±5.0	5-15	1/4" Sieve	30-50	±3.0	30-50	±7		±8
No. 8	0-7			-	±8	5-15		5-15	±6		±6
No. 10											
No. 16											
No. 40											
No. 50				3-7							
No. 80											
No. 100											
No. 200	0-5	±3.0	±1.7			2-5	±3.0	2-5	±2.5		±2
Asphalt Cement	6.0-12.0	±0.8	±0.44			As directed by Engineer		4-8[2]	±0.5		±0.5
Mixing Temp.	210-260					250-325°F	Job Mix ±20°F				

[1] Tolerances for 2, 4 and 5 tests also given.
[2] Range in bituminous material for porous aggregate 4-12%.
[3] Maximum aggregate temperature for viscosity of $800c_st$

1 in = 25.4 mm

To convert Fahrenheit temperature to Celsius temperature, use C = 5/9(F-32)

Quality Requirements - QA Specifications - Table 17

Table 17 shows the procedures used by agencies to measure and control QA requirements for density, thickness and smoothness of bituminous pavements.

Density - Six of the 10 agencies use a control test strip to establish a roller pattern that will assure a density meeting the target density. All agencies use the nuclear test method to measure and control the density during construction. Conformity is determined by a minimum requirement for percent of the target density. Two agencies use the density of compacted specimens from the road or laboratory to verify the target density.

Thickness - Five agency specifications have a general requirement that the surfacing shall conform with lines, grades, and thickness (and sometimes cross section) shown on plans. Methods used to measure and determine conformity include: measurement of pavement cores after compaction, depth of mix after breakdown, and rate of spread.

Surface Tolerance (Smoothness) - All but two of the ten agencies measure surface tolerances by a straight edge. One state specifies a road meter and one the BPR Roughometer. Seven use the 10-foot straight edge and one the rolling straight edge. Maximum deviations using the 10-foot straight edge range from 1/8 in. (3.1 mm) to 1/4 in. (6.3 mm) measured longitudinally. Four states have requirements for cross slope.

TABLE 17 QUALITY REQUIREMENTS - QA SPECIFICATIONS

AGENCY REQUIREMENT	ALASKA	CONN.	GEORGIA	KENTUCKY	LOUISIANA	NORTH DAKOTA	UTAH	VIRGINIA	W. VIRGINIA	FHWA SPECIAL PROVISIONS
Density										
Method of Measuring	Control Test Strip Density Standard: Average 10 one minute random nuclear counts.	Nuclear gauge or pavement core.	Control Test Strip. 5 random nuclear tests or cores.	Job-mix based on Marshall design.	Density determined by 5 random pavement samples	Control Test Strip. 400 sq. yds. 5 random nuclear tests - additional strips if needed.	Compaction procedures specified to obtain required density.	Control Test Strip. Field density determined by Engineer.	Control strip nuclear tests.	Control strip nuclear tests. Verified by cores 400 lane feet.
Conformity	5 nuclear tests per each 2500 tons 98% control strip.	95% target density value.	94% calculated voidless mix based on apparent specification gravity of aggregates.	Density of lot <96% design density.	95% minimum average for pavement samples.	95% Marshall Field density	96% Maximum or 93% Maximum lab density maximum specification (Rice).		Target density % within tolerance pay: 85-100 100% 80-85 98% 75-80 97% 70-75 93% <70 Special Action.	96% Target density.
Thickness										
Method of Measuring	Conform with lines grades and thickness shown on plans.	Depth of mix after breakdown rolling	By rate of spread (weight per sq. yd.) or by cores.	By cores Pavement 5 random samples	Average thickness. Road samples. for density use.	Reasonably close conformity to lines, grades thickness & typical cross sections on plans.	Conform to elevations grades and cross section shown on plans.	Base thickness. Conform with plans. Binder & surface thickness accord- into to ratio of application shown on plan.	Lot 2000 2 lanes, 5 sublots, 5 cores from each sublot. Retests permitted.	In close conformance with lines, grades and cross section shown on plans.
Conformity		Maximum variation: 3/4"	Surface course ±1/4" or 20-25 lbs. ratio of spread	±0.05 ft of plan thickness.	Plan thickness or less. Underthickness 0.25". Plan thickness >4". Underthickness 0.50".				Average of 5 cores. 80%->85% specified thickness. Retests: Average 15 cores specified thickness and at least 80%-85% specified thickness.	

1 in = 25.4 mm

TABLE 17 (Cont'd) QUALITY REQUIREMENTS - QA SPECIFICATIONS

AGENCY REQUIREMENT	ALASKA	CONN.	GEORGIA	KENTUCKY	LOUISIANA	NORTH DAKOTA	UTAH	VIRGINIA	W. VIRGINIA	FHWA SPECIAL PROVISIONS
Smoothness Method of Measuring	10 feet straight edge	10 feet straight edge. Test parallel to center line.	Project length over one mile. Road meter used.	10 feet straight edge parallel to center line.	Rolling straight edge	10 feet straight edge True to plans: Crown, alignment and grade.	Longitudinal 25 feet stringline. Transverse 10 feet straight edge.	10 feet straight edge	BPR Roughometer value (in per mi.)	10 feet rolling straight edge. 100 linear segment per 1/2 mi.
Conformity	Maximum deviation 3/16".	±1/4" surface ±3/8" base	Average Road Meter reading less than 400	Base ±1/4". Surface ±1/8" Cross slope 1/4" in 5'.	1/8" with - screed control. 3/16" without screed control.	3/16" parallel to center line.	Maximum deviation: Longitudinal 0.025 feet. Transverse 0.01 feet.	Maximum variation: 1/4".	(81 or less) 100% 82-85 90% Over 85 Special Evaluation.	Maximum deviation: not more than 10% over 1/8"

1 in = 25.4 mm

1 lb = 0.45 kg

1 sq yd = .836 m^2

1 ft = .305 m

1 ton = .907 Mg

Quality Requirements - Conventional Specifications - Table 18

Density - Three states base density on compacted specimens. One agency calculates the density and voids from the bulk specific gravity and maximum theoretical density by the ASTM D2041 method. The author assumed that the bulk specific gravity method was determined by ASTM D2726.

Thickness - Five agencies measure thickness and specify conformity to nominal thickness as practical. One agency calculates thickness on the rate of spread and one agency has tolerances for thickness and determining conformity.

Surface Tolerance (Smoothness) - All agencies use straight edges of 10 (3.05 m), 12 (3.66 m) or 16 (4.88 m) feet in length. Two agencies provide for the optional use of a stringline. Conformity is determined by maximum deviation ranging from 0.12 to 0.25 inches longitudinally. Five agencies specify maximum transverse deviations ranging from 0.24 (6.4 mm) and 0.31 inches (9.4 mm).

TABLE 18 QUALITY REQUIREMENTS - CONVENTIONAL SPECIFICATIONS

AGENCY REQUIREMENTS	CALIFORNIA	INDIANA	KANSAS	MICHIGAN	NEW YORK	WASHINGTON	AASHTO 1979 GUIDE SPECIFICATIONS
Density Method of Measuring	Compaction procedure and roller types.	Roller types and procedures.	Compaction procedure specified. Roller types.	Control test strip. Density based on Modified Marshall. Rollers specified Road density by nuclear tests.	Compactor types and procedure specified.	Types of rollers optional. Nuclear gauge or cores.	Rollers sufficient to obtain required density steel, pneumatic vibratory.
Conformity	Thoroughly compacted.	Density test strip, nuclear 95% maximum theoretical density.	Compact to a road Density> Field Mold density. Base course 94%. Surface 96%. Shoulders 94%.	100 percent Marshall control density. Density less than 98% requires adjustment in roller pattern.	No density requirements.	92% Max. density and Min. Optional density in place density and voids by Max. Theo. density.	92%+ of max. theoretical density or 95%+ of specified lab. density. Optional use of control strip with nuclear density check by cores.
Thickness Method Measuring	No Method specified.	No method specified.	Design or specicified thickness calculated from rate of spread per unit area.	Thickness specified by the Engineer	Near nominal thickness as practical.	No method specified.	No method specified.
Conformity	No requirements.	Substantial conformity with lines, grades and cross sections.	Substantial conformity required.	Substantial conformity	<1/4" for thickness <4". 1/2" for 4" to 8" - <5/8" over 8".	Reasonably close conformity with plans.	Reasonably close conformity with lines, grades, thicknesses and cross sections shown on plans
Smoothness Method of Measuring	12 ft. straight edge.	10 ft. straight edge.	10 ft. straight edge or 25 ft. stringline.	10 ft. straight edge.	16 ft. straight edge or stringline longitudinal lost straight-edge Transverse.	10 ft. straight edge.	10 ft. straight edge at selected longitudinal and transverse locations.
Conformity	Maximum deviation: Longitudinal 0.01 feet. Tranverse 0.02 feet.	Maximum deviation: 1/4 inch base 1/8 inch surface.	Maximum variation: 10 ft. 3/16" 25 ft. 5/16"	1/8" Lower courses.	Max. tolerance: 1/4" parallel and transverse.	<1/8" longitudinal. <1/4" transverse.	Maximum deviation 0.015 foot (suggested). Defective material replaced or overlayed.

1 in = 25.4 mm

1 ft - .305 m

Construction Requirements and Limitations - QA Specifications - Table 19

The primary purpose of Table 19 is to show the limitations of construction as affected by weather, base condition and temperatures during plant mixing, spreading and compacting hot asphalt concrete mixtures. All specifications have some limitation on ambient air or base temperature or require that the pavement be constructed under satisfactory conditions.

Various requirements for surface of base condition during paving include: dry, stable, clean, free from standing water, and not frozen.

Temperature limits of aggregates, binders and mixtures during plant mixing, spreading and compacting are listed in all specifications. The purpose of the requirements is to assure more uniform distribution of the asphalt and aggregates during plant mixing and to maintain workability of the mixture during spreading and compaction on the road. There are no consistent or standard procedures used by the various states. Critical temperatures are the maximum temperature during plant mixing and the minimum temperature during spreading and compaction.

The most important features of the requirements for limiting construction are those based on course thickness, mixture temperature and base or air temperature to establish the necessary time available to complete compaction and meet the density requirement. Four of the agencies having QA specifications base limitations on course thickness and either air or surface temperature (three use minimum temperature only). Three agencies use seasonal limitations. For agencies using conventional specifications, four base limitations on course thickness. Two agencies have seasonal limitations. One specifies air and base temperatures.

TABLE 19 CONSTRUCTION REQUIREMENTS AND LIMITATIONS - QA TYPE SPECIFICATIONS

AGENCY REQUIREMENT	ALASKA	CONN.	GEORGIA	KENTUCKY	LOUISIANA	NORTH DAKOTA	UTAH	VIRGINIA	W. VIRGINIA	FHWA
Weather limitations. Mixing & laying. Minimum air & base temperature.	Air temp. Dense mix >40°F open mix >60°F	No rain or fog. 1-1/2" thick + 30°F. 1" thick + 50°F.	Minimum air temp. for thickness 1" or less 55°F 1.1"-2" 45°F 2.1"-3" 35°F 3.1"-4" 30°F 4.1"-8" Construction discretion.	Dense surface mix. Ambient temp. 1" or less 45°F Base or binder mix 35°F Friction course. Ambient air temperature 60°F Seasonal limits may apply.	Temp. descending and air temp. in shade +45°F. Ascending +40°F. Dry surface Above applies for courses less than 3" thick.	Minimum air temp. 32°F.	Minimum air temp. 50°F. Seasonal 4/15 to 10/15.	Good weather and good surface conditions.	Satisfactory conditions. Seasonal 5/1 to 11/1.	Base dry, thawed. Surface temp. range: <1-1/4" 55°F 1-1/4"-2-1/2" 45°F 2-1/2"-4" 35°F >4" 25°F
Base condition during paving.	Surface dry Stable Thawed		Dry and not frozen apply.	Surface dry.	Dry, clean.	Not frozen.		Surface reasonably free of standing water.	>40°F Satisfactory to Engineer.	<1-1/4" 55°F 1-1/4"-2-1/2" 45°F 2-1/2"-4" 35°F >4" 25°F
Plant mixing, laying and compaction	250-325°F	Mix at plant 265-325°F. ±15°F of job-mix temp.	Max. aggregate Temp. 350°F. Temperature of control strips (specified by contractor).	Aggregate 240°F-325°F. Asphalt 225°F-325°F. Mix of plant 240°F-325°F in truck at job. Minimum 225°F ±15°F at job-mix temp.	Not less than 25°F below discharge temp.	Delivered to paver 190-290°F. ±20°F target.	Plant Mixing Temp. based on viscosity of 150-300 Cst. Dryer drum 220°F-260°F.	Plant Mixing 210-280°F. ±20°F job-mix Placement 30°F at job-can reject	Aggregate: Using asphalt 250°F-325°F. Using tar 200°F-270°F. Asphalt storage 250-325°F. Drum maximum temp 300°F.	Aggregate temp. ±30°F of AC temp. AC temp. based on viscosity. Temp. for viscosity of 150-300 cSt.

To convert Fahrenheit temperature to Celsius temperature, use C = 5/9(F-32)

TABLE 19 (Cont'd) CONSTRUCTION REQUIREMENT AND LIMITATIONS - QA TYPE SPECIFICATIONS

AGENCY REQUIREMENT	ALASKA	CONN.	GEORGIA	KENTUCKY	LOUISIANA	NORTH DAKOTA	UTAH	VIRGINIA	W. VIRGINIA	FHWA
Compaction temp.	Initial compaction +225°F. Final compaction +175°F.	Initial ±25°F from job-mix. Final compaction temp. 175.	None specified.	None specified.	None specified.	None specified.	Compaction complete before drop in temp. below 180°F.	Compaction for mixes except mix S-8 <1-1/2" base temp. +80°F for 1 roller <3/4" base temp. Temp. 80°F	Asphalt 325°F. Tar 270°F. Completed mix asphalt 300°F. Tar 270°F.	Placing temp. Asphalt 225°F Tar 150-225°F
Mixing time		Ross count 95% + coated.		Set by Engineer.				Min. 45 sec. or mix thoroughly coated.	45 sec. For less time use Ross Count >95%	To give complete uniform coating.
Moisture in mix						<2%	<2%	<0.5%	<1%	<1% in heated aggregate. Drum dryer mix <3%.

1 in = 25.4 mm

To convert Fahrenheit temperature to Celsius temperature, use C = 5/9(F-32)

Construction Requirements and Limitations - Conventional Specifications - Table 20

Table 20 shows the limitations of construction as affected by weather, base condition and temperatures during plant mixing, spreading and compacting hot asphalt concrete mixtures for conventional specifications.

All agencies using conventional specifications have requirements for limiting construction to satisfactory conditions. Four agencies specify minimum temperatures based on the thickness of the course being laid. Two agencies have seasonal limitations. One state uses cessation temperatures which are based on thickness and time for completing compaction. Four states specify roller types and roller pattern.

TABLE 20 CONSTRUCTION REQUIREMENTS AND LIMITATIONS - CONVENTIONAL SPECIFICATIONS

AGENCY REQUIREMENTS	CALIFORNIA	INDIANA	KANSAS	MICHIGAN	NEW YORK	WASHINGTON	AASHTO Suggested Values
Weather Limitations	Min. air temp. Dense mix. Surface 50°F. Base 40°F Open mix. Surface 70°F on bridges & structures. Surface Temp. 60°F.	Ambient temp. 2" or more. Temp. 45°F using density control. 1"-2" 45°F. Subgrade temp. 3". Paved surface temp. 25°F.	Minimum air temperature: 1-1/2" or less 50°F Over 1-1/2" 40°F	Seasonal limits for placing: lower Peninsula 5/15 to 11/1. 6/1 to 9/15 sand mix.	Season limits (1): Top course 4/1 to 11/15. Top course E&S 5/1 to 10/14.	Temperature rising. Surface Temp. <0.1" 55°F .1-2" 45°F .21-.35" 35°F .35" + Optional	Temperature limitations. Surface course. Surface Temp. thickness: <0.10 55°F 0.10-0.20 45°F 0.20-0.35 35°F >0.35.
Base Condition	Not frozen and proper condition.	Surface dry. Base condition during paving.	Dry-not frozen.	Threatening rain or moisture on surface.	Surface temp. 3" thickness or more 40°F Less than 1" 50°F	Friction course. Air temperature 60°F + dry surface.	Temperature limitations. Base surface temperature for thickness <0.10 55°F 0.10-0.20 35°F 0.20-0.35 25°F >0.35 25°F
Plant Mixing, Laying and Compaction	Dense mix spread and 1st coverage of roller ±250°F. Complete spread at not less than 200°F. Open mix spread in temp. 200-250°F.	Cessation Tables used.	Mix temperature on vis temperature 75-150 sec. See other Asphalt delivery Temperature 325-375°F. Delivery temperature satisfactory.	Max. batch mixing temp. 350°F. Drum mix 270-350°F. Minimum placement temperature over 100 lb/sq. yd. Above 40°F 100 lb/sq. yd. or less. Above 50°F sand-asphalt mix any thickness 60°F.	Mix from storage bins +20°F from pugmill discharge temperature.	Maximum temperature of asphalt 350°F ± 25°F of set temperature. Maximum mix temperature 325°F Friction course 260°F.	Maximum Range in temp. for aggregate and asphalt 25°F.

To convert Fahrenheit temperature to Celsius temperature, use C = 5/9(F-32)

TABLE 20 (Cont'd) CONSTRUCTION REQUIREMENTS AND LIMITATIONS - CONVENTIONAL SPECIFICATIONS

AGENCY REQUIREMENTS	CALIFORNIA	INDIANA	KANSAS	MICHIGAN	NEW YORK	WASHINGTON	AASHTO Suggested Values
	Compaction temp. preferably above 180°F. Complete above 150°F except open graded. Mix 1 pass immediately.	Test strips must be completed above 180°F.			Minimum comp. temp. 185°F. Minimum Vibroller 175°F.		Mix temp. Lowest to provide 95% + coating.
Roller pattern	Dense Mix: Initial 3 pass. Pneumatic 3 pass. Final 1 pass.	Rollers and roller pattern specified.		Rollers and roller pattern specified.	Rollers and roller pattern specified.		
Mix Time		Based on mix type. Range 30-40 sec.	Based on mix type. Range 30-40 sec.	Dry: min.10 sec. Wet: 25-50 sec.	Dry: 15 sec. Wet: 45 sec. May be adjusted by Engineer.	Complete and uniform coating. (95%) Thorough distribution of asphalt.	Dry mixing: 5 sec. Wet mixing: 25 sec.

1 in = 25.4 mm

1 lb/sq yd = .836 m^2

To convert Fahrenheit temperature to Celsius temperature, use C = 5/9(F-32)

Acceptance and Pay Adjustment - QA Specifications - Table 21

Table 21 gives the acceptance plans and pay adjustment schedules. Eight agencies include aggregate gradation, bitumen content and density in their acceptance plans. Surface tolerance (smoothness) is used in six of the specifications and thickness in four specifications. Two agencies include penetration and viscosity tests on asphalt cements in their acceptance plans.

All agencies base their acceptance and pay adjustment plans either on a day's production of quantities in tons or linear feet of roadway. When tonnage is used, the lot sizes vary from 500 ton (454 Mg) to 50,000 tons (45,360 Mg). Eight of the ten agencies specify either four or five random samples per lot.

In general, pay factors are determined using the mean value of individual tests on each lot. If the mean deviates from the job-mix by more than the tolerances in the acceptance schedule, pay adjustment factors are applied.

TABLE 21 ACCEPTANCE PLANS AND PAY ADJUSTMENT SCHEDULES

AGENCY REQUIREMENT	ALASKA	CONN.	GEORGIA	KENTUCKY	LOUISIANA	NORTH DAKOTA	UTAH	VIRGINIA	W. VIRGINIA	FHWA
Acceptance Plan Based on:	Deviation larger than allowed by tolerances for job-mix and quality requirements.	Deviation larger than allowed by job-mix and quality requirements.	Deviation larger than allowed by tolerances for job-mix and quality requirements.	Deviation of mean tolerances from job-mix formula and quality requirements.	Minimum or maximum deviations for requirements.	Average deviation from job-mix formula.	Average deviation from job-mix formula and tolerances for other quality requirements.	Process tolerances of plant samples to determine deviation from job-mix formula by using adjustment points.	Contractor shall design quality control plan.	Maximum deviation from job-mix.
Characteristics included:	Gradation Bitumen content. Compacted density penetration. Viscosity.	Gradation Bitumen content. Compacted density.	Gradation Bitumen content. Compacted density. Thickness and surface tolerance.	Gradation Bitumen content. Asphalt properties. Density.	Gradation Marshall stability. Roadway density. Surface tolerance.	Gradation Asphalt content. Density.	Gradation Asphalt content. Density; Thickness; Smoothness.	Gradation Asphalt content. Density; Thickness; Smoothness.	Gradation Asphalt Content.	Gradation Bitumen content. Density; Smoothness.
Size of Lot	2500 tons	500 tons - per day.	Days production.	Days production.	Days production.	Days production.	Days production.	2000 ton lot or 4000 ton. Over 50,000 ton each lot.	1000' lot for density. 500' lot for smoothness. 2000' lot for thickness.	Days production 1-5 random samples.
Samples per lot	5 random samples.	5 random samples.	1 to 8 random samples for gradation and asphalt content compaction. 5 tests per lot	5 samples.	4 or 5 stratified random samples.	4 random samples normal. 1 to 3 samples may be used for smaller lots.	5 random samples over 2500 tons. 1500-2500 tons 4. Less than 1500 tons 3 samples.	Mean of 4 random stratified samples per lot.	Divided 5 sublots. Density 5 cores. Thickness 5 cores per sublot and 10 cores.	Gradation Bitumen content. 5-10 samples. 1/100' smoothness.

TABLE 21 (Cont'd) ACCEPTANCE PLANS AND PAY ADJUSTMENT SCHEDULES

AGENCY REQUIREMENT	ALASKA	CONN.	GEORGIA	INDIANA	KENTUCKY	LOUISIANA	NORTH DAKOTA	UTAH	VIRGINIA	W. VIRGINIA	FHWA
Price Adjustment and Pay Factors	Determined by statistical formula with pay factors for each of above characteristics. Sum of factors determines price adjustment.	Based on additional tolerance and range for gradation and Bitumen content. Compaction percent of target density. Thickness and smoothness by amount of maximum tolerance.	Pay factor schedule for deviation at the mean value of 1 to 8 tests from job-mix formula. Compaction pay factor for percent of target density (lot average 5 tests) surface tolerance. Pay factor for maximum tolerance. Thickness tolerance based on rate of spread.	Percent of pay reduction for each percent beyond tolerance. Gradation 3/8" No. 4. No. 8 1% for each asphalt content, 3% density, 5% each 0.1 below 98, 10% plus 1% for each .1 below 96.	Pay factors for deviation of the mean tolerance. Gradation 3/8", No. 4. No. 8 (10). No. 200 sieve Asphalt content. Asphalt viscosity.	Price adjustments gradation deviation from control limits. Marshall Stability. Minimum value and % unit price. Density minimum value and % unit price per lot. Surface tolerance. % of roadway exceeding tolerance.	Lot accepted at an adjusted unit price based on deviation from job-mix and density and smoothness requirements.	Lot accepted at pay factors based on the mean deviations for grading and asphalt content. Density accepted.	Adjustment points for each sieve size and asphalt content for each lot. Unit bid price reduced by 0.05% for each adjustment point applied deficiencies in density. Surface tolerance and thickness corrected or replaced.	Price adjustment percent % lot within tolerance or density, smoothness and thickness.	Pay factors determined by level Deviations & range of test results for Gradation Bitumen content. Target density for compaction smoothness. Maximum tolerance.

1 Ton = .907 Mg

1 in = 25.4 mm

1 ft = 0.305 m

Summary of Responsibilities of the Agency and Contractor - Table 22

Table 22 summarizes the responsibilities of the agency and contractor for the quality assurance and conventional specifications. The number of states having contractors responsible for mix design is about equal for the QA and conventional specifications. The principal differences in contractor and agency responsibilities are shown in the quality control requirements in the QA specifications. As would be expected, the acceptance requirements are the agency's responsibility for both types of specifications. However, in the QA specifications, the acceptance is based on tests on random samples from a specified lot. Acceptance in the conventional specifications is based on judgment.

Table 22 Summary of Responsibilities of the Agency and Contractor

Responsibility	Number of Agencies QA (10)	 Conventional (7)
Contractor:		
Design job-mix	9	5
Furnish job-mix materials	7	6
Furnish certified technicians	6	0
Quality control plan	10	No provision
Construct road:	10	7
Use control strip for density	6	1 (optional)
Use nuclear density gauge	6	1 (optional)
Agency:		
Approve job-mix	10	5
Perform control testing	5	7
Make final acceptance	10	7
Use lot for acceptance	10	Based on judgement
Specify random samples	9	
Specify samples per lot	10	Based on judgement
Specify price adjustment	10	Based on judgement

IV. PERFORMANCE-RELATED SPECIFICATIONS

One of the objectives of this state-of-the art study was to develop a framework of a system of performance-related specifications for asphalt pavements and to identify test procedures that would support such specifications.

A performance-related specification may be defined as a specification that assures the construction of a pavement to meet the demands imposed by traffic and environment for a specified period of service life. The specification must contain only requirements for the properties of materials and construction processes that are directly related to performance. To accomplish this, the specification must define and provide methods to measure the essential properties that are related to performance. The construction processes also must be controlled to provide pavement surfaces that are resistant to skidding, are smooth-riding and durable.

In addition to using performance requirements, the specification should include quality assurance requirements for process control and acceptance. Insofar as possible, the acceptance should be based on end-result requirements. There are standard test methods that can be used to measure end-result requirements, such as density, smoothness, and skid resistance. However, existing new methods of evaluation, such as indirect tension, resilient modulus and creep, should be investigated further to replace conventional or indirect methods currently used. The use of in-place, non-destructive methods also should be expanded.

To develop a realistic performance-related specification for asphalt pavements, the selection of the requirements must be carefully evaluated. First, the decision to write a new specification must be based on the ability to identify the cause of distress resulting from inadequate specifications for materials and construction and to replace, revise or add new, or at times more restrictive, requirements that will assure better performance. The economics of any change in specifications should be recognized and the increase in costs should be offset by improved performance. Quality assurance specifications with proper sampling and testing programs should result in lower costs.

DISTRESS MODES FOR ASPHALT PAVEMENTS

For this study, seven distinct distress modes were selected, together with the material and construction factors that contribute to each type of distress, as shown in Figure 3. For this study, a distress mode is defined as: "a deficiency in pavement quality and performance shown by reduced serviceability." In general, the serviceability of pavements changes with time, due to the effects of traffic and environment on the properties of materials. The rate of change in serviceability depends on: (1) the adequancy of the structural thickness design, (2) the quality of materials, (3) mixture design properties, and (4) the quality of construction to meet the end result requirements for composition, density, thickness, smoothness (roughness) and skid resistance. Two of the objectives of this state-of-the-art study are to:

(1) define distress modes for flexible pavements that are due to construction methods or material properties, and
(2) evaluate existing specifications to identify those elements that relate directly to distress modes.

The distresses are usually observed in the form of some type of cracking, vertical or horizontal displacement, disintegration, low skid resistance, or poor riding quality. The last could include excess noise generated from the road surfaces and the vehicle. From a design engineer's viewpoint, the most important factor is the actual structural capacity of the pavement to meet the requirements for traffic, subgrade moisture and temperature conditions. Because the structural design of a pavement is a major subject itself, it was not included in the scope of this study. However, material and construction factors that are associated with structural design will be referenced and briefly discussed.

FIGURE 3 OUTLINE OF DISTRESS MODES AND CONTRIBUTING FACTORS

Distress Modes

1. Definition - deficiency in pavement quality and performance shown by reduced serviceability
    - 1.1 Cracking - load associated - fatigue
    - 1.2 Cracking - non-load associated
    - 1.3 Cracking - reflected
    - 1.4 Distortion, shoving, rutting and slipping
    - 1.5 Disintegration - ravelling
    - 1.6 Reduced skid resistance
    - 1.7 Riding quality - roughness

2. Contributing factors:
    - 2.1 Cracking - load associated fatigue
        - 2.1.1 Improper pavement design for traffic loading conditions
        - 2.1.2 Environment - temperature - moisture
        - 2.1.3 Improper mix design - asphalt and aggregate characteristics
        - 2.1.4 Improper compaction
    - 2.2 Cracking - non-load associated
        - 2.2.1 Improper mix design for environmental conditions
        - 2.2.2 Pavement thickness
        - 2.2.3 Asphalt - aggregate interactions
        - 2.2.4 Improper compaction
    - 2.3 Reflection cracking
        - 2.3.1 Underlying pavement
        - 2.3.2 Cement treated bases
        - 2.3.3 Thermal cracks from underlying course
        - 2.3.4 Shrinkage due to wet and dry conditions

    - 2.4 Shoving, rutting and slipping
        - 2.4.1 Improper mix design - asphalt and aggregates
        - 2.4.2 Improper construction equipment control during mixing, spreading and compacting

- 2.4.3 Improper mix temperature
- 2.4.4 Excessive tack coat
- 2.4.5 Improper bond with existing surface
- 2.4.6 Excessive moisture in mix during compaction

2.5 Disintegration - ravelling

- 2.5.1 Improper mix design - asphalt and aggregate
- 2.5.2 Segregation - non-uniform spreading
- 2.5.3 Improper compaction
- 2.5.4 Moisture susceptibility - stripping

2.6 Reduced skid resistance

- 2.6.1 Improper mix design - asphalt and aggregate
- 2.6.2 Wear susceptibility of aggregate
- 2.6.3 Moisture effects - flushing
- 2.6.4 Compaction - flushing
- 2.6.5 Micro and macro texture
- 2.6.6 Degradation of surface aggregates

2.7 Roughness

- 2.7.1 Rough surface - transverse and longitudinal tolerances, improper construction control - spreading and compacting
- 2.7.2 Mix uniformity - segregation
- 2.7.3 Surface texture - noise

3. Effects of Material and Mixture Properties on Distress Modes

3.1 Aggregates - improper selection of aggregate that may result in:

- 3.1.1 Excessive degradation during production
- 3.1.2 Excessive stripping or swelling and loss in strength of mixtures caused by moisture
- 3.1.3 Rapid wear by traffic to decrease frictional resistance
- 3.1.4 Lack of stability
- 3.1.5 Excessive asphalt absorption

3.2 Bituminous Binders - improper selection of bituminous binders that may result in:

- 3.2.1 Low strength or stiffness of mixtures under high pavement temperature and cause shoving and rutting

        3.2.2 High stability or stiffness at low pavement temperatures
        3.2.3 Excessive stripping, swelling and loss in low strength of mixtures due to moisture

3.3 Bituminous Mixtures - improper type of bituminous mix that may result in:

        3.3.1 Excessive void contents in dense graded mixtures to cause early binder hardening and pavement deterioration
        3.3.2 Tender mixture during construction
        3.3.3 Low frictional properties
        3.3.4 Low resistance to cracking
        3.3.5 Rutting and shoving

4. Effect of Construction Methods and Control on Distress Mode

    4.1 Handling of materials - non-uniform supply of materials to result in variable strength properties of bituminous mixtures and pavement layers

        4.1.1 Inadequate or intermittent source of supply of aggregates and bituminous binder
        4.1.2 Improper storage of materials on the job - aggregate and binder

    4.2 Mixing

        4.2.1 Non-uniform proportioning of aggregate and bituminous binder
        4.2.2 Non-uniform mix temperature control that results in variable workability for placing and compaction or overheating of mix to cause excessive binder hardening
        4.2.3 Inadequate mixing time that results in non-uniform distribution of aggregate and binder.
        4.2.4 Incomplete aggregate coating

    4.3 Spreading

        4.3.1 Non-uniform thickness
        4.3.2 Transverse and longitudinal
        4.3.3 Segregation of mix - non-uniform texture
        4.3.4 Tearing under screed

4.4 Compacting

- 4.4.1 Low density of mix - high voids
- 4.4.2 Poor surface texture
- 4.4.3 Uneven transverse and longitudinal joints
- 4.4.4 Roller marks

MIXTURE DESIGN CRITERIA

Figure 3 shows that mix design is a predominant factor in nearly all of the distress modes. The literature includes numerous references related to the criteria of bituminous mixture design. For example, Finn et al enumerated the following pertinent properties that should be considered (35):

- Stability (stiffness)
- Durability
- Flexibility
- Fatigue-resistance (cracking under traffic loads)
- Skid resistance
- Permeability (imperviousness)
- Fracture strength (tensile)

Using Finn's discussion and some amplification from other sources, the following summary was made for the material and mixture characteristics that need to be considered to optimize mixture design properties:

Stability - Stability has been defined as "resistance of a mix to permanent deformation under load." Deformation pertains to the permanent or plastic state resulting from many applications of loads applied at relatively high temperatures to result in rutting or slipping. Hveem and Vallerga (36) analyzed the following factors that affect stability: (a) frictional resistance, (b) cohesion, and (c) inertia. The authors indicated that interparticle friction resistance due to aggregate surface texture is a major contributor to resistance to deformation. On the other hand, improper compaction and excessive asphalt contents tend to reduce friction and permit plastic deformation to occur more readily. Thus, the selection of aggregates with good friction properties, proper mix design and construction will decrease the chance of instability.

Durability - Pavement durability can be defined as the resistance of the asphalt pavement surface course to change during service. Durability also has been defined as the long term resistance to the effects of aging or the ability of asphalt materials to retain their original properties. In defining durability of asphalt pavements, caution should be used to limit the definition of durability to one or more specific items such as: the asphalt, the aggregate or the mixture. For this study, durability will be limited to bituminous mixtures, asphalts and aggregates, and properties that are related to performance and are controlled by specification requirements. The durability of bituminous pavements is often shown by changes in the properties during plant mixing and in service, and, in some cases, to the action of water or water vapors. The effects of weathering and water often can be minimized using dense aggregate gradings with as high bitumen contents as possible and optimizing good durability with other desirable characteristics, such as stability and flexibility.

Flexibility - Flexibility has been defined as the ability of the mixture to conform to variations in surface, base and subgrade under the loads applied by traffic. The resulting differences in elevation can be attributed to long term settlements and compaction of the component layers in the pavement structure. The asphaltic mixture courses must be designed and constructed to conform to these differences in elevation without cracking. Proper grading of the aggregate, grade and amount of asphalt, and adequate compaction can improve flexibility.

Fatigue Resistance - Fatigue resistance can be defined as the resistance of asphalt concrete pavements to cracking from resilient or elastic deformations when subjected to many repetitions of traffic loads. The results of laboratory and field studies have been documented to show that failure occurs under the repetitive action of traffic. However, in studying fatigue cracking in asphalt pavement surfaces, factors such as intensity of loading, design thickness of the surface and the resilient characteristics of the underlying layers must be evaluated to determine the stress or strain to which the bituminous mixture will be subjected. Laboratory studies have shown that the number or load repetitions to failure is influenced by mix variables and whether the mix is tested under controlled stress or strain loading. Regardless of method of loading, longer resistance to fatigue cracking is associated with asphalt properties, asphalt content, and void content.

In 1979, NCHRP published Report No. 213 on the Bayesian methodology for verifying recommendations to minimize asphalt pavement distress (37). The objectives of the study were to: (1) develop a procedure based on Bayesian analysis methodology for verifying recommendations to minimize pavement distress, and (2) conduct a pilot implementation of the procedure for the specific mode of cracking from repetitive traffic loading.

A prediction model based on multiple regression techniques was developed from interviews with experienced representatives from six states, and four designer-controlled variables were identified as having the most significant effect on fatigue cracking:

(1) Asphalt penetration
(2) Asphalt content
(3) Proportion of asphaltic concrete (thickness)
(4) Base density

In six states, it was found that the fatigue life cycle increases with increase in asphalt penetration, asphalt content, proportion of asphalt concrete and base density. The model predictions can be used to evaluate design alternatives, assist in planning maintenance budgets, and estimate contract price adjustments for non-complying materials and construction.

<u>Skid resistance</u> - Skid resistance is the ability of the surface of an asphalt paving mixture to provide sufficient friction so that the vehicle will be able to brake to a stop within a reasonable distance under a vari-

ety of environmental conditions. For dense-graded mixtures, high friction generally is promoted by comparatively low asphalt contents, and rough textured and non-polishing aggregates, preferably those that have minerals of different wear characteristics.

For open-graded friction courses, the aggregates should be rough-textured and angular in shape. To improve durability, the asphalt film thickness should be sufficiently high in relation to the film thickness in dense-graded mixtures. Aggregate gradings should have a minimum of fines. A study of OGFC in Ontario concluded that both good macrotexture and microtexture qualities were required for good wet-pavement friction characteristics (38).

Permeability - Permeability can be defined as the ease with which water, including vapor and air, will pass through a compacted bituminous mixture. Dense-graded mixtures should be sufficiently impervious to result in long term durability of the asphalt. The degree of permeability depends upon the same factors which contribute to durability. For open-graded friction courses, the permeability should be sufficiently high to provide for the free passage of water to maintain good skid resistance under wet conditions. Usually the mixtures have asphalt contents high enough to result in thicker films of asphalt, and accordingly are more resistant to aging. Thus, aggregate type and grading, as well as binder content, are important from the standpoint of skid resistance and durability.

Fracture Strength - Fracture strength is considered to be the maximum strength which a mixture exhibits when subjected to tensile forces. The strength is dependent on the rate of loading and temperature. Mixture variables to be considered in evaluating fracture strength include asphalt content, aggregate gradation (including filler), and mixture density or void content.

The study by Finn (35) indicated that the variables discussed above must be evaluated for proper mixture design. Table 23 shows the influence of the variables on a comparative basis. To use this table, a compromise is required to balance the mix properties. For example, to obtain high stability or good skid resistance, the asphalt content for dense-graded mixtures may be too low to provide good durability or some of the other properties shown in the table. All of the optimum mixture properties require that the degree of compaction be high.

TABLE 23 DESIRABLE CHARACTERISTICS TO OPTIMIZE MIXTURE PROPERTIES (35)

MIX PROPERTY	ASPHALT CONTENT	AGGREGATE GRADATION	DEGREE OF COMPACTION
Stability	Low	Dense	High
Durability	High	Dense	High
Flexibility	High	Open	-
Fatigue resistance	High	Dense [a]	High
Skid resistance	Low	Dense	High [c]
		or open [b]	-
Imperviousness	High	Dense	High
Fracture strength	High	Dense	High

(a) Assuming a heavy-duty, comparatively thick layer of asphaltic concrete.

(b) Both types of gradations have indicated good skid resistance characteristics. What appears to be more important is the texture of the aggregate particles.

(c) Although compaction is not normally indicated for this property, it is implied to insure that aggregate particles will not dislodge under the tractive forces applied to the surface.

PAVEMENT PERFORMANCE STUDIES

To properly evaluate the incidence of each of the distress modes, several reports showing the results of surveys on pavement condition were selected. In some instances, both the number of pavements included in the survey and the relative magnitude of the distresses were shown.

During 1954-1956, the FHWA accumulated more than 300 asphalt samples from more than 285 identifiable construction projects in 37 states (39)(40)(41). The retained samples were extensively tested for fundamental as well as conventional properties.

In 1966, a study was initiated to sample a selected number of pavements where the known source asphalts had been used. A statistical number of survivor and non-survivor pavements were sampled on a random basis to determine the properties of the recovered asphalts after 11 to 13 years of service and relate the properties to the original asphalts. On the basis of available data, 53 projects in 19 states were selected for study. Nineteen projects had been resurfaced, 34 were still in service. A two-man rating team, consisting of one member of the FHWA and one from Materials Research and Development organization, examined and rated each of the pavements on the basis of usual surface characteristics. The team also randomly selected locations for sampling. Five to six samples were obtained and shipped to the FHWA materials laboratory for examination and testing.

Pavement samples were separated by sawing to obtain a 1-inch layer of the surface course for testing. The bulk and maximum specific gravities were determined and the asphalts were extracted and recovered. Extensive physical tests were made on the recovered asphalts and the aggregate. Representative portions of the recovered and original asphalts were sent to Materials Research and Development for chemical analyses by the Rostler method. All of the test data, including physical properties and chemical properties of the original, laboratory-aged and recovered asphalts were stored on computer cards. Other information stored included construction and traffic data from construction files, climatological information from the weather bureau, recovered aggregate gradations and petrographic analysis, pavement conditions and other miscellaneous information.

The types of distress observed during the field survey at the 34 in-service projects are summarized in Table 24. The principal forms of distress observed were longitudinal cracks formed by repetitions of traffic loads (fatigue), cracks that develop in the longitudinal construction joints, transverse cracks, polygon cracks and rutting. Of the 34 projects, 24 to 26 or 71 to 76 percent of the pavements had developed longitudinal or transverse cracks as shown in Table 25.

In addition to the forms at distress shown in Table 25, the amount of disintegration was observed and recorded in the survey data. Disintegration included ravelling, spalling, and loss of matrix. Twenty-three of the 34 pavements showed various amounts of disintegration.

Numerous correlation studies were made to associate pavement condition with properties of the asphalts before and after aging in laboratory tests and during service in the pavement.

In most cases, the correlations were obscured by the variability in properties of pavement samples and recovered asphalts. However, a few trends were found in the correlation studies that are of interest in this state-of-the-art study.

o Wide intra-project variation in mixture properties and properties of the recovered asphalts emphasizes the importance of multiple samples. Figure 4 shows the effect of air-void content on the viscosity of the recovered asphalt after 11 to 13 years of service. Each data point represents the values of void contents and viscosities for one sampling site within each of the 5 or 6 random sites. The figure shows that except for project 24, tests from a single site would not necessarily represent the conditions for the entire project. The conclusion is that pavements should be sampled at several random sites to obtain representative evaluations. For added interest, the relation between air void content and voids filled with asphalt are shown in Figure 5.

- Lower variability of bituminous mixture properties for asphalt and air-void contents, bulk and maximum specific gravities, and aggregate gradings were significantly characteristic of the higher rated "surviving" pavements.

TABLE 24 INCIDENCE OF DISTRESS FOR PERFORMANCE STUDY
FHWA - 1967

Rating	Type of Distress				
	Longitudinal Cracking (Load)	Longitudinal Cracking (Lane Joint)	Transverse Cracking	Polygon Cracking	Rutting
Severe 0-1	4	7	6	1	2
Moderate 1-2	5	6	5	0	4
Slight 2-3	15	12	15	13	16
None 3	10	9	8	20	12

TABLE 25 NUMBER OF PROJECTS AND PERCENT OF DISTRESS RANGING FROM SLIGHT TO SEVERE FHWA 1967

Type of Distress	Number of Projects	Percent
Longitudinal Load	24	71
Longitudinal Const.	25	74
Transverse	26	76
Polygon	14	41
Rutting	22	64

FIGURE 4 EFFECT OF AIR VOID CONTENT ON VISCOSITY OF ASPHALT AFTER 12 YEARS SERVICE

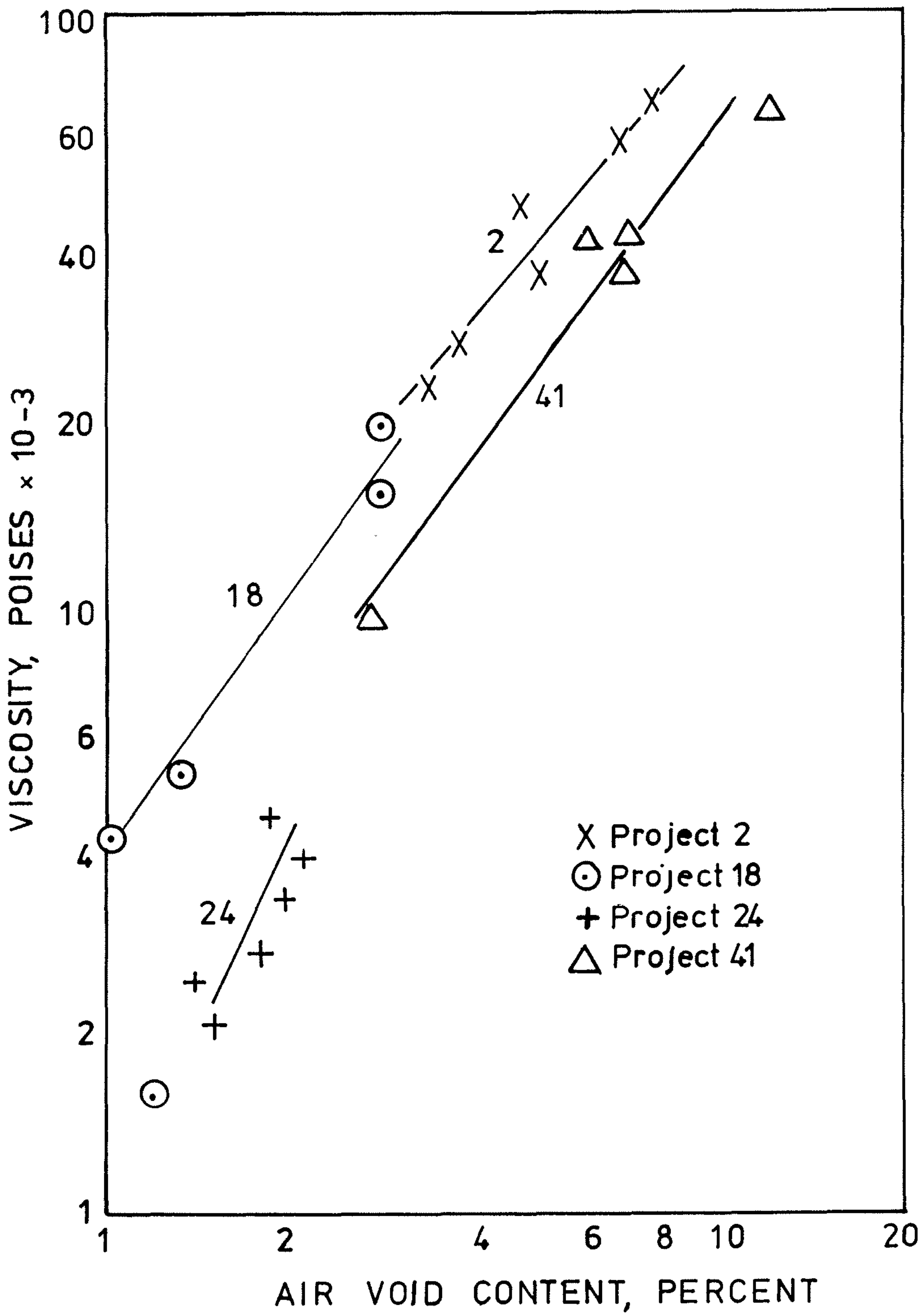
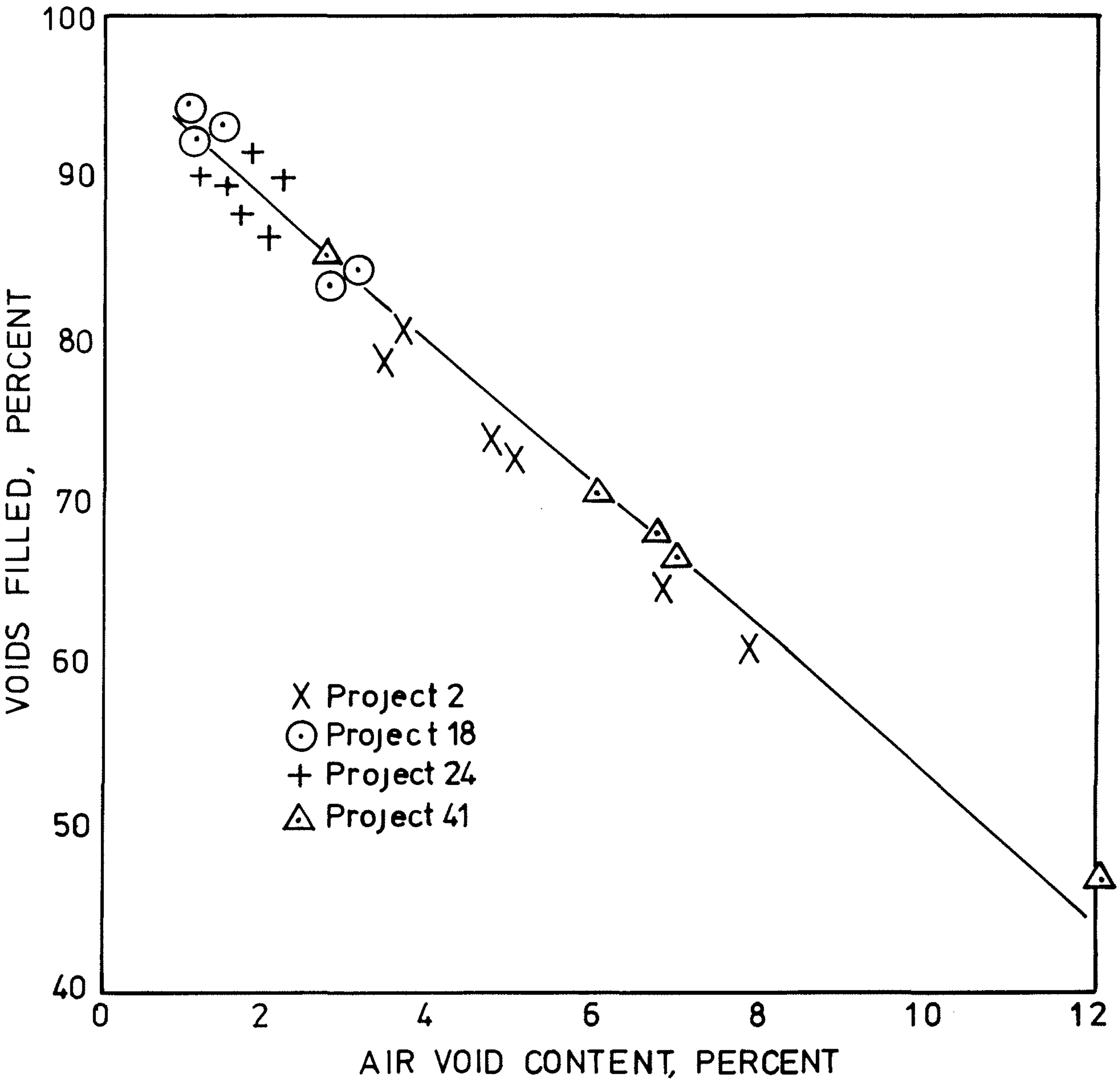


FIGURE 5 RELATION BETWEEN AIR VOID CONTENT AND VOIDS FILLED WITH ASPHALT



HIGHWAY CONDITION AND QUALITY SURVEY

1976 Survey

FHWA initiated a survey in 1976 to provide current information on the condition and quality of pavements (42). The survey was designed to measure the quality and performance of highway construction, the quality of on-going construction, and construction staffing. The survey included flexible pavements, rigid pavements and bridge decks. This summary will be concerned with flexible pavements only.

To evaluate condition, pavements were randomly sampled on a stratified basis for a 0-7-year period of service life. The intent of the study was to develop trends of performance criteria such as roughness, skid resistance and serviceability indices.

To assess quality levels of materials and procedures utilized in the construction of flexible pavements, ongoing projects were evaluated during the period from July 1976 to October 1976. Quality data were obtained for three production days on each project, and analyzed statistically with the Quality Index Procedure. This tool uses the results of project tests and inspections, specification requirements and statistical theory to estimate the quality of work performed. The results were intended to measure the quality of conformity to specifications. A 90 percent quality level was chosen on the basis of engineering judgment as the dividing criterion which distinguishes between a good quality level of work and levels where improvement should be made. The procedure for estimating the quality level is given in the report.

<u>Findings</u>. The present serviceability ratings (PSR) for both rigid and flexible pavements ranged from 2.5 to nearly 5.0. About 50 percent of the projects completed in the past two years had PSR values of below 4.00.

The skid resistance of flexible pavements showed the following distribution of skid numbers (SN):

SN RANGE	PERCENT OF PAVEMENTS WITHIN SN RANGES
64 Plus	5
56 - 64	19
48 - 56	28
40 - 48	26
32 - 40	16
Below 32	6

The principal types of distress observed in 633 flexible pavements (in percent of occurrence) were as follows:

DISTRESS TYPE	PERCENT OF PROJECTS SHOWING DISTRESS		
	LOW	MEDIUM	HIGH
Longitudinal Cracking	52	11	1
Rutting	50	10	2
Transverse Cracking	42	12	2
Alligator Cracking	15	3	
Edge Cracking	14	4	1
Block Cracking	10	2	
Ravelling	10	2	

Construction Quality Survey

Analyses of quality level were made on the basis of conformity to the applicable specification requirements. As indicated, a 90 percent quality level was chosen on the basis of engineering judgment as the dividing criterion to distinguish between good quality level work and work where improvements are needed. Use of this criterion indicated that quality control problems existed in flexible pavement construction. The following is a summary of the percent of projects that had quality levels less than 90 percent.

QUALITY CONTROL FACTOR	PROJECTS WITH QUALITY LEVEL LESS THAN 90 PERCENT
Mix Laydown Temperature	18 percent
Density	40 percent
Bitumen Content	30 percent
No. 200 Sieve	20 percent
Control Sieve	28 percent
Surface Smoothness	0 percent

Conclusions and Recommendations

The following conclusions and recommendations pertain only to the condition and the quality of construction of flexible pavements:

1. The serviceability in terms of the present serviceability ratings (PSR) were quite variable and, on the average, somewhat low.

   o Recommendation - that performance type specifications for riding quality be developed. Also, that initial serviceability indices such as roughness or profilometer measurements be made on new pavements prior to opening to traffic.

2. The emphasis on skid resistance is indicated by the preponderance of skid numbers (78%) that were above 40.

   o Recommendation - that the emphasis on improving skid resistance be continued.

3. The survey of on-going construction indicated that quality control problems existed. In some construction projects, the specification limits were unrealistic and did not recognize the normal testing and process variability. In other projects, the accept-

ance of the work was based on one test and a provision for resampling and testing. In both instances the practices accounted for low quality levels found in the survey. Some states have found that quality assurance type specifications are performance related and account for normal testing and processing variability.

- Recommendations - Improve quality control of density, bitumen content and gradation. Where needed, specifications limits should be adjusted to accommodate normal testing and process variability. This will have to be accomplished on a state-by-state basis.

The riding quality should be monitored by roughometers, profilometers or other means so that strategies can be developed to improve the overall riding and overall serviceability of flexible pavement.

Comprehensive training programs should be initiated to develop and maintain a highly skilled cadre of technicians.

Recommended Strategies

- Concepts of pavement management be promoted.
- Develop performance type specifications.
- Improve construction process controls and procedures.
- Develop rapid test methods for use in control and acceptance plans - density, texture, and riding quality.
- Improve the utilization of manpower resources.
- Improve processes which apply accepted techniques that improve engineering management.

- Develop comprehensive training program.

- Identify research and development needs.

1979 Survey

In 1979, the FHWA continued the 1976 survey of Highway Condition and Quality of Highway Construction survey to develop the following information for flexible pavements (43):

- Provide current information on the condition of pavements

- Identify problem areas in the quality of highway construction

- Provide information required to formulate strategies to improve quality and performance of pavements

- Generate additional information on project staffing and productivity.

Based on experience gained from the 1976 survey, there were significant improvements in the survey forms and data collecting techniques. The 1979 report was believed to be more complete with factual data representing the current quality of highway construction.

General Trends and Findings A total of 311 projects were reviewed on a nationwide basis to determine the general condition of total pavements after 3 years of service. Some of the general trends and findings for pavement distresses were:

- Individual statewide average PSR varied from 3.15 to 4.73. There were 82.1 percent of individual projects over 3.5.

- Individual statewide average SN varied from 31 to 78. There were 80.7 percent of individual projects over 40.

- No observable distress was found in 27 percent of projects surveyed; 28 percent exhibited only one type of distress and 5 percent exhibited four or more distress types. The occurrence of distress for all flexible pavements is shown in Table 26.

TABLE 26

DISTRESS TYPES FOUND IN FLEXIBLE PAVEMENTS - 1979 SURVEY

DISTRESS TYPE	PERCENT OF PROJECTS SHOWING DISTRESS
Longitudinal Cracking	38
Transverse Cracking	36
Rutting	35
Bleeding	11
Patching	7
Polishing	6
Alligator Cracking	6
Block Cracking	4
Potholes	4
Pumping	1

TABLE 27

SUMMARY OF PROJECTS WITH QUALITY CONTROL FACTORS BELOW 90 QUALITY LEVEL FOR 1976 AND 1979 (SURFACING)

QUALITY CONTROL FACTOR	PERCENT OF PROJECTS WITH QUALITY LEVELS LESS THAN 90	
	1976	1979
Laydown Temperature	18	19
Density	40	46
Bitumen Content	30	34
No. 200 Sieve	20	27
Control Sieve	28	32
Thickness	53	69

Overall, the 1979 survey indicated that there was a decline in quality of construction from 1976 to 1979. No specific causes were found for the decline; however, there were certain general construction practices that were identified in both the 1976 and 1979 surveys that may contribute to the overall low quality of construction. These are:

- The use of specifications that do not allow for normal process and/or sampling and testing variability.
- The use of conventional practices where acceptance of the work is based on single tests and resampling and/or testing of failing materials is allowed.

A comparison of the number of projects with quality levels less than 90 in 1976 and 1979 are shown in Table 27.

Some states found that quality assurance type specifications are performance-related and take into account that normal testing and process variability may be beneficial on major items of work. The authors suggested that FHWA regional and division offices adopt procedures that will allow a statistical analysis of construction quality control levels so as to reveal unrealistic specifications and practices.

The following specific recommendations were offered in addition to the above:

- Of the construction factors, thickness followed by density had the greatest degree of non-conformity to specifications. Not all states have density requirements for bases, binder and bituminous surfacing. Recommendations include studies to determine whether minimum density requirements are realistic, achievable and represent the desired end result. Also, in those states where there are no density requirements, efforts should be made to develop and implement such specifications.

- Thickness quality levels were extremely low for the data submitted. A review of specifications indicated that the lack of adequate construction tolerances contribute to the problem. Recommendations were made to develop and implement tolerances that represent actual construction and testing variability.

- The composition of bituminous mix, as measured by bitumen content and gradation of aggregate, indicated a significant lack of conformity. Individual project mix designs should be reviewed to determine whether the requirements are achievable and economical and that the specifications are representative of the end result.

Suggested Strategies. The strategies included in the 1976 Survey, with some minor revisions, should continue to be promoted as an effort to improve the quality of construction. The strategies that could be applied directly to the quality of construction of flexible pavements include:

- Develop performance-type specifications for flexible pavements which address specifically the rideability, skid resistance and structural capacity.

- Improve construction process controls and procedures for each of the quality control factors for bituminous pavements.

- Develop rapid and positive procedures for process control and for acceptance testing of surface texture, and skid resistance, and riding quality.

DISTRESS AND RELATED MATERIAL PROPERTIES

In 1979, Kennedy, Roberts and Rauhut (44) reported on a study sponsored by the FHWA with the overall objectives to (1) identify the various types of distress for flexible, rigid and composite pavements, (2) select the distresses that occur in premium pavements, and (3) identify the related material properties. The effort was subdivided into the following four tasks:

1. To develop a complete set of distresses for each type of pavement, engineering properties related to the distress type and factors affecting the engineering properties of the materials.

2. To assess the relative importance of distress types in terms of frequency of occurrence and to evaluate the effect of meeting the requirements of zero maintenance pavements.

3. To assess the relative importance of material properties in each of the important distresses.

4. To summarize the distresses and related material properties that have sufficient impact on pavement performance and maintenance requirements to warrant further consideration.

The study included all three types of pavements, but only that portion of the data and discussion pertaining to flexible pavement specifications will be included here. An appreciable amount of the work outlined in the above tasks is similar to and is of value to this state-of-the-art study in asphalt pavement specifications.

Of particular value is the up-to-date set of definitions prepared by Kennedy and his associates. The definitions that pertain to this state-of-the-art report are repeated here:

1. Distress is a condition of the pavement structure that reduces serviceability or leads to a reduction in serviceability.

2. Distress manifestations are the visible consequences of various distress mechanisms, which usually lead to a reduction in serviceability.

3. Structural failure is a fracture or distortion that may or may not cause an immediate reduction in serviceability but will lead to a future loss of serviceability.

4. Fracture is the state of a pavement material that is breaking.

5. Distortion is a permanent change in the shape of the pavement or pavement component.

6. Disintegration is the state of a pavement that is decomposing or abrading into its constitutive elements.

7. Reflection cracks are cracks that occur in the surface course of a pavement and that coincide with and are caused by the relative movement of cracks or joints in underlying layers.

8. Low-temperature cracks are generally transverse cracks that are caused when tensile stresses induced by frictional resistance of the underlying layer to thermal contraction of the surface layer exceed the tensile strength of the surface material.

9. Raveling is the progressive disintegration of an asphalt concrete layer from the surface downward by the dislodgement of aggregate particles. This can be caused by insufficient binder in the mix, hardening of the asphalt binder, wet or dirty aggregate, or aggregate with a smooth surface texture.

10. Ruts are longitudinal depressions that form in the wheel paths of flexible or composite pavements and result from compaction or lateral migration of one or more of the pavement-layer materials under the action of traffic and environment.

11. Polished aggregates are surface aggregate particles that have smooth, rounded surfaces with fine microtexture, either in their original condition or after abrasive wear by traffic.

12. Fatigue cracks are cracks in a pavement layer caused by the combination of repetitive strains and apparent reduction of tensile

strength caused by fatiguing of the layer material. The repetitive strains that cause fatigue are usually the result of passing wheel loads but may include thermally-induced strains or other types of strains.

The authors made an extensive study to identify and categorize the various pavement distresses and the engineering properties that affect the distresses. Engineering material properties were defined as those properties that can be used with a constitutive equation to predict the physical behavior of a material in a particular environment.

In 1976, Darter and Barenberg (45) surveyed 19 pavements located in 9 states that had widely different environments and were subjected to moderately high traffic volumes. The projects surveyed varied in age from 7 to 24 years with a mean of 14 years (43). The distresses found are summarized in Table 28. Each project was given a subjective rating by the project staff during the field visit.

In the survey, the authors considered longitudinal cracking to be the distress that develops in the longitudinal lane joint or those cracks that form in the wheel path due to repetitions of wheel loads or a combination of lane and load associated cracking.

Kennedy et al (44) used Darter and Barenberg data shown in Table 28 as a basis for a second study cycle. The information in the first study cycle was modified to limit the categories of distress to fracture, distortion and disintegration. The types of distress in each of the three categories are shown in Table 29. The study was expanded during the second cycle to identify the environment, mix designs, construction and traffic factors that influence the material properties.

TABLE 28

TYPES AND NUMBER OF DISTRESSES FOUND

TYPE OF DISTRESS	TOTAL PROJECTS DISTRESSED	PERCENT DISTRESSED
Longitudinal Cracking	11	58
Transverse Cracking (includes reflection cracking)	10	53
Alligator (fatigue cracking)	9	47
Polishing aggregate	8	42
Rutting	6	32
Weathering asphalt	4	21
Depressions	3	16

From Darter and Barenberg (45)

TABLE 29

PAVEMENT DISTRESS BY DISTRESS CATEGORY FOR FLEXIBLE PAVEMENT

FRACTURE	DISTORTION	DISINTEGRATION
Fatigue Cracking Thermal Cracking Slippage Cracking	Differential frost heave Differential compaction-swelling Shoving Rutting Corrugations	Stripping Raveling Reduced Skid Resistance

Kennedy et al (44)

Kennedy et al show the relation between material properties and distress by type of material. For this discussion, only the material properties and their relation to distresses for asphalt concrete and asphalt treated bases were used, as shown in Table 30. Kennedy et al also indicated that the dependent material properties, i.e., density, aggregate gradation, air voids, etc., were not generally included in the list of properties prepared for their studies. Since the dependent material properties are related to the independent properties, and are more easily and conveniently measured, they can be used in place of the independent material property in an engineering analysis. For example, density, aggregate gradation and type, air voids, etc., are related to the fatigue characteristics of an asphalt concrete mixture.

Kennedy et al used the information shown in Tables 29 and 30 to select those distresses that are of primary concern in producing premium pavements, and that must be considered in the analysis or design of pavement structures to minimize the occurence of distress and associated effects. Thus, only those pavements were included in their analysis of distresses in pavements that met the requirements of zero-maintenance.

The priority ranking of pavement distresses given in Table 31 will be used in further research to more clearly define the material properties that most affect the occurrence and extent of distress.

RESPONSE AND DISTRESS MODELS

As indicated earlier, pavement design methods and criteria are not included within the scope of this report on the state-of-the-art in specifications for asphalt pavements. However, work has been reported on the development and use of theoretical and empirical models to predict significant distress in asphalt pavements using material properties and other engineering parameters. Because they introduce correlations of distress and material properties, the models are summarized here.

TABLE 30

RELATION BETWEEN MATERIAL PROPERTY AND DISTRESS FOR ASPHALT CONCRETE SURFACE AND ASPHALT TREATED BASE

MATERIAL PROPERTY	CRACKING		RUTTING	RAVELING	STRIPPING	REDUCED SKID RESISTANCE
	FATIGUE	LOW TEMP.				
Stiffness	a b	a b	a b	a	a b	
Coef. Thermal Expansion		a b				
Tensile strength		a b				
Permanent Deformation			a b			
Aggregate Characteristics					a b	a
Bond (Adhesion)					a	a b
Fatigue Constants (K_1 & K_2)	a b					

Kennedy, Roberts and Rauhut (44)

a = Asphalt concrete surface

b = Asphalt treated base

TABLE 31

PRIORITY RANKING OF SIGNIFICANT DISTRESSES
SELECTED FOR FUTURE STUDY

PRIORITY RANKING	FLEXIBLE PAVEMENTS
1	Fatigue cracking
2	Rutting
3	Low-temperature cracking
4	Reduced skid resistance

MODELS FOR PREDICTING DISTRESSES

Rauhut, Roberts and Kennedy (46, 47) presented an evaluation of the various contemporary mathematic models and selected those that were most capable of predicting distresses in terms of significant material properties. They described briefly the distress models and the material properties considered to affect the occurrence of each distress condition. For asphalt pavements, the types of distress studied and considered for use in their project were as follows:

Rutting
Fracture cracking (Fatigue)
Low-temperature cracking
Reduced skid resistance

A large number of distress models were studied, but only VESYS A, PDMAP, OPAC and WATMODE included models for rutting, fracture cracking, and low-temperature cracking. The Shell Method considered rutting and fatigue cracking. The literature on skid resistance deals mainly with the magnitude of skid numbers for different types of pavements and the change in measured skid numbers over periods of time.

VESYS A is a sophisticated computer code that accepts 23 central variables and 44 independent variables that describe a pavement structure. It is capable of predicting fatigue cracking, rut depth, slope variance, present serviceability index, and expected service life as functions of time correlated with truck traffic. The low-temperature cracking model used in VESYS A was developed by Haas using multiple-regression equations using data collected from Canadian pavements (48). Independent variables include age of pavement, thickness of layer, winter design temperature and stiffness of the original asphalt cement. VESYS A is considered to be the most complete distress model for asphalt pavements. It considers a broad range of materials in the sub-systems.

PDMAP stands for probabilistic distress models for asphalt pavements, and includes models for fatigue cracking and rutting. The low-temperature cracking distress model is a separate computer program called COLD. The fatigue cracking and rutting models are based on the AASHO Road Test data and depend on elastic layer structural model. The rutting model in PDMAP predicts seasonal rate of rutting for permanent deformation per equivalent load application. The model for fatigue distress is similar to that used in most fatigue predictions except that the effects of the stiffness of the asphalt concrete are considered.

OPAC is a system of pavement design developed for the Province of Ontario and incorporated in a later model called WATMODE. These models can be used to predict distresses from rutting, fatigue cracking and low-temperature cracking. These models are generally based on statistical correlations between laboratory tests on material from the Brampton and Ste. Anne test roads and measured roadway responses.

Table 32 summarizes the types of distress, related material properties, and distress models selected for asphalt pavements. Most forms of distress and their related material properties are of interest in the present state-of-the-art study. Here the distress models are associated with controlled variables and the contributing material properties. For example, load associated (fatigue) cracking is affected by the dependent controlled variables: void content, stiffness and layer thickness, which in turn are affected by independent properties of the asphalt, aggregate and asphalt concrete mixtures.

PERFORMANCE-RELATED DISTRESS MODES

Figures 6 to 12 show the distress modes, the controlled variables, the contributing material properties, and the short and long range methods of evaluation. The distresses considered here are the same as shown in Figure 3 for the outline of distress modes and contributing factors. Based on the information in studies and surveys cited previously, a consensus of major distresses shows that the incidence of longitudinal cracking is rated highest; transverse cracking, second; distortion (rutting), third; and the incidence of reflection cracking, fourth. The incidence of disintegration, smoothness and loss of skid resistance varies with the scope of the studies and surveys. However, programs on rehabilitation, resurfacing and reconstruction are of national importance in correcting, reducing or preventing these distresses and providing safe, smooth and structurally sound pavements.

TABLE 32

TYPES OF DISTRESS, MATERIAL PROPERTIES AFFECTING DISTRESS AND THE MODEL SELECTED

DISTRESS	MATERIAL PROPERTIES THAT SIGNIFICANTLY AFFECT DISTRESS	MODEL SELECTED FOR DISTRESS STUDIES
Fatigue cracking	Fatigue constants K (T) and K_2(T) for AC surface Stiffness modulus for AC surface Stiffness modulus for base materials	VESYS A
Rutting	Stiffness modulus for AC surface Permanent deformation parameters for AC surface Stiffness modulus for subgrade soil Permanent deformation parameters for subgrade soil	VESYS A PDMAP OPAC WATMODE
Low-Temperature cracking	Coefficient of thermal expansion for AC Stiffness modulus for AC Tensile strength for AC	VESYS A PDMAP
Reduced skid resistance	Aggregates wear and polishing potential	Study separate from primary factorial study
Reflection cracking	Stiffness Modulus for AC overlay Thermal coefficient for existing pavement Creep modulus for AC overlay	RFLCR

From Rauhut, Roberts and Kennedy (46, 47)

FIGURE 6

DISTRESS MODE FOR LOAD-ASSOCIATED (FATIGUE) CRACKING, CONTROLLED VARIABLES, CONTRIBUTING MATERIAL PROPERTIES & EVALUATION METHODS FOR SHORT & LONG RANGE USE

DISTRESS MODE PERFORMANCE RELATED	CONTROLLED VARIABLES (DEPENDENT)	CONTRIBUTING MATERIAL PROPERTIES (INDEPENDENT)			EVALUATION METHODS	
		ASPHALT	AGGREGATE	MIXTURE	SHORT RANGE	LONG RANGE
Load Associated Cracking (Fatigue)	Air-Void Content	Amount (a) Grade (b) Aging	Gradation (c) VMA (d) VFA (e) Shape or Crushed (f) Absorption(g)	Filler-Bitumen Ratio (h) Compaction Temperature (i) Moisture Content (j)	Mixture Design Methods Hveem Marshall Compressive Gyratory Shear	Non-Destructive Tests for Void Content
	Stiffness	(a, b) Vis-Temp Properties	(c,d,e,f,g)	(h,i,j) Aging	Stability Methods, Indirect Methods, Bit. Test Data Chart, Pen-Vis No.	Develop New In-Place Methods, Resilient Modulus, Stiffness Modulus
	Thickness	-	-	Workability	Cores, Rate of Spread	Non-Destructive Methods, Radar, Other

(a) Amount of Asphalt.
(b) Grade of Asphalt.
(c) Gradation of Aggregate.
(d) VMA - Voids in Mineral Aggregate.
(e) VFA - Voids Filled with Asphalt.
(f) Shape, Percent Crushed Particles.
(g) Aggregate Absorption.
(h) Filler-Bitumen Ratio.
(i) Compaction Temperature.
(j) Moisture Content.

FIGURE 7

DISTRESS MODE FOR NON-LOAD ASSOCIATED CRACKING, CONTROLLED VARIABLES, CONTRIBUTING MATERIAL PROPERTIES & EVALUATION METHODS FOR SHORT & LONG RANGE USE

DISTRESS MODE PERFORMANCE RELATED	CONTROLLED VARIABLES (DEPENDENT)	CONTRIBUTING MATERIAL PROPERTIES (INDEPENDENT)			EVALUATION METHODS	
		ASPHALT	AGGREGATE	MIXTURE	SHORT RANGE	LONG RANGE
Non-Load Associated Cracking (Thermal)	Air-Void Content	(a,b)	(c,d,e,f,g)	(h,i,j) Densification	Mix Design, Compaction Methods	Non-Destructive Tests for Creep, Modulus
	Stiffness	(a, b) Vis-Temp & Shear Susceptibility, Aging, Special Requirements	(c,d,e,f,g)	(h,i,j)	Indirect Methods, Bit. Test Data Chart, Pen-Vis No.	Develop New In-Place Methods, Stiffness Modulus
	Thickness	-	-	Workability Densification	Cores, Rate of Spread	Non-Destructive Methods, Radar, Other

For Low Temperature Cracking:

Components: Sand or Clay Base
Fracture Temperature
Tensile Splitting Test

FIGURE 8

DISTRESS MODE FOR REFLECTION CRACKING - CONTROLLED VARIABLES, CONTRIBUTING MATERIAL PROPERTIES & EVALUATION METHODS FOR SHORT & LONG RANGE USE

DISTRESS MODE PERFORMANCE RELATED	CONTROLLED VARIABLES (DEPENDENT)	CONTRIBUTING MATERIAL PROPERTIES (INDEPENDENT)			EVALUATION METHODS	
		ASPHALT	AGGREGATE	MIXTURE	SHORT RANGE	LONG RANGE
Reflection Cracking	Air-Void Content	(a,b) Vis-Temp Properties	(c,d,e,f,g)	(h,i,j) Additives, Admixtures	Mix Design	Special Treatments
	Stiffness	(a, b) Aging	(c,d,e,f,g)	(h,i,j)	Stability, Indirect Methods: Bit. Test Data Chart, Pen-Vis No.	Stiffness Modulus, Creep
	Thickness	-	-	-	Mix Design	Special Treatments, Interlayers

FIGURE 9

DISTRESS MODE FOR DISTORTION, CONTROLLED VARIABLES, CONTRIBUTING MATERIAL PROPERTIES & EVALUATION METHODS FOR SHORT & LONG RANGE USE

DISTRESS MODE PERFORMANCE RELATED	CONTROLLED VARIABLES (DEPENDENT)	CONTRIBUTING MATERIAL PROPERTIES (INDEPENDENT)			EVALUATION METHODS	
		ASPHALT	AGGREGATE	MIXTURE	SHORT RANGE	LONG RANGE
Distortion	Air-Void Content	(a,b) Aging	(c,d,e,f,g)	(h,i,j) Densification	Mix Design: Marshall, Hveem, Other	Develop New In-Place Methods, Creep
	Stiffness	(a, b) Aging	(c,d,e,f,g)	(h,i,j) Densification	Mix Design: Marshall, Hveem	Develop New In-Place Methods, Creep, Indirect Tension
	Thickness	-	-	Degree of Compaction Workability	Cores, Rate of Spread	Non-Destructive Tests: Thickness, Density

FIGURE 10

DISTRESS MODE FOR DISINTEGRATION, CONTROLLED VARIABLES, CONTRIBUTING MATERIAL PROPERTIES & EVALUATION METHODS FOR SHORT & LONG RANGE USE

DISTRESS MODE PERFORMANCE RELATED	CONTROLLED VARIABLES (DEPENDENT)	CONTRIBUTING MATERIAL PROPERTIES (INDEPENDENT)			EVALUATION METHODS	
		ASPHALT	AGGREGATE	MIXTURE	SHORT RANGE	LONG RANGE
Disintegration	Air-Void Content	(a,b)	(c,d,e,f,g) Moisture Susceptibility, Quality Durability	(h,i,j) Permeability, Moisture - Susceptibility	Mix Design, Mix Type	Develop In-Place Method
	Stiffness	(a, b) Vis-Temp Properties, Aging	(c,d,e,f,g) Quality	(h,i,j)	Water Immersion - Strength Tests: Marshall, Compression, Wet/Dry	Develop In-Place Method, Tensile Splitting Test: Wet/Dry

FIGURE 11

DISTRESS MODE FOR SMOOTHNESS, CONTROLLED VARIABLES, CONTRIBUTING MATERIAL PROPERTIES & EVALUATION METHODS FOR SHORT & LONG RANGE USE

DISTRESS MODE PERFORMANCE RELATED	CONTROLLED VARIABLES (DEPENDENT)	CONTRIBUTING MATERIAL PROPERTIES (INDEPENDENT)			EVALUATION METHODS	
		ASPHALT	AGGREGATE	MIXTURE	SHORT RANGE	LONG RANGE
Roughness	Air-Void Content	(a,b)	(c,d,e,f,g)	(h,i,j) Workability	Mix Design, Uniform Production	Develop Improved In-Place Method of Measuring Uniformity
	Stiffness	(a, b)	(c,d,e,f,g)	(h,i,j)	Mix Design, Construction Control By Samples	Develop Improved In-Place Method
	Thickness of Courses	-	(c,f)	Construction: Uniformity of Spreading, Compaction	Profilometer Straight Edge Roughness (See Note 1)	Develop High-Speed Method

Note 1:
30 Ft. Rolling Straight Edge
20 Ft. Rolling Straight Edge
GMR Profilometer
APL (French Profile)
Chloe
Roughometer
Mays Meter
PCA Meter

FIGURE 12

DISTRESS MODE FOR SKID RESISTANCE, CONTROLLING VARIABLES
CONTRIBUTING MATERIAL PROPERTIES & EVALUATION METHODS FOR SHORT & LONG RANGE USE

DISTRESS MODE PERFORMANCE RELATED	CONTROLLED VARIABLES (DEPENDENT)	CONTRIBUTING MATERIAL PROPERTIES (INDEPENDENT)			EVALUATION METHODS	
		ASPHALT	AGGREGATE	MIXTURE	SHORT RANGE	LONG RANGE
Skid Resistance	Air-Void Content	(a,b)	(c,d,e,f,g) Type Surface Texture	(h,i,j)	Mix Design, Petrographic Analysis Polishing Characteristics	Texture Meter, Photographic, New Non-Destructive Methods
	Stiffness	(a, b) Vis-Temp Properties, Shear	(c,d,e,f,g) Surface Texture	(h,i,j) Open & Dense Graded	Mix Design, New Pavement Before Service	In-Place Methods, Skid Trailer SN New Pavement After Service

Of particular importance in Figures 6 to 12 are the short range and long range methods of measuring and evaluating the properties of materials and mixtures and the construction requirements. Short range methods include those that have been standardized and are in current use. Long range methods are those of a fundamental nature, some of which are in use, consisting primarily of new methods that are in the research stage or proposed methods that measure performance-related properties.

Both the short range and long range methods can be used in performance-related specifications; however, the long range methods are preferred because they can be adapted to pavement design and to quality assurance programs. In most cases, the short range methods are the traditional methods currently in use for asphalt pavement specifications. Standard long range methods available for use in performance-related specifications include:

1. <u>Bituminous Materials</u>

a. Kinematic viscosity	ASTM D 2170
b. Vacuum capillary viscosity	ASTM D 2171
c. Cone and plate viscosity	ASTM D 3205
d. Sliding plate viscosity	ASTM D 3507

2. <u>Bituminous Mixtures</u>

a. Dynamic Modulus	ASTM D 3497
b. Resilient Modulus	ASTM D 4123

METHODS FOR MIX DESIGN AND EVALUATION

There is considerable interest in developing new methods for use in evaluating and characterizing materials and mixture designs. In addition, improved sampling methods and techniques are needed for use in performance-related specifications and for control and acceptance of materials and construction. FHWA is conducting and sponsoring research to develop more significant and rapid test procedures for performance and quality assurance specifications. Some of the findings to date indicate that satisfactory determinations of asphalt content can be made by either the nuclear gage, the vacuum extractor or the vacuum pycnometer. The vacuum extractor is recommended because of its low cost and its ability to produce a clean aggregate for further testing. Research also is underway to study current methods for acceptance of aggregates for bituminous construction. The use of optical techniques show the best promise for further development. Development of equipment to measure and monitor density and surface temperature during compaction is nearing completion. Road trials of the device are planned for 1983 construction season. Other studies by FHWA include the development of more rapid and less expensive methods for monitoring aggregate gradation, and of methods to determine what are acceptable requirements for use in bituminous construction.

New dynamic modulus and resilient modulus standard methods have an advantage over the conventional methods, such as Hveem and Marshall, because they are more fundamental and can be associated more closely with asphalt pavement design methods. The scope and significance of the new methods are:

- <u>Dynamic Modulus of Asphalt Mixtures</u> - ASTM D3497

  A sinusoidal (haversine) axial compression stress is applied to a specimen of asphalt concrete at a given temperature and loading frequency. The resulting recoverable axial strain response of the specimen is measured and used to calculate dynamic modulus. The value can be used for both asphalt paving mixture and asphalt pavement thickness design.

- <u>Indirect Tension Test for Resilient Modulus of Bituminous Mixtures</u>- ASTM D4123

  The repeated-load indirect tension test for determining resilient modulus of bituminous mixtures is conducted by applying compressive loads with a haversine or other suitable wave form. The load is applied vertically in the vertical diametral plane of a cylindrical specimen of asphalt concrete. The resulting horizontal diametral deformation of a specimen is measured and, with an assumed Poisson's ratio, is used to evaluate the relative quality of materials as well as to generate input for a pavement design or pavement evaluation and analysis. The test can be used to study the effects of temperature, loading rate, rest periods, etc. The method is not intended for use in specifications.

For comparison, the scope and significance of conventional methods are as follows:

Resistance to Deformation and Cohesion of Bituminous Mixture by Means of Hveem Apparatus - ASTM D1560 (AASHTO T246)

These methods cover the determination of (1) the resistance to deformation of compacted bituminous mixtures by measuring the lateral pressure developed when applying a vertical load by means of the Hveem stabilometers, and (2) the cohesion of a compacted bituminous mixture by measuring the force required to break or bend a cantilever beam sample by means of the Hveem cohesiometer. The results of the deformation and cohesion tests can be used for specification purposes and for mix design purposes or both.

Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus - ASTMD 1559 (AASHTO T245)

This method covers the measurement of the resistance to plastic flow of cylindrical specimens of bituminous paving mixture loaded on a lateral surface by means of the Marshall apparatus. The method is used in the laboratory mix design of bituminous mixtures. Specimens are prepared in accordance with the method and tested for maximum load and flow. Density and void properties may also be determined.

Compressive Strength of Bituminous Mixtures - ASTM D1074 (AASHTO T167)

This method for compacted bituminous mixtures of the hot-mixed, hot-laid type provides a measure of compressive strength of these paving mixtures. The compressive strength of specimens prepared and tested by the method along with density and void properties are used for the design of bituminous mixtures.

Compaction and Shear Properties of Bituminous Mixtures by Means of the U.S. Army Corps of Engineers Gyratory Testing Machine - ASTM D3387

This method employs two separate modes of operation of the Gyratory Testing Machine. The fixed roller mode is employed for compaction and strain indices. The oil-filled roller mode is employed in testing for strength properties as well as compaction and strain indices.

Evaluation of Classical Techniques

Recently, Lee, Terrel and Mahoney reported on a study to develop a technique and necessary test equipment to produce an intimate mixture consisting of reclaimed bituminous material, modifying agent, new asphalt and new and reclaimed aggregates (49). To study the efficiency of mixing, several detection techniques were used. They were categorized as either classical and non-classical techniques. A summary of the evaluation of classical techniques is shown in Table 33.

The potential value of the conventional Marshall and Hveem tests, the more fundamental tension, diametral resilient and repeated load tests are compared. The diametral resilient test was rated excellent and the repeated load tests were rated good. The other methods were rated fair.

TABLE 33

EVALUATIONS OF CLASSICAL TECHNIQUES

INVESTIGATIVE PROCEDURE	POTENTIAL VALUE FOR MIXTURE EFFICIENCY DETERMINATION
1. Diametral Resilient	Excellent, very sensitive determination
2. Hveem Stability	Fair, not sensitive to asphalt properties
3. Marshall Stability (flow)	Fair, much data scatter
4. Indirect Tension	Fair, much data scatter
5. Direct Tension	Fair, much data scatter
6. Beam Fatigue	Good, but much data scatter
7. Repeated Load Triaxial	Good, difficult to calibrate and historical data is scarce

The non-classical techniques included two basic categories: detection and measuring techniques. They were separated into the following five groups:

1. Scanning methods

2. Scanning and discrete sample techniques

3. Discrete sampling techniques

4. Utilization of mixed properties

5. Measuring techniques

Of the non-classical tests, a dye chemistry technique was determined to be the most acceptable method based on the overall feasibility and associated costs. The dye technique consists of incorporating a small amount of dye chemical into the recycling agent and then detecting the developed dye in the mix. A "dye print technique" was developed by making a dye print impression of a cut face of an asphalt concrete specimen.

V. REFLECTION CRACKING AND OVERLAYS

One of the tasks of this state-of-the-art in asphalt pavement specifications is to determine the extent to which the condition of the underlying base, or of the underlying surface in case of an overlay, can influence the properties of a new asphalt pavement or overlay. The seriousness of the problem as it effects pavement performance is substantiated by the extensive amount of laboratory and field research on reflection cracking and overlay construction that has been reported in the literature. A few of the reports are summarized in this chapter of the report.

The condition of the underlying subgrade, bases and surface courses greatly influences the performance of the total pavement structure. Numerous studies have emphasized the importance of proper moisture and density control of the subgrade during construction. The 1976 and 1979 FHWA surveys showed that 42 percent of the projects had moisture control quality levels below 90 percent and 38 percent had density control quality levels of less than 90 percent (42)(43). Studies by Haas also have shown that the type of subgrade is an important factor in considering low-temperature cracking problems (48). Subgrades having low swell potential have little effect on the performance of the pavement and subsequent maintenance. However, if the subgrade soil is clay, the designer should carefully consider selecting materials that prevent or resist low-temperature cracking. Water infiltration through the cracks will produce subsequent movements in the subgrade soil through swelling.

REFLECTION CRACKING STUDIES

Monismith and Goetzee defined reflection cracking as "the cracking of a resurfacing or overlay above underlying cracks or joints with its probable cause being movement of some form in the underlying pavement" (50).

The authors presented recent developments in the field of fracture mechanics that might be useful in making decisions on the design of overlays. The major conclusion was that fracture mechanics applications are appealing and have the potential to provide solutions for crack reflection through pavement overlay design procedures. The report includes discussions of analytical approaches using finite element methodology and versions of elastic fracture mechanics. The latter suggests that cracking may be arrested by using delamination or debonding or by using materials at the interface that will withstand high strains.

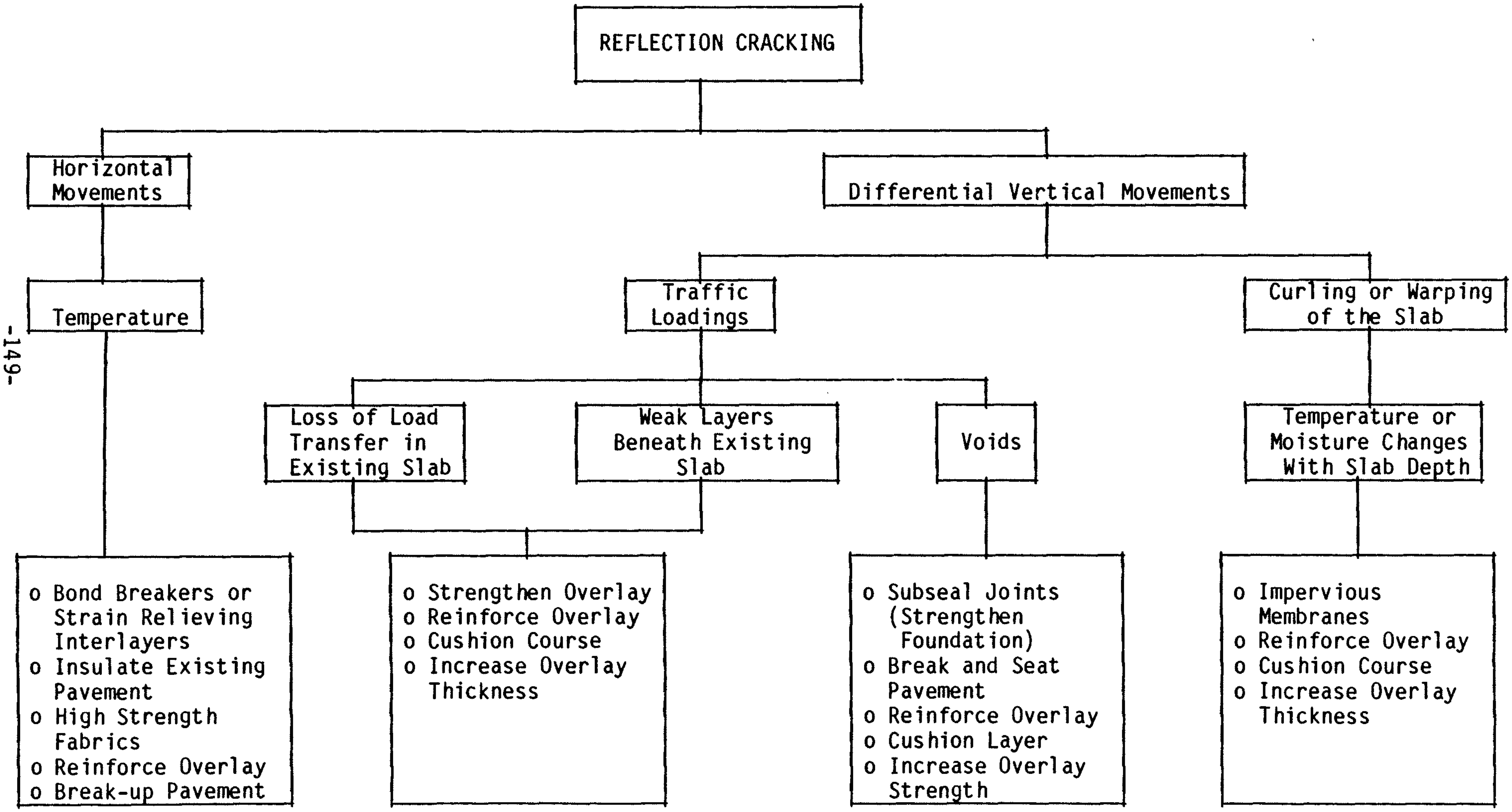
A procedure by Austin Research Engineers, using an analytical procedure for reflection crack analysis without applying fracture mechanics, was discussed. Two failure modes were considered: (1) horizontal movement due to temperature reduction, and (2) shearing action resulting from differential deflection across a joint or crack caused by traffic loads. The authors included a flow diagram to determine a treatment which can be considered to reduce reflection cracking. The flow diagram in Figure 13 is reproduced here to show the various treatments which can be considered to reduce reflection cracking.

Goetzee and Monismith utilized the finite element procedure to examine the distribution of stresses in an overlay in the vicinity of a crack with and without a rubber on asphalt membrane. Finite element programs were used to estimate the effect of variables such as stress distribution and the effect of temperature.

Way reviewed Arizona's practices for the prevention of reflection cracking in Arizona (51). In 1972, Arizona DOT constructed 18 test sections to evaluate reflection cracking and the development of new materials and methods to prevent reflection cracking. After about three years of service, the following treatments were found to have significantly reduced reflection cracking:

FIGURE 13

FLOW DIAGRAM TO SELECT A TREATMENT WHICH CAN BE CONSIDERED TO REDUCE REFLECTION CRACKING
(PROC. AAPT VOL 49 1980)



- Asphalt-rubber membrane seal coat under asphalt concrete friction course (ACFC)
- Asbestos plus 3 percent asphalt
- Heater scarification with reclamite
- Asphalt-rubber membrane flushed into asphalt concrete overlay
- 200-300 penetration asphalt.

Asphalt-Rubber Materials - Vallerga, et al reported on the applicability of asphalt-rubber membranes in reducing reflection cracking (52). The report characterized the asphalt-rubber material used for a membrane and described various asphalt-rubber systems, design considerations, and construction details. The asphalt-rubber membrane materials are manufactured by blending 20-25 percent of selected types of vulcanized and reclaimed crumb rubber with 75-80 percent asphalt. Small amounts of solvent or extender oil (1 to 5 percent) may be added to the asphalt-rubber systems to facilitate blending, depending on the grade of asphalt and the type of rubber used.

Several types of asphalt-rubber treatments have been used. The SAMI (stress absorbing membrane interlayer) treatment consists of applying the asphalt-rubber material on an existing cracked asphalt or portland cement pavement prior to placing an overlay.

The SAM (stress-absorbing membrane) treatment consists of applying the asphalt-rubber in the form of a surface treatment with aggregate cover. One of the advantages is the greater thickness of the application of asphalt-rubber.

The plant-mixed SAM approach consists of mixing asphalt-rubber with chip aggregate in a conventional plant and spreading the plant-mixed aggregate chips with a conventional spreader. Experimental sections have been constructed.

Fabric Interlayers - The use of man-made woven fabrics as membranes in interlayer systems to prevent reflection cracking was first tried about 1966 (53). Since then, several fabric types have been used both experimentally and in full scale overlay resurfacing projects. The principal fabric materials are polypropylene and polyester. Estimates are that several million square yards of fabric have been installed throughout the U.S. in highway and other traffic associated applications. Observations conclude that properly applied fabric interlayers will prolong the life of a pavement structure for several years and reduce maintenance costs.

As early as 1932, open-graded penetration macadams were used as overlays on portland cement concrete pavements to control reflective cracking (54). The State of Tennessee constructed several miles of open-graded mix in the middle 1950's, and in 1967 they still were giving excellent performance. Today, the open-graded aggregate mixtures are used extensively in Arkansas and are giving excellent performance as a crack relief layer.

Basic grading used in Tennessee and Arkansas for crack relief layer are given below:

	PERCENT PASSING		
SIEVE	A	B	C
3 in (76mm)	100		
2-1/2in (64mm)	95-100	100	
2in (51mm)	-	-	100
1-1/2in (38mm)	30-70	35-70	75-90
3/4in (19mm)	3-20	5-20	50-70
3/8in (9.5mm)	0-5		
No. 4 (4.75mm)		-	8-20
No. 8 (2.35mm)		0-5	-
No. 100 (150μm)		-	0-5
No. 200 (75μm)		0-3	
Asphalt Content	1.6	-	2.5
Asphalt Grade	AC-40 or (AC-30), AR 8000, 60/70 Pen minimum thickness 3-1/2in (89mm)		

Finn et al presented a summary of different systems devised to control reflection cracking (55). The methods generally fall into one of the following classifications:

1. Increase the ability of the asphalt concrete overlay to withstand the stresses or strains which cause cracking.
    - (a) Use of asphalt-rubber in mix.
    - (b) Use of rubber in thin treatments.

2. Place an intermediate stress-relieving layer.
    - (a) Aggregate blanket.
    - (b) Bond breaker.
    - (c) Stress-relieving interlayer of ground rubbers, sand and asphalt emulsion.
    - (d) Membrane of rubber and asphalt.
    - (e) Reinforcing materials - synthetic fabric or wire mesh.

3. Preparation of underlying pavement.
    - (a) Undersealing portland cement pavements.
    - (b) Slab breaking or seating.

4. Overlay with relatively thick layer of asphalt concrete.

Finn concluded that the most reasonable approach to minimizing reflection cracking appears to be some type of stress relieving interlayer between the old pavement and the overlay.

If old Portland cement concrete pavements are badly cracked or vertical support is needed, undersealing with asphalt or cement mortar prior to overlay may be necessary. An overlay of 4 1/2 inches (113 mm) of asphalt concrete has been suggested. Vertical slab movement can be corrected by breaking the slabs by hammering, or seating the slabs with heavy rollers followed by the asphalt concrete overlay.

PAVEMENT EVALUATION AND OVERLAY DESIGN METHODS

The Asphalt Institute Manual on Asphalt Overlays and Pavement Rehabilitation (56) proposes a way to salvage, strengthen and modernize deficient roads and streets with asphalt concrete. The scope includes recommendations for geometric and structural improvements to increase traffic capacity, load-bearing ability and safety of existing roads. The manual covers:

- Methods for making pavement condition surveys
- Methods for thickness designs of overlays
- Information on the design of asphalt pavement widening and shoulders
- Tips on geometric improvements
- Information for preparing pavements for overlays
- Information on construction of asphalt overlays
- Testing procedures and guide specifications.

The adequacy of the existing pavement structure is determined from the subgrade strength value, design traffic number and effective thickness derived from the pavement examination. Structural evaluation is made to determine what thickness overlay is needed to strengthen an inadequate pavement so that it will carry traffic for some future time, and to estimate how long it will be before an overlay is needed. Procedures are given for finding the thickness of overlay.

In 1979, Monismith presented a summary of methods being used in evaluating pavements for overlays (57). To assist the engineer in deciding what pavement maintenance or rehabilitation to do and when to perform it, pavement performance must be measured on a systematic and continuing basis. Functional performance which describes how well the pavement serves the user, such as roughness or skid resistance, and structural performance, is related to how well the pavement can sustain loads.

Monismith pointed out that visual condition surveys are well established and should be a part of the maintenance and rehabilitation methodology of every organization that has responsibility for pavements.

The author summarizes various methods used for pavement evaluation and overlay design up to 1979. Non-destructive testing devices that were used by various organizations are shown below.

DEVICE	USED BY
Benkelman Beam	Asphalt Institute
Traveling Deflectometer	California Department of Transportation
Deflectograph	U.K. Transportation and Road Research Laboratory. National Institute of Transportation and Road Research, Pretoria, Africa
Light Vibrators:	
Road Rater	Kentucky Department of Transportation
Dynaflect	Louisiana Department of Transportation Federal Highway Administration (Road Research Engineers, Inc.)
Heavy Vibrators	U.S. Army Corps of Engineers
Falling Weight deflectometer	Shell Research B.V., Amsterdam

Overlay-pavement design can be accomplished by tests on samples of existing pavement materials, deflection measurement at the pavement surface, or a combination of both. The ARE method, for example, requires that samples of the pavement layers be obtained and laboratory stiffness determinations be made. This, together with deflection data, ensures that stiffness properties of the pavement components are reasonable. Monismith concludes that there are many overlay design procedures available. Procedures also are available for performance and condition surveys and methods for statistical treatment of deflection data. A summary of other evaluation and thickness design procedures include the following:

Dynamic Deflectometer - Dynamic surface deflections obtained with the road rater were used in conjunction with elastic theory to analyze pavement behavior (58). The deflections were used to estimate the elastic modulus of the foundation material and the determination of the equivalent thicknesses of new material that approximate the behavior of the structure. The estimated moduli and the equivalent thicknesses can be used as inputs to design overlay thickness. An analysis of the deflections of the road rater makes it possible to distinguish weaknesses in asphalt concrete layers as well as weaknesses in the supporting foundation. A step-by-step procedure is given for use in the thickness design of an asphalt concrete (AC) overlay applied to an existing AC pavement.

Falling Weight Deflectometer - Deflection measurements made with a falling weight deflectometer (FWD) can provide the road engineer with meaningful data on a pavement structure (59). From these data, the state of the pavement (e.g., in terms of residual life) can be evaluated in an analytical way, and, if necessary, the structural restrengthening measure (e.g., in terms of overlay thickness) that should be undertaken can be determined. The data provided by the FWD are sufficiently accurate to tailor the design to the individual circumstances and, at the same time, are produced quickly enough for routine investigations.

Shell Design Charts - The charts in the Shell Pavement Design Manual can be used by the designer, without resort to computer calculations, to determine analytically the overlay thickness required for a variety of circumstances. Examples are given showing the influence of subgrade strain criteria and temperature conditions on the required minimum overlay thickness.

Layer Analysis - Methods are available that may be used to design overlay thickness. The basic approach is categorized as a pavement layer analysis where a strength value is assigned to each layer and the behavior of the total pavement is predicted using a mathematical model. The monolithic approach uses the in-place load-carrying capability of the existing pavement. All monolithic methods use surface deflection as a measure of the load-bearing capability.

Information is given in the NCHRP Synthesis No. 9 on the application of the various design procedures, which includes those developed by the Asphalt Institute, Corps of Engineers, AASHTO, Canada, state highway departments, and the Portland Cement Association (60).

VI. REHABILITATION

PAVEMENT ROUGHNESS

A report on the state-of-the-art on measurement and analysis of road roughness was published in 1981 (61). Road roughness is considered to be one of the major elements of performance-related specifications. Measurements of road roughness are of interest to the engineer as a means for determining the acceptance of new or resurfaced pavements. It is of interest to the maintenance engineer in determining pavement safety, serviceability and a means of assessing pavement distress. The highlights of the roughness study include the following:

Methods for Measuring Road Roughness

- Response type - measures the response to roughness and records the dynamic response of mechanical systems as they travel across the rough road at some constant speed. The first response type equipment known as a roughometer was developed by the Bureau of Public Roads (now FHWA) in 1925. Later response type equipment, generally called roadmeters, include the PCA Meter (developed by the Portland Cement Association) and the Mays Meter. These meters are the least expensive and simplest but should be used only when calibration procedures are followed.

- Profiling equipment - the simplest type is a straight edge or its modification. Spans of 10 to 30 feet (3.05 to 9.15 m) are used by various agencies. The first modern profiling equipment was developed by General Motors Research Laboratory and has become known as: General Motors Profilometer (GMR), rapid travel profilometer (RTP) and surface dynamics profilometer (SDP). The authors expressed some concern that the GMR is not more widely used in the highway community. It is more costly, although there are more than 40 states that have skid testers at almost the same price.

Potential uses of road profile data include the following:

USE	DATA
Construction	Specification-surface profile limits for new construction and evaluation of costs to improve road.
Maintenance	Prediction of loss in serviceability criteria for maintenance and replacement.
Vehicle Behavior	Correlation with vibrational response and fatigue damage in vehicles, passenger comfort criteria, effects on braking and steering.

Standardization of road roughness measuring devices are under study by the American Society for Testing and Materials in three subcommittees.

The studies include:

- Methods of measuring profile and roughness
- Measurement and control of roughness
- Methodology for analyzing pavement roughness.

Hudson (62) reported on a paper in which he summarized the importance of rational and compatible measurements of road roughness and some of the problems and possible methods for making such compatible measurements. He pointed out that there was a worldwide need for an index for comparing roughness on paved and unpaved surfaces and evaluating serviceability and vehicle operating costs. Hudson presented a detailed analysis of methods that are available to calibrate and standardize roughness measuring devices and techniques. Part of the problem is to provide simple, direct and relatively inexpensive roughness measurements that remain stable from day to day and year by year around the world. Further development of high quality measuring equipment and calibration techniques for regular worldwide use should be continued.

IOWA'S SMOOTHNESS SPECIFICATION

In 1982, Iowa implemented a specification for pavement smoothness using the 25 foot (7.6 m) California Profilograph (63). The new specification applies to all primary and interstate portland cement and asphalt concrete paving projects, full depth patching and asphalt concrete resurfacing projects.

Each of Iowa's six districts was provided with a profilograph and appropriate training. The profilograph produces a profile trace of the pavement surface at full scale or 1"= 1" (25 mm = 25 mm) vertically and 1"= 25' (25 mm = 7.6 m) longitudinally. It can be used to locate 1/2 inch (13 mm) bumps for correction, to compute the profile index, to diagnostically evaluate pavement smoothness problems and provide its permanent document in case of price adjustment disputes. Disadvantages are slow testing speed, sensitivity to vibrations, trace reduction requirements, possible non-uniformity of profile trace reduction requirements, and distorted smoothness measurements when bumps occur at multiple wavelengths of the 25 foot (7.6 m) profilograph.

The new smoothness specification requires testing at 1/4 point in both directions of main-line paving only with the 25 foot (7.6 m) profilograph. A preliminary and final profile index are determined to allow the contractor to correct deficient pavement area before final price adjustments are allowed. Corrected areas must have a texture similar to the adjoining areas. All bumps greater than 1/2 inch (13 mm) must be removed. Two schedules of payment are used as shown in Table 34.

Iowa conducted a training school in 1982 to train district materials technicians how to perform 25-foot profilograph testing. Although there were a number of questions during the early part of the construction season, the number of questions declined and testing for compliance was fairly routine by fall. Contractors were provided similar training at workshops during the winter. The contractor training improved acceptance of the new smoothness specification. There have been improvements in smoothness as a result of the specification.

NCHRP made an intensive study of response-type road roughness measuring systems (primarily Mays and PCA Road Meters) for the purpose of developing calibration and correlation procedures (64). A simplified method for calibrating road meter systems was developed, and offers potential for use over the moderate-to-rough range of roughness. It offers a means to collect and analyze data on pavement surface characteristics, pavement rehabilitation and management programs, and testing and research activities. The report includes a section on uses of Response-Type-Road Roughness Measuring systems (RTRRM systems). These include the BPR roughometer, the Mays Meter and the PCA Meter. If the RTRRM systems are well maintained and calibrated, they are capable of measuring roughness for road condition surveys of highway network to determine a general indication of serviceability. Because of the large random error, the utility of measurements on individual road sections, as may be needed for maintenance decisions or evaluating the quality of new construction, are limited.

SKID RESISTANCE

The literature is replete with information on the various factors that influence skid resistance of asphalt pavements. Skid resistance is

TABLE 34

IOWA'S SMOOTHNESS SPECIFICATION

Schedule A

Applies to rural paving and urban
paving in areas with speed limits of
45 MPH or greater

Daily Profile Index	Percent of Contract Unit Price
0-15	100.0
15.1-18	98.0
18.1-21	94.5
21.1-24	91.0
24.1-27	87.5
27.1-30	84.0
30.1-33	80.5
33.1-36	77.0
Over 36	Correct or remove & replace

Schedule B

Applies to ramps, tapers, short sections between
50' (15.4 m) and 250' (76.2 m) in length,
and urban paving in areas with speed limits of
less than 45 MPH.

Daily Profile Index	Percent Of Contract Unit Price
0-30	100.0
30.1-40	95.0
40.1-50	90.0
50.1-60	80.0
Over 60	Correct or remove & replace

included here because of the important role that asphalt pavements play in the design and construction of pavement having high frictional characteristics. Skid resistance is another of the seven distress modes for performance-related specifications. Figure 12 of this report shows the distress mode for skid resistance, the controlled variables, contributing material properties and evaluation methods for short and long use. While there are many aspects of the overall problem, only the contribution of asphalt materials and mixtures to pavement surface texture will be discussed here.

In 1980, Balmer and Hegmon presented a paper summarizing the state-of-the-art of research on pavement surface texture (65). They emphasized the importance of microtexture (fine texture) and macrotexture (coarse texture) from the standpoint of skid resistance under different speeds of travel and wet or dry conditions.

Microstructure contributes to skid resistance at all speeds with a prevailing influence at speeds less than 50 km/h (31 miles/h). Microstructure depends largely on the mineral composition, rugosity of the aggregate, and the sharp, fine particles that permit intimate contact between the tire and roadway.

Coarse macrostructure is essential to safe high-speed travel under wet conditions. It can be obtained by controlling the gradation of the surface aggregate, which also should be composed of hard, angular, coarse, and polish-resistant particles. Open-graded asphalt friction courses are an example of this type of surface. While the aggregate characteristics are of primary importance in skid resistant surfaces, proper asphalt mixture design also is essential to good performance. Mix properties can be controlled by aggregate, gradation, type and amount of asphalt, void content, and stiffness.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The state-of-the-art in asphalt pavement specifications shows that a number of the present methods of test and specifications for pavement materials and construction were developed and standardized during the period from 1900 to 1925. Since then, these and new tests have provided a means for measuring and controlling the properties that, through experience, were found adequate for the construction of pavements having good performance. Many thousands of miles of high quality pavements were constructed and served to meet the traffic requirements of the time.

With the advent of the interstate program in the 1950's, the tremendous increase in the quantities of materials, processes and construction presented problems of adequate quality control during construction and acceptance of the final product. Thus, during the past 20 years the development of specifications, sampling procedures and methods of tests have been directed towards statistically-oriented end-result specifications (ERS). A vast amount of information relative to the variability in the test properties has been developed and numerous reports have been published showing the various aspects of statistical quality control and acceptance plans. Many states and other government agencies are using, have used experimentally with, or are planning to use one or more elements of ERS in asphalt pavement construction. Many of the specifications include provisions for pay adjustments for those materials and items of construction that do not conform with the quality requirements.

Substantial progress has been made since the quality assurance programs were first initiated. In general, the following essential requirements have been accepted:

- Proper allocation of responsibilities of the contractor and agency

- Effective and realistic quality control by the contractor
- Lot by lot acceptance of construction
- Use of random sampling methods
- Selection of effective end-result requirements
- Use of statistically-oriented acceptance plans
- Use of pay adjustments for non-conforming materials and construction.

Surveys show that pay adjustment practices used by states differ largely from state to state. The practice differs not only in the specific tests used by the states but also the amount of deviation permitted by the specifications. For example, in terms of the maximum deviation in asphalt content, the same asphalt mix supplied to two different states could be rejected by one state and receive full payment by another state.

Important publications on the implementation of quality control are the FHWA Model Aggregate Gradation Control Programs and the manual prepared by NAPA for quality control for hot plant mix and paving operations.

The most important objective of this state-of-the-art study was to provide background information for the development of performance-related specifications for asphalt pavements. The literature is replete with information on laboratory studies of the relationship of asphalt properties to mixture characteristics but is limited in the direct relationship of these characteristics to pavement performance. To evaluate the problem, distress modes were selected together with the material and construction factors that contribute to each form of distress. For five of the seven distress modes, mixture design was the most common material factor contributing to distress conditions. Compaction was the most critical construction factor affecting performance. Information on the relative importance of the various forms of distress was found in a few reports on pavement condition surveys. A consensus of findings indicated that longitudinal load associated cracking (fatigue) was the most prevalent form of distress, followed by transverse cracking and displacement. Density or void content was found to be a major factor in all forms of distress.

One of the tasks in the development of performance-related specifications concerns the extent to which the properties of the subgrade and base courses influence the performance of the surface course and reflection cracking in case of an overlay. Numerous studies have emphasized the importance of optimum moisture content and the degree of compaction of the subgrade during construction. The literature also contains the results of numerous treatments that can be used to reduce or prevent reflection cracking and preventative and corrective actions that do not involve major alterations of the pavement. Several methods for designing overlays are available.

Methods of rehabilitation are included within the scope of performance-related specifications. Rehabilitation includes a variety of practices, some of which are described above, to result in improved riding quality, skid resistance and upgrading the load-carrying capability of the existing pavement. The determination of the extent of rehabilitation must be based on periodic condition evaluations. This can be determined by visual condition surveys, in-place measurement of the pavement strength or stiffness by deflectometers, or by evaluating individual pavement layers by stiffness or other methods.

RECOMMENDATIONS

1. Because of the disparity of methods and tolerances for pay-adjustment factors, uniform and equitable pay adjustments based on sound engineering judgment should be adopted.

2. Continue research and testing to assess effects of variations from specification limits for properties of materials and construction processes.

3. Develop guidelines for a quality control and acceptance program that can be incorporated in a performance-related specification for asphalt pavements.

4. Improve quality control procedures for density, bitumen content and aggregate gradation to reduce variability.

5. Develop detailed performance-related specifications that will include requirements for optimum mixture design for structural capacity, rideability, and skid resistance.

6. Promote more research on the application of fundamental methods such as dynamic modulus and resilient modulus to material evaluation and mixture design that can be related to pavement performance.

7. Encourage the use of currently available rapid methods and the development of new methods for control and acceptance of materials and construction processes.

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