Quality Management of Hot Mix Asphalt

Dale S. Decker, editor

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Peer Review Policy

Each paper published in this volume was evaluated by two peer reviewers and at least one of the editors. The authors addressed all of the reviewers' comments to the satisfaction of both the technical editor(s) and the ASTM Committee on Publications.

To make technical information available as quickly as possible, the peer-reviewed papers in this publication were prepared "camera-ready" as submitted by the authors.

The quality of the papers in this publication reflects not only the obvious efforts of the authors and the technical editor(s), but also the work of these peer reviewers. The ASTM Committee on Publications acknowledges with appreciation their dedication and contribution of time and effort on behalf of ASTM.

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Foreword

The Symposium on Quality Management in Asphalt Pavement Construction was held 5 December 1995 in Norfolk, Virginia. ASTM Committee D-4 on Road and Paving Materials sponsored the symposium. Dale S. Decker, National Asphalt Pavement Association, Lanham, Maryland, presided as chairman and is editor of this publication.

Contents

Overview

Worldwide, organizations are focusing on producing products and processes using principles of total quality management (TQM). In the last 20 years, some form of TQM has been used in every type of organization, both public and private.

The hot mix asphalt industry, while getting a late start in quality management, is actively working to embrace the concepts in order to improve its product. However, the process for building an HMA pavement is not simple. There are many phases involved and many different activities that constitute the process of constructing a high-performance, quality HMA pavement.

The nomenclature of this quest for quality pavement varies. Some organizations call the process quality management, others call it quality control/quality assurance, and still others call it field management. Depending on the author, the reader may encounter any or all of these terms, all of which describe the control of the HMA manufacturing and placement processes.

Quality management of HMA ensures high performance in HMA pavements. Central elements of the quality management process are:

- The contractor must be responsible for the manufacturing process. Responsibility for process control is crucial.
- All elements of pavement construction must be considered as one activity. Mix design, structural design, and construction must be inextricably linked to ensure the overall process results in high-performance pavements.
- Process control must ensure the design and construction of high-performance pavements rather than checking for poor quality: building it right rather than inspecting to see if it's wrong, in other words.
- Cooperation and communication between all stakeholders in the process is critical.

Symposium Purpose

This symposium was organized to provide a forum to highlight practical implementation of several approaches to achieving quality in HMA pavements. While the central themes previously noted will be echoed throughout many of the papers, vastly different approaches are taken by different organizations to address quality management.

Some of the papers present broad concepts on development of quality management systems in organizations, while other papers present specific technical information on operation of quality management programs. Thus, the reader can get both broad and specific information on quality management in this special technical publication.

Summary

Improving the performance of hot mix asphalt is an ongoing goal for the pavement industry. Advances in mix design, structural design, and construction may provide tools to assist the industry. However, if the manufacturing process is not appropriately controlled with some type of quality management system, the best equipment and materials can be sacrificed. Embracing quality management concepts and philosophies is crucial to the manufacture and placement of high-performance hot mix asphalt.

This special technical publication contains information that will provide the reader with an understanding of how quality management systems can, and do, function in real world applications.

Dale S. Decker, P.E.

Vice-president of Research and Technology,
National Asphalt Pavement Association.
Symposium chairman and editor.

Daniel E. Wegman [1]

MINNESOTA'S QUALITY MANAGEMENT PROGRAM " A PROCESS FOR CONTINUOUS IMPROVEMENT"

REFERENCE: Wegman, D. E., "**Minnesota's Quality Management Program: A Process for Continuous Improvement,**" Quality Management of Hot Mix Asphalt, ASTM STP 1299, Dale S. Decker, Ed., American Society for Testing and Materials, 1996.

ABSTRACT: Minnesota's Quality Management Program began in 1986 when the Minnesota Department of Transportation (Mn/DOT) and the Minnesota Asphalt Pavement Association (MAPA) formed a partnership to develop a process for improving the quality of asphalt pavements within the state. A Quality Management Task Force was formed with members representing Mn/DOT Construction and Materials, Counties, Cities, Consultants, FHWA, Hot Mix Asphalt (HMA) Contractors and a Consultant hired as a technical advisor. The Task Force was charged with the goal to "Develop and Implement a Quality Management Program to Assure Construction of Quality Asphalt Pavements". This was the beginning of a continuous evolution which has and will continue to guide the production and placement of HMA Mixtures.

Today the key components of the program are:

1. **Volumetric Quality Control(QC), Quality Assurance (QA) and Independent Assurance Sampling and Testing (IAST)**
2. **Technical Certification**
3. **Plant Certification**
4. **Incentives/ Disincentives**
5. **Program Evaluation through Data Analysis**
6. **An Issue Resolution Policy**

KEYWORDS: quality control (QC), quality assurance (QA), independent assurance sampling and testing (IAST), certification, incentives, technical training, volumetric control, asphalt testing

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DISCLAIMER

Any views or opinions expressed or implied within this document do not necessarily represent the Minnesota Department of Transportation, the Minnesota Asphalt Pavement Association or any other agency or organization.

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VOLUMETRIC QC, QA and IAST

Minnesota's Quality Management Program utilizes volumetrics in mix design, field control and acceptance of HMA mixtures. "Good volumetrics" implies having the right proportion or volume of aggregate, asphalt and air in a HMA mixture to assure good pavement performance. Another important aspect of good volumetrics is making sure a quality HMA product can be supplied in a practical and economical way. This typically involves utilizing locally available resources within constraints that are flexible to allow for contractor ingenuity while strictly adhering to volumetric properties which indicate a high probability for good performance. Achieving good volumetrics requires a commitment to quality and partnership by all parties involved in construction. These efforts must be ongoing in order to truly achieve a process for continuous improvement.

Mix Design/Preproduction Parameters and Criteria

The two most important mix design and mix performance parameters are Voids in Mineral Aggregate (VMA) and Voids in the Total Mix (VTM). Minnesota's Quality Management Program assures adequate VMA through specification of a minimum asphalt content and gradation controls. Air voids are maintained by continuous testing through contractor quality control and state quality assurance. Virtually all Quality Management (QM) mix designs are performed by the contractor and verified by the agency. Mix design and preproduction procedures are summarized as follows:

1. Contractor submits representative aggregate for quality testing.
2. Contractor performs Marshall mix design and submits in writing a proposed Job Mix Formula (JMF) which includes aggregate source and combination along with the optimum percentage of asphalt cement for the design air void content (typically 4.0%). Test data required with the submittal includes:
   - aggregate gradations and proportions of each material
   - composite gradation based on the above and plotted on FHWA 0.45 power paper
   - extracted asphalt content of salvaged asphaltic aggregate and the extracted asphalt content of the total recycle mixture (required for Recycled Asphalt Pavement (RAP) mixtures only)
   - percentage of Asphalt Cement (AC) added, based upon the total weight of the mixture
   - mix design with a minimum of four points (at least one above and below the optimum asphalt percentage) with the maximum specific gravity at each AC content
   - Marshall test results for the individual and average bulk specific gravity, density, height, stability and flow of at least three specimens at each AC content
   - percent air voids (VTM) and voids in mineral aggregate (VMA) at each AC content
   - fines to asphalt (F/A) ratio calculated to the nearest tenth of a percent
3. Contractor submits a 15,000 gram uncompacted sample plus three Marshall briquettes compacted at the optimum asphalt content and Marshall design blows conforming to the JMF for laboratory examination and evaluation.
4. An interlab comparison is performed prior to production on hot/cold-reheated samples to make mixture property comparisons between contractor and agency laboratories.

Production Quality Control (QC), Quality Assurance (QA) and Acceptance

Under QM, asphalt cement and contractor quality control testing are included in the price paid for the asphalt mixture as a whole. In most cases asphalt relative to aggregate has a higher cost, thus contractors will strive to design and control asphalt mixtures at the lowest possible asphalt content allowable by the specifications. This means the contractor typically controls mixture air voids primarily through adjustments of one or more of the individual aggregate components while operating in close proximity to the specified minimum asphalt content. Since adequate VMA is assured through minimum asphalt content the contractor will usually operate in close proximity to the minimum VMA. This condition results in asphalt mixtures being placed at a low cost (typically $15.00 to $22.00 per ton) with specification constraints to assure uniformity. It also emphasizes the importance of proper contract administration and maintaining good QC and QA which dictate acceptance and ultimately payment for the product supplied.

QC is the responsibility of the contractor. This responsibility includes:

1. Making sure his production material has been properly represented in his mix design.
2. Having qualified personnel and sufficient equipment meeting all technical certification requirements to conduct quality control testing. This includes calibration and correlation testing requirements.
3. Performing all tests in conformance with the Schedule of Materials Control for Quality Assurance .
4. Maintaining and providing quality control charts and documentation on an ongoing basis.
5. Taking appropriate action when testing shows material properties are moving toward specification limits. Shutting down when two consecutive moving average points are outside the specifications.

QA is the responsibility of the Agency. The purpose of quality assurance is to assure all materials and related activities are in compliance with the specifications. Comparison samples are tested by the Agency in accordance with standard procedures and compared with the contractors' quality control tests. Contractors' tests are used for acceptance and payment only when they are verified by quality assurance comparison tests. Guidelines for allowable differences between contractor and agency tests are used for verification and validation. Quality assurance activities include:

1. Reviewing the on-site QC records and charts for accuracy and completeness.
2. Overseeing the ongoing QC operations while in progress to minimize variance inherent in split sampling, audit sampling and comparison sample testing.
3. Monitoring contractor QC actions to assure they are in compliance with specifications.
4. Obtaining companion (split) samples , testing and verifying contractors' QC tests.

Conducting additional testing when necessary to properly validate contractor QC operations (investigative and audit testing).

Definitions: Split Sample - A QC/QA sample that is split into two parts. One half is tested by the Contractor for process control and the other half is tested by the Agency to verify the Contractor's test results. Focus is on proper equipment and test procedures.

Audit Sample - A sample which is obtained and tested by the Agency to assure compliance of the Contractor's Quality Control Program. Audit samples are taken at any time and tested at the Agency's discretion . The Contractor is allowed to test a split of any audit sample taken. Audit samples were introduced for the Certified Plant Program.

The statistically based sampling and testing process for QC/QA utilizes upper and lower specification limits for assuring key asphalt mixture properties/parameters meet requirements. Individual and running average of four test results are determined and plotted on control charts to:

A. Determine if the production process is in control or experiencing excess variation.
B. Help determine when to take corrective actions before the process falls out of specification.
C. Help identify root causes of noncompliance or excess variability.
D. Allow Statistical Process Control (SPC) to be used in targeting more consistent operating strategies leading to better quality and economics in operations.

Sampling and testing by the contractor is performed at a rate of approximately one set of tests for every one thousand tons produced. Agency sampling rates are the same with at least one of every four contractor tests verified by agency testing. The other agency samples are held for a minimum of seven days to be tested on an as-needed basis. The process is set up to minimize the potential for noncompliance material being produced and placed without having to do an impracticable amount of testing.

Independent Assurance Sampling and Testing (IAST)

IAST is an unbiased independent evaluation of all the sampling and testing procedures used in the QC/QA acceptance program. Independent assurance tests are not used as a basis for material acceptance but are utilized as an overall process check for the quality management program. IAST activities are performed by certified agency technicians who do not have direct responsibility for project QC or QA verification sampling and testing. IAST personnel are excellent candidates for establishing regional experts who can learn and pass on new initiatives of an evolving quality management program. They typically are in contact with and have good relationships with all key individuals of the program.

Annual QC/QA program validation is also a function of the IAST program. Program validation is performed by using standard statistical tests. Both the means and variances of the results from the QC tests and associated QA verification tests are compared statistically on an overall program basis. Mn/Dot's automation of the QC/QA data acquisition and analysis process will allow all pertinent data to be statistically analyzed. Prior to the automated system air voids were the key property used in this analysis since they are used for control and acceptance in the field. A statistical "F" test for variances and "t" test for means were considered but not used in program analysis and evaluation on an annual basis. These statistical tests can be used to compare QC and QA tests and determine the likelihood they are from the same population. The reason for not using this type of analysis is the differences between QC and QA test results beyond those naturally inherent may be attributed to the practice of reheating QA samples for voids determination. The reheated samples were considered to be a variable which could potentially compromise the statistical validity of the "F" and "t" analysis.

All three components of Volumetric Quality Management are vital to the success of the program. The program can be expressed in equation form as: QM= QC+QA+IAST. The equation and thus the program is not valid without each component in place and properly applied.

Volumetric Control Information

The current Mn/DOT mixture specifications developed under the QM program are summarized below:
"Broad Band" Aggregate Gradation Requirements

Percent Passing	Type 31		Type 41		Type 47		Type 61	
Sieve Size (mm)	Size A	Size B	Size A	Size B	Size A	Size B	Size A	Size B
19	---	100	---	100	---	100	---	100
12.7	100	---	100	60-98	100	60-98	100	60-98
4.75	40-85	40-85	40-85	40-85	40-85	40-75	40-85	40-85
.075	2 - 8	2 - 8	2 - 8	2 - 8	2 - 8	2 - 8	3 - 7	3 - 7

Type 61 mixtures require 100% crushing in the primary aggregate (80% of total) and are used on roads that have greater than 10 million (design) Equivalent Standard Axle Loads (ESAL).
Type 47 mixtures require 70% crushed coarse aggregate and 25% crushed fine aggregate. These mixtures are typically used on 3 million to 10 million (design) ESAL roads.
Type 41 mixtures require 55% crushed coarse aggregate and are typically used on roads with less than 3 million ESALs.
Type 31 mixtures have no crushing requirements and are typically used on low volume and base mixtures.
Size A is typically used on wearing course mixtures. Size B is typically used on non wear mixtures.

No RAP is allowed in Type 61. Up to 50% RAP is allowed in non wearing and up to 30% RAP is allowed in wearing courses of all other mixtures at the contractor's option.

Guidelines For Allowable Differences Between Contractor & Mn/DOT Tests

Test Type	Allowable Difference* (Individual Test)	Allowable Difference* (Moving Average of 4)
Gradation	± 2 on 0.075 mm sieve ± 6 on other sieves	± 1 on 0.075 mm sieve ± 3 on other sieves
Maximum Specific Gravity	.019	.010
Bulk Specific Gravity	.030	.015
Percent Air Voids	2.0	1.0
Percent Extracted Asphalt	0.81	0.40

* The allowable differences are based on precision and bias statements of AASHTO during the early stages of Minnesota's QM program. The allowable difference for larger families of test results is the allowable difference for an individual test divided by the square root of the number of tests (N).

TECHNICAL TRAINING & CERTIFICATION

Technical bituminous training and certification is a cooperative effort between Mn/DOT and Industry (MAPA). All program decisions are made by the Technical Certification Advisory Committee. This Agency/Industry group is composed of representatives who are active in all fields of highway construction encompassing the overall program. Course Instructors are obtained from Mn/DOT, private industry and educational institutions. Most instructors have hands on field experience which is a major emphasis in the training.

Certification is required for specified contractor and agency personnel on all Federal Aid, State Aid and State projects. The program consists of courses in two levels of certification:

Level I An entry level which is referred to as a "tester" or "field tester". This level is aimed at individuals with limited responsibilities who commonly work under the direct supervision of another.

Level II A more advanced certification which is usually referred to as an "inspector". This level is aimed at individuals who work more independently and are in roles of a decision making capacity.

The program consists of course completion, written examination and in some cases hands on performance evaluations. Certifications are good for five years at which time recertification is required. Experience and continued training during the certification period are important factors in determining requirements for recertification. Permanent laminated certification cards signed by the Mn/DOT Construction Engineer are used to check that certification requirements are fulfilled.

Other important program components are:

Test-outs: Those who are already experienced in a particular area are allowed to test out of the course by taking the written exam and showing proof of experience.

Provisional Certification: A temporary certification where the applicant shows competence in a specific area and meets other criteria until the required certification course can be taken.

Grandfathering: Those with a minimum of twenty years experience working in field construction and/or materials testing and five recent years experience in the specific area of certification.

Decertification: Revocation of the certification privileges for acts which are detrimental to the Certification Program. Administration of decertification appeals is through a Technical Certification Advisory Board.

It does not take long for skills and knowledge to get outdated with the fast pace of change in the world today. Research innovations and the ability to share new information create an environment where continuing education is essential in keeping up with technological advances. The more things people know how to do and the better they do them, the more valuable they become. Construction quality is directly related to the abilities and values of the people associated with it. This is quite evident in Minnesota where Technical Certification has become the backbone of the Quality Management Program.

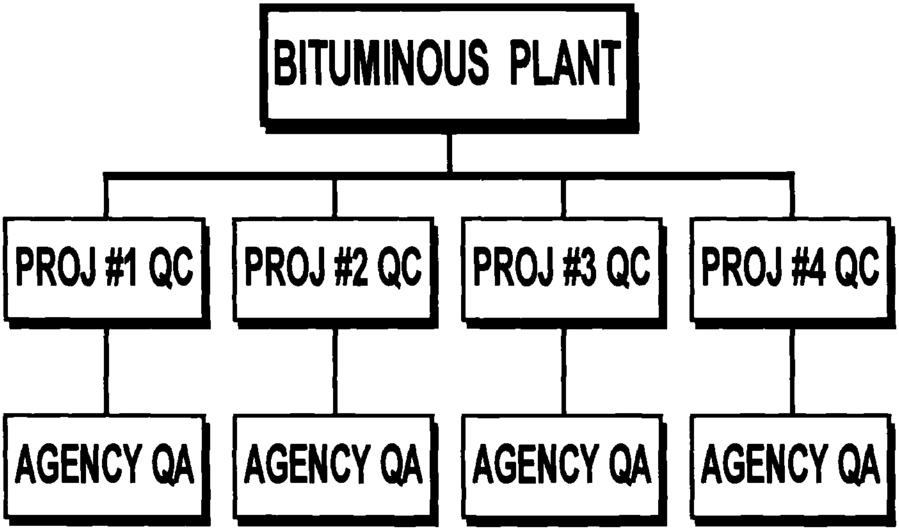
PLANT CERTIFICATION

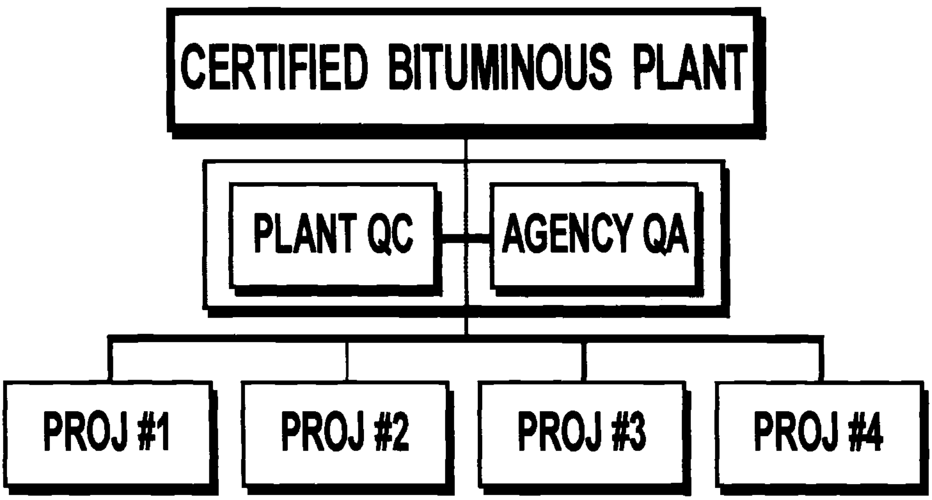
By 1992, six years after initiation of Minnesota's Quality Management Program, over ninety percent of the total HMA tonnage used on State Projects was administered using Quality Management Specifications. Mn/DOT, in the process of reassessing staffing testing costs, service to clients and overall program efficiency, developed the Plant Certification Program. The program focus was to eliminate sampling and testing redundancy and allow for better utilization of existing inspection resources. With FHWA approval of the Plant Certification concept, the program was formally adopted for the 1992 construction season. The program began with pilot projects and has expanded to full utilization in the Minneapolis/St. Paul metro area with discretionary use in other areas.

Under plant certification, the producer/contractor works with the agency through a formal, mutually agreed-upon process. A summary of this process is as follows:

1. Contractor completes application form/request for plant inspection by agency.
2. Contractor provides site map of aggregates and stockpile locations.
3. Pass plant and testing facility inspection via signed plant inspection report (both parties sign).
4. By signing, the plant-authorized agent agrees to calibrate and maintain all plant and lab equipment within allowable tolerances set forth in Mn/DOT specifications and certified plant requirements.
5. The contractor/producer may elect to submit materials for an agency mix design or commonly the contractor will perform their own mix design and submit representative material and paperwork for verification testing and approval by the agency.
6. The proposed mix(es) for the project are tested/evaluated based on established Marshall mix criteria, such as gradation, aggregate quality, crushing, stability, air voids and asphalt content.
7. The agency provides an approved mix design recommendation prior to production. The mix design may carry over year to year or project to project when using the same material source.
8. To maintain certification, the plant must produce, test and document all certified plant mix(es) by Mn/DOT requirements on a continuous basis. Testing is performed on a "plant" tonnage instead of a "project" tonnage basis.
9. The plant certification procedure must be performed annually for a permanent plant or any time a portable plant is moved to a new location.
10. Random numbers are used to establish when process control sampling is conducted. In addition an audit sample can be taken at any time by the agency to monitor the contractor's process control. All samples are split so both the agency and contractor have the ability to run comparison testing.
11. Contractor and agency testing is in accordance with volumetric criteria set forth in Mn/DOT Quality Assurance specifications which include bulk specific gravity, maximum specific gravity, and air voids. Aggregate gradation, percent crushing and AC content are also monitored with mix properties.
12. QA split samples not run by the agency are retained for a minimum of seven working days in case they are needed for additional comparison testing. When comparison testing reveals the contractor test results are invalid, agency test results are used for acceptance and payment.
13. Asphalt samples are taken by the contractor on the project in accordance with Mn/DOT Certified Source Specifications. Under the Certified Source program, additional sampling and testing is conducted at the AC supplier's facility and verified through agency comparison tests.
14. Documentation is the responsibility of the contractor or their representative, who must:
    - Number and record all test results according to specifications
    - Fax all test results to an agency representative by noon of the day following production
    - Verify daily asphalt usage by tank measurements and/or spot checks and supply data
    - Provide agency with asphalt delivery invoices on a daily basis
    - Be responsible for *all* requirements of QC, which includes maintaining control charts, showing individual and running average test results and recording the agency's corresponding documentation including QA test data for verification
    - Provide a daily plant diary and account for all tonnage on a real time basis
    - Provide daily and final project/plant summaries upon request

The following figure is a visual representation of a standard and certified bituminous plant.


BITUMINOUS PLANT
PROJ #1 QC
PROJ #2 QC
PROJ #3 QC
PROJ #4 QC
AGENCY QA
AGENCY QA
AGENCY QA
AGENCY QA


CERTIFIED BITUMINOUS PLANT
PLANT QC
AGENCY QA
PROJ #1
PROJ #2
PROJ #3
PROJ #4

INCENTIVES / DISINCENTIVES

Quality Management is a process which reduces the chance for substandard work by continuously monitoring production and placement and making necessary corrections before an unacceptable product is incorporated into the project. However, utilization of the low bid process creates an environment where the contractor must determine and use the least expensive means for complying with the specifications. When exceeding the specification adds cost in either a real or perceived way, the natural inclination is to target the limits of the specification in order to gain a competitive bidding advantage. When operating in close proximity to the specification limits, even the best contractors will occasionally waver and cross the boundaries into the area of substandard work. Poor contractors may cross that boundary frequently creating a situation where the end product suffers.

Incentives are used to reward a contractor for exceeding the specification in areas where additional value is provided in terms of performance of the finished product. Disincentives or penalties are applied when a contractor does not meet specifications on work already incorporated into the project that does not warrant removal and replacement. An Incentive/Disincentive specification is intended to give conscientious contractors with good quality control a bidding advantage over contractors with poor quality control. In a competitive environment, incentives provided up front in the contract documents will normally result in very little if any additional project costs. A good contractor will be confident of achieving the incentives and bid accordingly in order to improve his chances of getting the work. Of course, this assumption relies on the premise that it doesn't cost any more to do quality work. This premise has been proven over and over by good quality conscious contractors.

Mn/DOT's Incentive / Disincentive specifications are currently used on a limited number of "pilot projects". They cover three critical areas:

1. UNIFORMITY (mixture air voids)
2. DENSITY (in-place air voids)
3. SMOOTHNESS (ride)

Uniformity

The uniformity incentive rewards the contractor for producing a uniform Hot-Mix Asphalt (HMA) mixture in close proximity to the target air void content. Of course, the contractor must be in compliance with all other specification requirements such as minimum asphalt, aggregate properties and gradation. The intention is for the contractor to build uniformity into his mixture from the initial stages of processing aggregates through hauling and placing the mixture in the field. Reducing variability in all operations such as crushing, stockpiling, handling, proportioning, transporting and laying materials shows up in uniformity of the finished product. The Incentive/Disincentive for air void uniformity uses specifications like those reported by Parker and Hossain [1]. Specification calculations are as follows:

- ♦ A lot consists of four continuous individual air void tests on a given mix design. Air void tests are taken on the average of one per thousand tons. Lots may contain tests from one or more days.
- ♦ The absolute value of the deviation from target for each individual air void test is computed as follows: $|Deviation\ from\ target| = 4.0 - test\ value$
- ♦ The arithmetic average of absolute value deviation from the target (Δ) is computed as follows:
  $(Sum\ of\ |deviation\ from\ target|)\ /\ (number\ of\ tests\ in\ lot)$

The following pay factor table is applied to material represented by a lot size of four tests.

For	Pay*
$0.00 \le \Delta 4 \le 0.30$	103%
$0.31 \le \Delta 4 \le 0.55$	101.5%
$0.56 \le \Delta 4 \le 1.05$	100%
$1.06 \le \Delta 4 \le 1.24$	95% (97.5%)
$1.25 \le \Delta 4 \le 1.40$	90% (95%)
$1.41 \le \Delta 4$	80% (90%)

*For pilot projects pay factor values shown in parenthesis ( ) are used for values less than 100%

The uniformity specification pay factor table was derived from analysis of quality levels achieved on previous projects. The analysis utilized the previous year's historical data base collected from projects controlled with traditional specifications. Current and future pilot project Incentive/Disincentive data will be used to establish a new data base for updating the specification and future pay factor tables.

Density

The intent of the pilot density special provision is to provide a monetary incentive for achieving a density ≥ 92% of Maximum Theoretical Density (MTD) and to increase the penalty when the average density falls below 91% MTD. Density uniformity is also factored in by including provisions for the lowest sublot of five, with two cores per sublot. A void factor provision was also instituted to discourage the potential practice of "flooding" the mix with asphalt cement in order to achieve lower in-place voids and thus higher densities. Incentive/Disincentive guidelines encourage project designers to use the density and uniformity provisions together. The contractor will then have an incentive to design and produce a mixture conducive to good uniformity and density and in turn increase the quality and performance of the pavement. Uniform aggregate production, increased film thickness and greater compactive effort are some of the areas where improvements can be made and the value of incentives can be realized.

Densities can also be determined by using a calibrated nuclear density gage when specified in the contract. Both cores and nuclear gage readings are referenced to MTD as determined by the Rice test. Pay factor tables for the Density Incentive Specification are as follows:

MODIFIED SPECIFIED DENSITY PAY FACTORS

Mean of 10 Cores as % of MTD	Pay Factor A
93.0% or Greater	1.02
92.5% to 92.9%	1.015
92.0% to 92.4%	1.01
91.0% to 91.9%	1.00
90.0% to 90.9%	0.99
89.0% to 89.9%	0.965
88.0% to 88.9%	0.94
87.0% to 87.9%	0.90
Less than 87.0%	(a)

Lowest Mean of any Sublot Ave.	Pay Factor B
91.0% or Greater	1.02
90.0% to 90.9%	1.01
89.0% to 89.9%	1.00
88.0% to 88.9%	0.99
87.0% to 87.9%	0.97
86.0% to 86.9%	0.94
85.0% to 85.9%	0.90
Less than 85%	(a)

(a) Denotes that Engineer will determine disposition of material.

VOID FACTORS

% Air Voids (Lot Average)	Void Factor
3.41 to 3.50	0
3.31 to 3.40	0
3.21 to 3.30	0.01
3.11 to 3.20	0.02
3.01 to 3.10	0.03
≤ 3.00	0.05

Total Pay Factor = [(Pay Factor A) x (Pay Factor B)] - [Void Factor]

Pavement Smoothness

Good ride is the single most important aspect of a pavement that the general public uses to judge quality. Research has also shown that smooth pavements will outlast rough ones with other factors being equal[2]. Several factors within a contractor's control contribute to a good ride on asphalt pavements:

1. Good equipment and operations.
2. Keeping the paver running at uniform speed.
3. Keeping a consistent head of material in front of the screed.
4. Making as few transverse joints as possible.
5. Taking time to make good transverse joints when necessary.

While these are not the only factors that affect ride, they go a long way in producing a smooth pavement.

In the past, Mn/DOT did not have an effective smoothness specification or a good incentive for the contractor to produce a smooth ride. If specifications were met, the contractor was paid the same if he paved a road with a Present Serviceability Rating (PSR) of 3.5 or 4.0 even though the quality differed significantly. In 1994, eight incentive/disincentive pilot projects were constructed. All projects utilized the California profilograph and the California Test Method 526 to measure ride. Data from the eight pilot projects is summarized in the following table:

Road	# Segments	# Inc.	#Disinc.	Inc. $$	IRI m/km	PSR
TH59	275	243	2	34 530	0.75	4.1
TH210	348	338	1	48 330	0.73	4.1
TH75	133	133	0	19 479	...	...
TH9	361	334	2	47 955	0.81	4.0
TH9	188	146	4	19 873	0.88	3.9
CSAH46	298	268	0	89 162	0.82	4.0
I90	220	177	7	21 090	0.93	3.9
TH60	132	122	5	15 480	0.93	3.9
TOTALS	1955	1761	21	295 999	...	4.0

(Note: IRI is International Roughness Index; PSR is a subjective measure of ride used by Mn/DOT)

A total of $296,000 in incentives were paid on contracts totaling almost 12 million dollars. This equated to approximately 2.5% of the contracts paid out in incentives. In return for this investment the average ride on these projects, as measured by Mn/DOT PSR indices, was 4.0. This compares to an average PSR of 3.6 on similar (4" overlay) projects constructed in previous years. Additional research will be conducted to analyze the deterioration of ride over time to provide information on the actual return on investment.

SMOOTHNESS SPECIFICATION PAY FACTORS

Initial Profile Index* (Inches per mile) per 0.1 mi. seg.	Specification "A" Incentive $$ per Segment	Specification "B" (CSAH46) Incentive $$ per Square Yard
0 - 1.0	150	0.50
1.1 - 2.0	120	0.50
2.1 - 3.0	90	0.35
3.1 - 5.0	0	0.35
5.1 - 7.0	0	0
7.1 - 8.0	(120) Deduct	0
8.1 - 9.0	(240) Deduct	0
9.1 - 10.0	(480) Deduct	(0.35) Deduct
10.1 - 12.0	Corrective work required	(0.50) Deduct
over 12.0	Corrective work required	Corrective work required

* 0.2 inch blanking band used

The next step beyond Incentives/Disincentives will be to completely turn over the responsibility of assuring performance to the contractor through warranties; Mn/DOT is currently investigating their use.

STATISTICAL DATA ANALYSIS

Considerable data are generated through the continuous sampling and testing performed under the Quality Management Program. Capturing and utilizing these data are crucial to project success and achieving continuous program improvements. In the past, quality management data were recorded and collected through hard copy summary sheets and control charts. Realizing the need to better utilize data, Mn/DOT initiated a program in 1993 called CONLAB to collect and analyze all project test data. Under CONLAB, a QM Automation Program was developed and piloted in 1994. The computerized program is set up for all HMA test data to be input and analyzed as it is obtained in the field. The contractor is required to have a computer capable of running the program and providing a real time accounting of every ton of HMA supplied. All quality control and quality assurance data is input as soon as it becomes available. The program is set up to perform all necessary calculations and flag conditions where the specifications are in jeopardy so corrective actions can be taken immediately. Running averages are utilized so that mixture trends can be identified and corrections made before any material is produced out of specifications. Control charts are plotted and posted at the contractor's quality control laboratory to help facilitate the identification of mixture trends which may dictate the need for adjustments.

The QM Automation Program provides a means for tracking a project during construction and downloading individual project or certified plant data for statistical analysis of all projects. Virtually all test data from the construction projects can be analyzed on a project or program basis. This includes air voids, asphalt content, gradations, specific gravity determinations and more. The program will also analyze differences between state and contractor test results to assure validation prior to acceptance of the mixtures. Upper and Lower Control Limits (UCL and LCL) can also be calculated with SPC software which is an optional tool the contractors may use to help them control their process.

The following statistical data on mixture air voids was obtained through manual input from randomly chosen hard copy summary sheets. Air voids were chosen for analysis because they are the primary means of control and acceptance of HMA mixtures under Minnesota's QM program.

Note: each test represents approximately 1000 tons of HMA. Within limits percentages are based on specification limits for mixture air voids of 2%-6% on an individual and 3%-5% on a running average basis.

1995 CONTRACTOR HMA MIXTURE VOIDS
virgin mixtures = 238 tests ; rap mixtures (recycle) = 207 tests

	AVG	STD DEV	UCL	LCL	within limits indiv voids (2-6)	within limits running avg (3-5)
VIRGIN	4.029	0.878	5.504	2.554	96.6%	94.9%
RECYCLE	3.893	0.875	5.463	2.323	96.1%	96.6%

1995 STATE HMA MIXTURE VOIDS
virgin mixtures = 270 tests ; rap mixtures (recycle) = 320 tests

	AVG	STD DEV	UCL	LCL	within limits indiv voids (2-6)	within limits running avg (3-5)
VIRGIN	4.155	1.037	5.852	2.458	95.2%	N/A
RECYCLE	3.894	0.873	5.347	2.441	97.8%	N/A

1994 CONTRACTOR HMA MIXTURE VOIDS
virgin mixtures = 161 tests ; rap mixtures (recycle) = 290 tests

	AVG	STD DEV	UCL	LCL	within limits indiv voids (2-6)	within limits running avg (3-5)
VIRGIN	3.769	0.754	5.118	2.421	98.7%	93.4%
RECYCLE	3.943	0.849	5.378	2.508	96.9%	95.9%

1994 STATE HMA MIXTURE VOIDS
virgin mixtures = 465 tests ; rap mixtures (recycle) = 442 tests

	AVG	STD DEV	UCL	LCL	within limits indiv voids (2-6)	within limits running avg (3-5)
VIRGIN	3.839	0.954	5.343	2.335	97.0%	N/A
RECYCLE	4.059	0.980	5.685	2.433	97.0%	N/A

1993 CONTRACTOR HMA MIXTURE VOIDS
virgin mixtures = 349 tests ; rap mixtures (recycle) = 666 tests

	AVG	STD DEV	UCL	LCL	within limits indiv voids (2-6)	within limits running avg (3-5)
VIRGIN	3.974	0.679	4.816	3.132	99.4%	97.1%
RECYCLE	3.999	0.829	5.034	2.964	98.9%	94.7%

1993 STATE HMA MIXTURE VOIDS
virgin mixtures = 194 tests ; rap mixtures (recycle) = 115 tests

	AVG	STD DEV	UCL	LCL	within limits indiv voids (2-6)	within limits running avg (3-5)
VIRGIN	3.777	1.114	5.303	2.251	93.3%	N/A
RECYCLE	3.649	1.039	5.509	2.238	95.6%	N/A

The data provided shows there has been good control and compliance with specifications for mixture air voids under Minnesota's Quality Management Program. Overall, this is true for both virgin and recycle mixtures. Upper and lower control limits derived through SPC analysis are well within the upper and lower specification limits for individual mixture air voids of 6% and 2% respectively. This implies the contractors in Minnesota have little difficulty in controlling their production process. The specification for maintaining mixture air voids between 5% and 3% on a running average basis and the expertise developed by contractors under the QM program are primary contributors to this success. The running average specification allows contractors the ability to spot trends early in their production process so that adjustments can be made to correct problems and keep the material within specification on a continuous basis. Turning QC responsibilities over to the contractor has also resulted in better and more economical HMA through optimized use of locally available resources. However, it must be emphasized that Quality Management is not a guarantee for success. It is only a means for monitoring and controlling uniformity. Therefore, as the quality of locally available material diminishes and the demands placed on pavements increase, specification improvements will be essential. The QM framework allows for these improvements through expanded data acquisition and sound engineering practices.

ISSUE RESOLUTION PROCESS (Construction & Materials Policy Development Partnership)

In 1994 Mn/DOT, in cooperation with the Minnesota Asphalt and Concrete Pavement Associations, implemented a pilot process called the Construction & Materials Policy Development Partnership. The purpose is to provide a forum to resolve policy issues between Mn/DOT and the paving industries.

If an issue develops that cannot be resolved through normal department/industry processes, the issue can be brought to the Executive Committee of the Construction Materials Policy Development Partnership. The Executive Committee's primary role is to establish and oversee task forces composed of stakeholders to study the issue and recommend a resolution to the Executive Committee.

The Executive Committee is chaired by the Mn/DOT Construction & Materials Engineer and the vice chair is the appropriate Paving Association Executive Director. The Executive Committee has eight standing members plus four members that rotate between asphalt and concrete as required by the issue. A flowchart of the issue resolution process is provided on the following page.

SUMMARY

Minnesota's Quality Management Program is a process and a philosophy where continuous improvements are made through cooperative efforts between Agencies (Mn/DOT, Counties & Cities) and Industry. Improvements are implemented through new specifications that are developed, piloted, refined and approved prior to formal adoption into the program. Volumetric QC, QA and IAST along with Technical and Plant Certification are standard components of the program. Incentives/ Disincentives and the Issue Resolution Process are currently being piloted and refined. Data analysis capabilities are being developed and piloted through QM Automation. All of these components make up a synergistic core of the overall program.

The advent of SHRP research and the subsequent Superpave process offer additional areas where improvements can be made to supplement Minnesota's Quality Management Program. Currently, Mn/DOT is looking at several areas where better quality can be realized through additional testing procedures. The Iowa method for Vacuum Saturated Specific Gravity of Aggregates is being evaluated as a means to identify aggregate absorption and provide a timely means of determining VMA during production. The Modified Lottman test (ASTM D 4867), is being piloted to assess the stripping potential of asphalt mixtures. A mobile testing laboratory equipped with a Superpave Gyratory Compactor is being utilized to conduct field research and promote the Superpave process. Data gathered in all of these evaluations will be used to reassess mix design verification and QC/QA test procedures currently used.

A timeline of Hot Mix Asphalt events in Minnesota is provided at the end of the text of this paper.

ISSUE RESOLUTION PROCESS

Construction & Materials Policy Development Partnership

STAKEHOLDERS

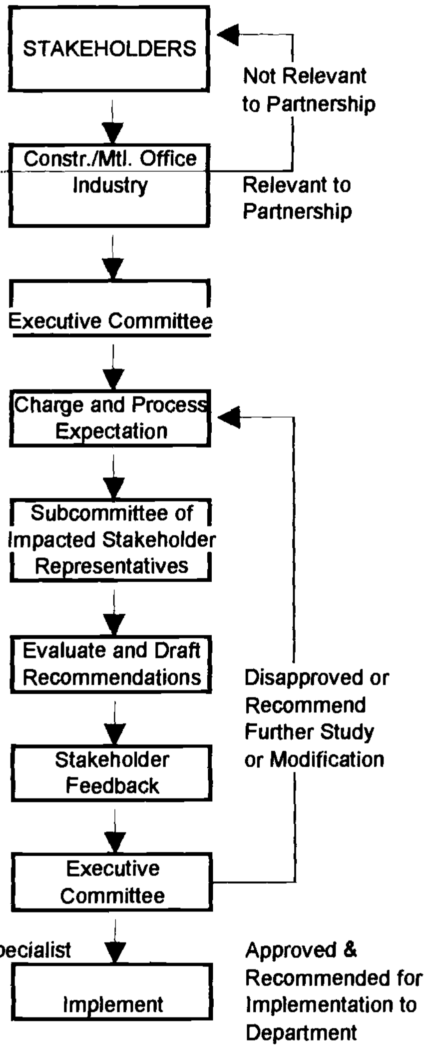
MN/DOT
- Operations Management
- Central Office (C.O.) Construction
- State Aid
- Materials
- Pavement Section
- Construction Section
- Assistant District Engineer
- District Materials Engineer
- Research

Partnership Committee Stakeholders

OTHER AGENCIES
- FHWA
- COUNTIES
- CITIES
- Mn. Pollution Control Agency
- Mn. Dept. of Natural Resources
- University of Minnesota
- etc.

INDUSTRIES
- Contracting Industry
- Association of General Contractors (AGC)
- Material Suppliers
  - Aggregate
  - Asphalt
  - Additives
- Cement
- Private Labs.

EXECUTIVE COMMITTEE
- Operations
- Construction & Materials Engineers
- C.O. Construction & Appropriate Materials Specialist
- Pavement Engineer
- District Materials Engineer
- State Aid
- AGC
- Contracting Industry (2)



HMA IN MINNESOTA

Timeline of Events

Minnesota's first hot mix recycle project 20 - 40 % RAP	⇒ 1976	• City of Maplewood
Minnesota's first rural hot mix recycle project 50 - 60 % RAP	⇒ 1977	• I-94 near Fergus Falls
Permissible RAP Specification Adopted	⇒ 1979	• Most Agencies accept RAP
Minnesota's Quality Management Program initiated through QM task force QM Asphalt Training Program begins	⇒ 1986	• Formation of Quality Management Task Force
Quality Assurance specification piloted on Mn/ DOT projects	⇒ 1987	• Voids primary control • Introduced one pay item for HMA • Density (91% MTD)
Refinement and expanded use of Quality Assurance specification	⇒ 1988 1991	• Many specification changes • Low Volume specifications
Technical Certification Program initiated	⇒ 1989	• Agency / Industry partnership
Quality Assurance specification accepted as standard Promoted to all levels of Government	⇒ 1990	• One pay item for HMA
Certified Plant concept introduced and piloted on Mn/DOT projects	⇒ 1992	• Discretionary use
Quality Management Data Base established for data analysis. Certified Plant adopted by all levels of Government in Metro area	⇒ 1993	• Validity of QA spec. confirmed • Certified Plant mandatory in Metro area
Incentive / Disincentive specifications introduced and piloted on Mn/ DOT projects	⇒ 1994	• Ride, Uniformity and Density
Policy Development Partnership Process formally adopted between Mn/ DOT and Industry	⇒ 1994	• Issue Resolution Adopted
Superpave implementation plan in development	⇒ 1995	• Draft presented to NCUPG

ACKNOWLEDGMENTS

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John B. Metcalf[1] and Thomas G. Ray[2]

EVALUATION AND MODIFICATION OF A STATISTICAL SPECIFICATION FOR HOT MIX

REFERENCE: Metcalf, J. B. and Ray, T. G., **"Evaluation and Modification of a Statistical Specification for Hot Mix,"** Quality Management of Hot Mix Asphalt, ASTM STP 1299, Dale S. Decker, Ed., American Society for Testing and Materials, 1996.

ABSTRACT: Louisiana's current statistically based specification system was initiated in 1967. This system was based upon contractor quality control and department acceptance testing using known variability concepts. A materials data base was also initiated at that time to archive materials test results and information. Since inception of the data base and system, major changes have been incorporated into the standard specifications. Further, there have been advances in equipment and operational control devices that can further reduce construction and test variation.

With these changes in mind and the presence of an excellent data base for analysis, this study was directed at updating the system to reflect current operations and to exert pressure for quality improvements where this was practicable. The study began with a statistical analysis of the data, collected for various plants and mix types and proceeded to establish a framework for revision of the specification and quality control system. Its conclusion will be with recommendations for changes that would facilitate the improvement of overall quality of the hot-mix asphaltic concrete.

It is believed that the procedures used, experience gained and knowledge developed by involved personnel will assist those with similar problems in reaching results which improve operations and quality of the final product in a timely manner.

KEYWORDS: hot-mix, quality control, quality systems

A system for quality control of hot-mix for the Louisiana Department of Transportation and Development(LaDOTD) was implemented in 1967. The system was structured to penalize the contractor should any of the characteristics chosen for control

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of quality fall outside what were defined as acceptable limits for the specific items. The specification was revised in detail several times, with major revisions in 1977, 1982, 1987, and 1992, but the broad approach of using reduced payment schemes where the quality fell below specified levels was retained. In 1971, a data base of material test results (MATT) was implemented to collect and preserve information on materials purchased by LaDOTD. Over the years the data base system also was changed, yet it continues to provide an extensive source of test results on construction materials. Data from the MATT system on hot mix asphalt quality was reported by Shah [1].

THE EXISTING SYSTEM

Specifications

Louisiana's standard specifications [2] describe the departmental requirements for asphaltic concretes. Marshall stability, compacted density, surface tolerance and gradation, with limits on the #4, #40 and #200 sieves, are incorporated in the reduced payment scheme. The Standards also require the prescence of an anti-stripping additive, but this, the surface tolerance and gradation requirements are not addressed in this paper.

In this initial study the critical parameters of density and stability were selected for analyses. Later work will consider the other factors in more detail.

The specification requirements, given in the 1982 Standard Specification are as follows;

Clause 501.12 LaDOTD Specification 1982

Asphaltic concrete ....shall meet all the requirements of Table 1....Sampling and testing for the purpose of determining acceptability shall be conducted on each lot(1000 t)...for...

a) Marshall stability
b) Aggregate gradation
c) Pavement density
d) Surface tolerance

The Marshall stability requirement for type 1 mix was that the mean of four tests from a lot exceed 5,338 N (1200 lbs), and no individual results should be below 4,448 N(1000 lbs), for 100% payment. There was then a declining scale of payment until the rejection limit that, should the mean of four fall below 4,448 N (1000 lbs), the engineer was empowered to remove the materials or to pay only 50% of the bid price. An interpretation of the clause as an operating characteristic (OC) curve is given in Figure 1.

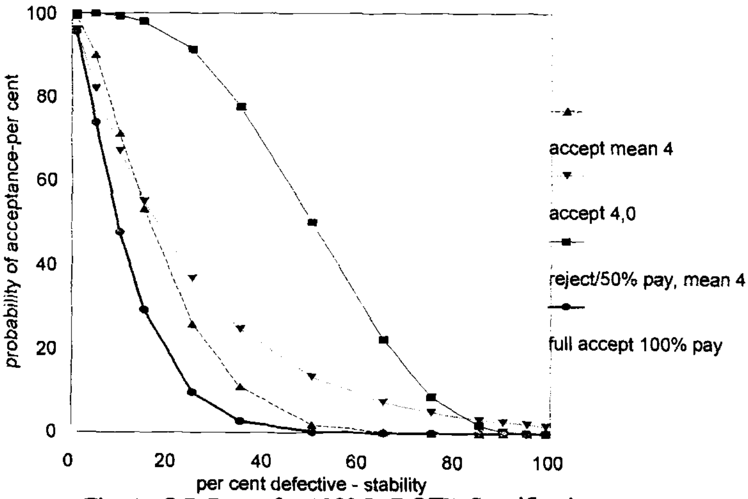

Fig. 1--OC Curve for 1982 LaDOTD Specification Requirements for Hot-Mix Asphaltic Concrete Marshall Stability

The density requirement was that *the mean of five samples be greater than the specified minimum, which could be 94 or 95 per cent of the laboratory compacted Marshall density*. An OC curve for this requirement is given as Figure 2.

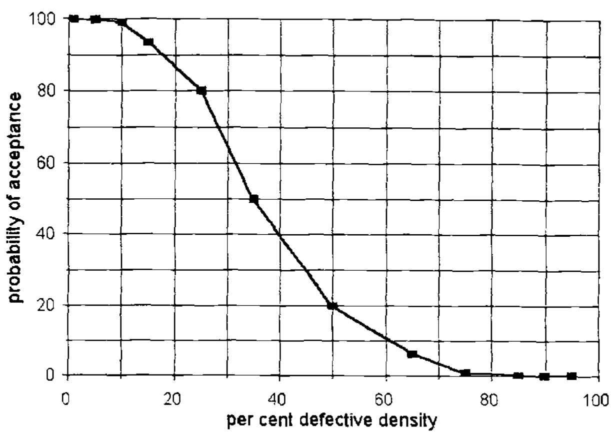

Fig.2--Operating Characteristics Curve for 1982 LaDOTD Specification Requirements for Hot-Mix Asphaltic Concrete - Compacted Density

The Existing Data Base

The MATT system data base has been in existence for almost 25 years, but for this study data from 1987 to date has been analyzed in order to have as homogeneous a population as possible for the study and to relate it to particular revision of the Standard. Some 27,000 sample results were extracted, representing the 55 plants across the nine administrative districts of the State. For the Type 1 mix discussed here, analysis is based on about 6,000 tests.

The data base contains four categories of data; project location and specifics, aggregate and other material source details, mix data - results of stability, gradation density, asphalt, additive and surface tolerance tests and, date, approval and use information. In the initial definition there were 93 fields which have since been extended to 129.

The data from 1987 were extracted to a data base file on a PC and then sorted and written to spreadsheets for interpretation.

As a first step in the project, the data for Type 1 mixes were extracted and analyzed. Data have been processed for stability, density, gradation, anti-strip, surface tolerance and asphalt content. However, only the stability and density analyses are complete and reported in this paper.

THE PROCEDURE FOR EVALUATION

Analysis of variance of the existing data

The first step in the evaluation involved the analysis of the existing data. The data base was first sorted by mix type and production facility. This information was then arranged by geographic distribution (road administration districts) of the production facilities. Once this was accomplished, the means and variances of the five quality characteristics were calculated on the basis of mix type produced at a given plant. This information becomes the basic building block in the analysis but, at this stage assumes that the output of a plant may be treated as a unique population. This may not be so and later studies will examine in detail the output of individual plants..

First, the statistics for the production of a given mix type in a given area were analyzed to determine any significant differences within the area. This was done by comparing the within plant variation to the between plant variation. If there was a significant difference in the output of a given plant, it was separated from the group. Once extreme performers were removed, or if there were no extreme performers, the group statistics were pooled. The pooling of the several groups gives another set of groupings for analysis to determine if there are significant differences between geographic groupings (districts) of production facilities.

In a similar manner to the procedure followed for the combination of the plants in the areas, the statistics of the areas can be combined to represent the overall geographic area (state).

Once the overall statistics for each quality characteristic had been determined, an analysis was performed, checking the overall statistical results of the quality system. This is being done by mix type, determining the overall probability of rejection of the composite product through the probability of rejection on each of its components.

The overall probability of rejection can then be compared with the actual percentage of jobs rejected i.e. jobs for which there were reductions in pay due to quality problems. Significant differences between expected and actual rates of 'rejection' would indicate that either;

a) there are deficiencies in application of the procedures,

b) the data were unreliable, or

c) the operating characteristics have been interpreted in a manner different from that intended or applied in practice.

Initial Results

Early analyses of results from the data base have suggested that there are significant opportunities for improvement of quality. This is stated as a result of preliminary analysis which indicates that certain quality characteristics appear to be homogenous in the population.

The distribution of the number of tests by number of plants, Figure 3, indicates the relative levels of output, and emphasizes the need for any quality control or acceptance procedure to be designed to operate with small sample sizes.

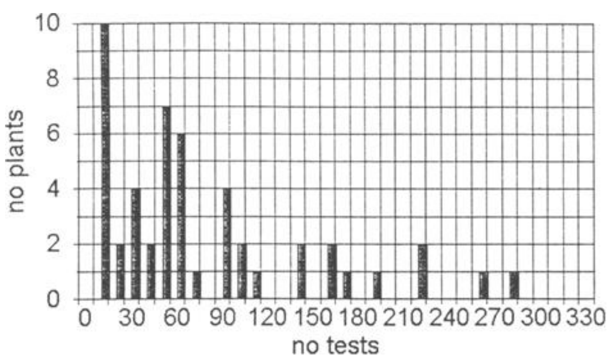

Fig.3--Number of Tests Reported by All Plants, 1987-94

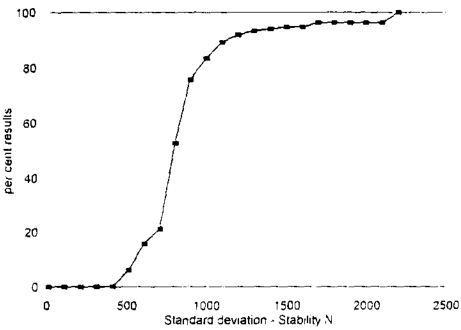

Fig.4--Distribution of Standard Deviation of Marshall Stability, Type 1 Mix 1987-94

The data for Marshall stability were analyzed to derive the distribution of mean, standard deviation and proportion defective for the plants in the system, with the data weighted by the number of tests recorded for each plant. Figure 4 shows the distribution of standard deviation and that a figure of 900 N is not unreasonable to apply to the calculation of the operating characteristic for stability; the weighted mean standard deviation was 850 N, compared to an average of 1300 N in 1975-77 (1). The distribution of proportion defective, calculated for each plant separately but weighted by number of test results, revealed that 93 per cent of the results were less than 0.5 per cent defective. The weighted mean stability was 7,740 N, which gave a mean proportion defective of 0.01 per cent to the specified minimum of 4,448 N (1000 lbs).

Figures 5 and 6 give the results for compacted density.

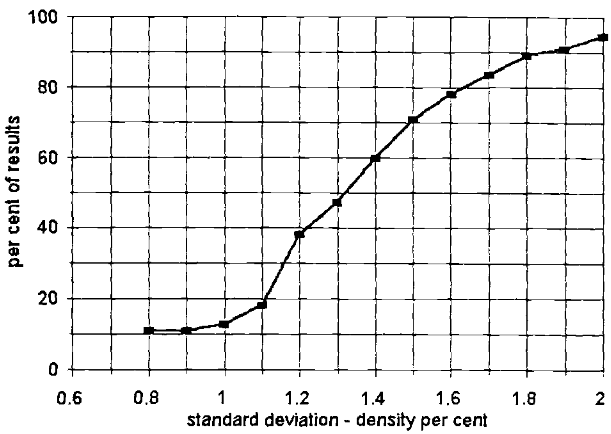

Fig.5--distribution of Standard Deviation of Compacted Density, Type 1 Mix 1987-94

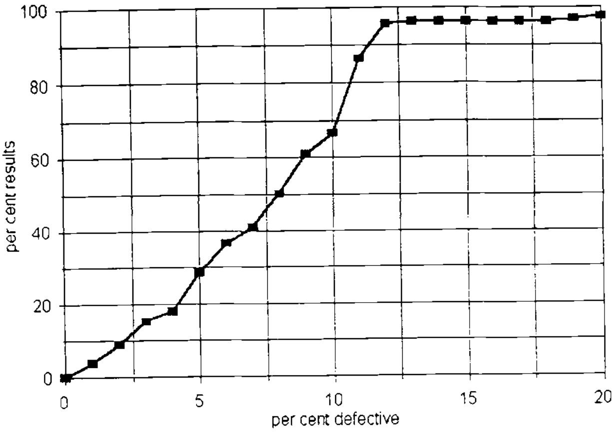

Fig.6--distribution of Proportion Defective of Compacted Density, Type 1 Mix 1987-94

The data for asphalt content have not yet been fully analyzed, but the distribution of standard deviations is available, Figure 7, and reveals that the distribution is no different from that reported in 1976 on Australian data with a mean standard deviation of 0.25 percent [3]. Shah [1] reported an average standard deviation for asphalt content of Louisiana plants of 0.39 percent in 1975-77, indicating that plant process control has improved over the last ten years.

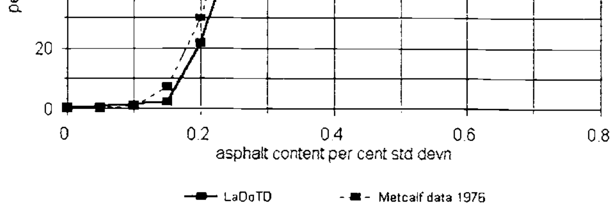

Fig.7--Distribution of Standard Deviation of Asphalt Content, Type 1 Mix 1987-94

The results suggest that the product characteristics are relatively stable but improving.

The data also suggest that the specification operating characteristics for stability, figure 1, are such that they would call into operation the financial penalties for 'poor' quality for less than 2 percent of the output. Material effectively would be rejected or paid for at half price very infrequently. Similarly, Figure 6 shows the average proportion defective density to be 8 percent; the operating characteristic curve for density, Figure 2, effectively would always accept this quality.

Steps Toward Improvement of Quality

Given that the quality levels reported are from acceptable asphaltic concrete now in service, consideration must be directed toward the long term objectives of the quality program. A program can be meeting minimum requirements and accomplishing very little toward the improvement of quality. If the concern of management is quality improvement, steps must be taken to continuously update quality requirements and validate the effects on system output.

From the data analysis conducted it is intuitive that there are differences in the quality characteristic statistics of the output of the various plants. The fact that at a given level of significance, the hypothesis that the variances within plant and between plants are not significantly different is proven, does not change the reality that some of the plants within an area produce an output that has a higher mean value and smaller variance for a given quality characteristic than the other plants within the same area. If this condition, lower variability, is consistent with "better quality", then potential for greatly improved performance exists, as does the potential economy if mean values can be moved closer to design requirements.

The difficulty in implementing a system to effect change in a case where the entities involved are not unified under the leadership of a single organization, lies in the fact that there are many inconsistent, conflicting and, sometimes, adversarial objectives. This problem will be recognized and then passed over in the effort to develop a system for improvement of the overall quality.

Further, this work assumes that the best quality will not be that which meets minimum or maximum requirement limits but that which falls midway between the limits of the control variables specified and has minimum variance.

Conclusions

The results to date show reasonable levels of variability in the stability, density and asphalt content quality parameters, and could indicate that the asphalt industry operates a stable process producing acceptable quality levels in accordance with the current specifications. The variability of asphalt content and stability has decreased over the past ten years, presumably as a result of plant improvements. However, the distribution of standard deviation of asphalt content reveals a considerable spread of performance between the various plants, and the variability of stability and density shows the effects of both plant and lay down processes. Both will now be examined in more detail to determine where improvements in processes and the products may be possible.

The analysis to date suggests that the 1982 specification exerted little pressure to reduce variability and that the producers elected to minimize the risk of reduced payment by using a high mean stability. There is potential for changes in the specifications to exert pressure on industry to reduce variability and perhaps also to reduce the high mean stability values, if this would reduce costs. A more detailed plant by plant analysis will now be carried out to determine actual 'rejection' rates and to estimate the impact of any proposed changes in specifications and practice

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Prithvi S. Kandhal[1], Kee Y. Foo[2], and John A. D'Angelo[3]

FIELD MANAGEMENT OF HOT MIX ASPHALT VOLUMETRIC PROPERTIES

REFERENCE: Kandhal, P. S., Foo, K. Y., and D'Angelo, J. A.;**"Field Management of Hot Mix Asphalt Volumetric Properties,"** Quality Management of Hot Mix Asphalt, ASTM STP 1299, Dale S. Decker, Ed., American Society for Testing and Materials, 1996.

ABSTRACT: The Federal Highway Administration (FHWA) Demonstration Project No. 74 has clearly shown that significant differences exist between the volumetric properties of the laboratory designed and plant produced hot mix asphalt (HMA) mixes. The volumetric properties include voids in the mineral aggregate (VMA) and the voids in the total mix (VTM). This project was undertaken to develop practical guidelines for the HMA contractors to reconcile these differences thereby assisting them to consistently produce high quality HMA mixes. The HMA mix design and field test data from 24 FHWA demonstration projects were entered into a database. The data included mix composition (asphalt content and gradation) and volumetric properties. The data were analyzed to identify and, if possible, quantify the independent variables (such as asphalt content and the percentages of material passing No. 200 and other sieves) significantly affecting the dependent variables (such as VMA and VTM).

Based on the preceding work, troubleshooting charts have been constructed to correct and reconcile differences between the volumetric properties of the job mix formula and the produced mix.

KEYWORDS: hot mix asphalt, asphalt concrete, asphalt paving mixtures, field management, volumetric properties, quality control, quality assurance, air voids, VMA

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INTRODUCTION

Demonstration Project No. 74, "Field Management of Asphalt Mixes" initiated by Federal Highway Administration studied 17 mixes from 15 State Highway Agency (SHA) paving projects [1]. Of the 17 mixes, there were only two mixes where the actual production met the mix design targets. Ten mixes should have been modified during production while five mixes should have been totally redesigned. The Demonstration Project confirmed that current laboratory mix design procedures do not represent actual mix production. Flawless laboratory-designed mixes can incur mix-related problems during production which can lead to premature pavement deterioration. Field management of hot mix asphalt (HMA) provides a viable tool to identify the differences between plant produced and laboratory designed HMA mixes and effectively reconcile these differences [2].

Demonstration Project No. 74 concluded that a field mix verification of the material produced at the HMA plant should be included as a second phase in the design process. Mix verification is defined as the validation of a mix design within the first several hundred tons of production . The void properties established from mix verification proved to be an effective tool in identifying mix production variations or any differences between plant produced and laboratory designed HMA mixes. However, the measures recommended in the project to correct the identified problems were somewhat generalized. It was recommended that the job mix formula (JMF) should be adjusted to make the gradation more uniform and/or move the gradation away from the maximum density line. It was also noted that (1) gap-graded mixes and mixes which plot close to the maximum density line are generally sensitive mixes, and (2) mixes with a hump near the No. 30 sieve are generally tender mixes.

A significant amount of data has been collected by Demonstration Project No. 74. Analysis of these data could yield more practical guidelines to reconcile differences between plant produced and laboratory designed HMA mixes.

OBJECTIVE

The objective of this project was to develop practical guidelines to reconcile differences between plant produced and laboratory designed HMA mixes. This has been achieved by analyzing the data collected by the Demonstration Project No 74, and identifying and quantifying independent variables which significantly affect the void properties (dependent variables) of the produced mix.

The above objective has been accomplished by completing the following tasks:

Task 1 - Preparation of data base

Task 2 - Analysis of data

Task 3 - Method for reconciling differences between mix design and production

Task 4 - Field verification of proposed method of reconciliation.

TASK 1: PREPARATION OF DATA BASE

Twenty four Demonstration Project No. 74 reports were obtained from the Federal Highway Administration (FHWA). A total of 26 asphalt mixes were used in these 24 demonstration projects. These vast amounts of data contained in these reports were grouped into three major groups and entered into a data base.

The first data group contains information about the HMA plant such as plant type, production rate, dust collection system, and type of mix storage system. Of the 24 demonstration projects, 19 projects used drum mix plants and five projects used batch mix plants. Baghouse dust collection system was used in 17 projects, wet scrubber was used in five projects, and cyclone dust collection system was used in two projects.

The second data group contains information about the 26 HMA mixtures used on the 24 demonstration projects such as mix type, maximum nominal aggregate size, amount of natural sand, coarse aggregate type, fine aggregate type, Los Angeles abrasion loss, sand equivalent value, percent hydrated lime, and percent reclaimed asphalt pavement (RAP) used. Thirteen mixes were used in surface course, six in binder course, and two in base course. The use of five mixes is not known. Four mixes had 9.5 mm (3/8 inch) maximum nominal size. Eleven mixes had 12.5 mm (½ inch) maximum nominal size. Nine mixes had 19 mm (3/4 inch) maximum nominal size. Two mixes had 25.4 mm (1 inch) maximum nominal size. Seven mixes contained natural sand. Seven mixes contained hydrated lime, and four mixes contained RAP.

The third data group contains information about the asphalt content, void properties, and aggregate gradation specified by (a) mix design, (b) obtained from the verification process, and (c) obtained during production. Basically, production data has been analyzed rigorously to identify and quantify independent variables which significantly affect the void properties of the produced mix. The following information, if available, is contained in the third data group: (a) asphalt content and void properties of JMF, verification, and production, (b) aggregate gradation of JMF, verification, and production, and (c) the location of aggregate gradation curve at the time of production with respect to the maximum density line (MDL). The MDL was established according to Superpave Level 1 mix design procedures. The location of aggregate gradation during production can be summarized as follows: 15 mixes were "above" MDL, two mixes were "slightly above" MDL, five mixes were "on" MDL, three mixes were "slightly below" MDL, and one mix was "below" MDL. It was observed that design gradations and production gradations were generally different. Production gradations more accurately represent the aggregate gradation for the project. Therefore, the maximum nominal size and maximum size of the aggregate for the project have been based on the production gradation rather than the JMF gradation for entry into the database.

It was believed at the beginning of the project that void properties may be affected differently in surface and base/binder mixes during production because of differences in the maximum aggregate sizes, gradations, and asphalt contents. To investigate and detect such effects, the date base was split into "surface" and "base/binder" mixes. "Surface" mix is the mix with maximum nominal aggregate size equal to or less than 12.5 mm (½ inch) and "Base/Binder" mix is the mix with maximum nominal aggregate size more than 12.5 mm (½ inch). The relationship between the independent variables and voids in mineral aggregate (VMA) and voids in total mix

(VTM) was analyzed for each mix type. No significant differences in relationship were found between these two mix types. Therefore, the data base was combined for subsequent analyses.

TASK 2: ANALYSIS OF DATA

The focus of this project are VMA and VTM of the HMA mix produced in the asphalt plant. It is therefore necessary to identify those factors that (1) can be controlled easily at the HMA plant and (2) have a significant effect on VMA and VTM of the produced mix. Therefore, VMA and VTM were chosen as dependent variables. The independent variables are those factors that can generally be controlled at the HMA plant. Independent variables were asphalt content and percentages passing the #200, #100, #50, #30, #16, #8, #4, 9.5 mm, 12.5 mm, 19 mm, 25 mm, and 37.5 mm sieves.

The objective of this task is to identify which independent variables are the best predictor of the void properties such as VMA and VTM. The identified best predictors can then be used to reconcile differences between mix design and production in the next task. Two techniques were used to identify the best predictive variables: linear regression and stepwise multi-variable regression. Single and multi variables predictive models were then constructed with the best predictive variables.

Linear Regression -- The coefficient of correlation (R value) generated by the linear regression gives a measure of how well the independent variable is correlated to the dependent variable. In the linear regression analysis, all independent variables were individually correlated to the dependent variable for each project. The R values of the independent variables for each project are given elsewhere [3]. A broad range of R values from 0.00 to 0.96 were generated. These R values can be used directly to rank the independent variables in each project but it is more desirable to rank the independent variable based on all projects. Therefore, the R values for each independent variable based on the averaged R values is given in Table 1. The averaged R value does not have any specific statistical meaning. It is used only as a tool to rank the independent variables for all projects. The following observations are made based on Table 1:

1. With respect to VMA, the top five independent variables are the percentages of aggregate passing #8, #16, #30 and #50 sieves, and asphalt content. This indicates that the relative proportions of coarse and fine aggregates are very important and can be used to adjust the VMA.
2. With respect to VTM, the top ranking variable is the asphalt content, followed by the percentages of aggregate passing #30, #50, #100 and #200 sieves. This indicates that the VTM is also a function of VMA which is controlled by the relative proportions of coarse and fine aggregate as mentioned above.

The combined rankings from all projects were not completely adequate in identifying important variables affecting VMA but were somewhat able to identify the important variables affecting VTM during production. The preceding analysis was impeded by including high quality control projects which had low variation in VMA and

TABLE 1 -- Averaged R values and combined rankings of independent variables.

Variable	All Projects				High Variability Projects			
	VMA		VTM		VMA		VTM	
	R (Average)	Ranking	R (Average)	Ranking	R (Average)	Ranking	R (Average)	Ranking
Asphalt Content	0.333	4	0.401	1	0.263	8	0.479	1
#200	0.301	9	0.300	4	0.407	4	0.361	3
#100	0.294	10	0.301	3	0.406	5	0.354	5
#50	0.331	5	0.283	5	0.472	2	0.356	4
#30	0.372	1	0.302	2	0.483	1	0.384	2
#16	0.347	2	0.268	6	0.449	3	0.328	6
#8	0.345	3	0.247	7	0.381	6	0.298	7
#4	0.316	6	0.199	10	0.300	7	0.229	9
9.5 mm	0.314	7	0.214	8	0.261	9	0.238	8
12.5 mm	0.304	8	0.214	9	0.252	10	0.192	10

VTM resulting in clustered data points. The FHWA examined the test data from 17 paving projects in a previous study and found that the pooled mean VMA standard deviation was 0.47 and the mean VTM standard deviation was 0.66 [1]. Therefore, projects with VMA standard deviation less than 0.47 and VTM standard deviation less than 0.66 were then excluded to increase the sensitivity of the preceding analysis. Twelve projects were excluded from the VMA analysis and ten projects were excluded from the VTM analysis. Table l also tabulates the averaged R value and combined rankings for the selected high variability projects. The following observations are made.

1. With respect to VMA, the top six ranking variables consist of mix gradation passing #8, #16, #30, #50, #100, and #200 sieves. This means that the relative proportion of the fine aggregate in the mix and the amount of material passing #200 (P200) sieve are very important in affecting the VMA. However, the percentage of material passing #30 and #50 sieves have the highest rankings. These percentages are generally influenced by the presence and amount of natural sand in the mix.

2. With respect to VTM, the top ranking variable is the asphalt content followed by the aggregate gradation passing #16 and finer sieves. Again, it indicates the dependence of VTM on VMA which was also affected by these sizes. The P200 material ranked third and, therefore, is considered important.

Stepwise Multi-Variable Regression -- A Forward Selection Procedure is available in the SAS program [4] to determine which independent variables are closely related to VMA and VTM. The selection procedure begins by finding the variable that produces the optimum (highest R^2) one-variable model. In the second step, the procedure finds the variable that, when added to the already chosen variable, results in the largest reduction in the residual sum of squares (highest R^2 value). The third step finds the variable that, when added to the model provides a reduction in sum of squares considered statistically significant at a specified level. The output of the Forward Selection Procedure for each project including partial R^2 values for each independent variable is given elsewhere [3]. The R^2 value for each project as generated by the Forward Selection Procedure ranged from 0.24 to 0.99.

There are two possible methods to rank the independent variables in each project from the Forward Selection Procedure output. The first ranking method (Method 1) is according to the order they were selected by the Forward Selection Procedure. The second method (Method 2) is to rank the independent variables according to their partial R^2 values. As mentioned in Linear Regression, it is desirable to rank the independent variables based on all projects rather than each individual project. To obtain a combined ranking for all projects using Method 1, the first variable selected is assigned 1 point, the second variable selected is assigned 2 points and so on. A combined ranking is then possible by averaging the assigned points for all projects. For the second ranking method (Method 2), the partial R^2 values of each independent variable were averaged over all projects. A combined ranking is then possible based on the averaged partial R^2 value. The averaged partial R^2 values do not have any specific statistical meaning except to be used as a tool to rank the independent variables.

Table 2 summarizes the combined rankings for selected projects with relatively - lower quality control (standard deviation more than 0.47 for VMA and more than 0.66

TABLE 2 -- Combined rankings of independent variables using forward selection procedures methods 1 and 2 (high variability projects).

Variable	Method 1				Method 2			
	VMA		VTM		VMA		VTM	
	Avg. Point	Ranking	Avg. Point	Ranking	Avg. ΔR^2	Ranking	Avg. ΔR^2	Ranking
Asphalt Content	6.07	8	2.00	1	0.032	8	0.219	1
#200	4.86	2	5.23	3	0.068	6	0.110	2
#100	3.92	1	5.07	2	0.149	1	0.097	3
#50	5.08	3	5.27	4	0.103	4	0.076	5
#30	5.93	7	5.87	6	0.084	5	0.028	8
#16	5.54	5	5.57	5	0.136	3	0.060	6
#8	5.62	6	6.85	10	0.143	2	0.035	7
#4	5.39	4	6.06	8	0.031	9	0.020	9
9.5 mm	7.36	10	6.00	7	0.028	10	0.080	4
12.5 mm	6.25	9	6.14	9	0.038	7	0.018	10

for VTM) using Methods 1 and 2. The combined ranking obtained by both methods are similar to those obtained by correlation analysis (Table 1). However, the combined ranking by Method 2 shows better resemblance with the combined ranking by correlation analysis than Method 1. Intuitively, Method 2 being rational seems to be a better approach for quantitative analysis than Method 1 and thus obtaining a combined ranking of the independent variables.

Best Predictive Variables -- The best predictive variables selected by linear regression analysis (R value), and Forward Selection Procedure Method 1 (Point Value), and Forward Selection Procedure Method 2 (ΔR^2 value) are shown in Table 3. The statistical analyses include the projects with high standard deviations for VMA and VTM, as mentioned earlier. Both techniques, linear regression analysis and Forward Selection Procedure, used to select the best predictive variables have their own inadequacy. The linear regression evaluates a single variable, while Forward Selection Procedure can evaluate several variables. However, each analysis does provide a useful suggestion as to which variable has the best predictive power. The following observations are made based on the combined ranking data (given in Table 3) from these ranking analyses.

1. The best practical predictive independent variables for VMA are the #8, #16, #30, #50, #100, and #200 sieves. In other words, the relative proportion of the fine aggregate and the amount of material passing #200 sieve is important.
2. The best practical predictive variables for VTM are asphalt content (AC) and #200 sieve, followed by #8, #16, #30, #50, and #100 sieves.

There seems to be reasonable rationale to support the result of the analysis. It is generally accepted that VTM is most significantly affected by AC. VTM and VMA are also significantly affected by the percentage of material passing the #200 (P200) sieve which fills the spaces between aggregate particles. In addition, it is generally believed that the amount of fine aggregate (percent passing #8) has an effect on VMA and VTM. Generally, an increase in percent passing the #8 sieve (fine aggregate) also increases the percent passing the smaller sieve sizes (#16, #30, #50, #100, #200). The higher rankings received by the #30 and #50 sieves seem to reflect the effect of natural sand in HMA mixes.

TASK 3: METHOD FOR RECONCILING DIFFERENCES BETWEEN MIX DESIGN AND PRODUCTION

The objective of this project was to develop guidelines to reconcile differences between mix design and production. The guidelines must be practical and applicable within the confine of practical asphalt plant operation. It was determined in Task 2 that the best predictive variables for VMA are the #200, #100, #50, #30, #16, and #8 sieve and the best predictive variables for VTM are asphalt content, #200, #100, #50, #30,#16, and #8, sieve. Asphalt content and, in some cases, #200 sieve can be independently controlled and adjusted to reconcile differences between produced and

TABLE 3 -- Results of ranking analysis by three methods.

	Combined Ranking Using		
Combined Ranking	R value (Average)	Point Value (Average)	ΔR^2 (Average)
VMA			
1	#30	#100	#100
2	#50	#200	#8
3	#16	#50	#16
4	#200	#4	#50
5	#100	#16	#30
6	#8	#8	#200
VTM			
1	AC	AC	AC
2	#30	#100	#200
3	#200	#200	#100
4	#50	#50	3/8
5	#100	#16	#50
6	#16	#30	#16
7	#8	3/8	#8

TABLE 4 -- Changes in VMA caused by changes in P200 sieve.

Analysis	Projects Analyzed	β_1	R^2
1	Projects with $\sigma_{VMA}>0.47$	-0.3103	0.1242
2	Projects with $\sigma_{VMA}>0.47$ and VMA>16%	-0.3723	0.1385
3	Projects with $\sigma_{VMA}>0.47$ and 14%<VMA>16%	-0.3339	0.1267
4	Projects with $\sigma_{VMA}>0.47$ and VMA<14%	-0.2543	0.1177

laboratory designed HMA mixes. However, the other sieve sizes (#100, #50, #30, #16, #8) cannot be controlled independently because they are related to the proportion of coarse or fine aggregate. Increasing the fine aggregate portion will increase the amount of material passing all the sieve sizes (#200, #100, #50, #30, #16, #8), and the magnitude of increase will depend largely on the gradation of the fine aggregate. Since the finer sieve sizes are inter-related, it is recommended that the finer sieve sizes should be combined as one predictive variable (that is the amount of fine aggregate) rather than six (6) individual predictive variables.

For practical reasons, attempts to reconcile differences between mix design's VMA and productions's VMA should be achieved by first adjusting the amount of P200 material and then, if necessary, by adjusting the other sieve sizes by changing the amount of fine aggregate. Attempts to reconcile differences between mix design's VTM and production's VTM should be achieved by first adjusting the amount of P200 material if it deviates significantly from the JMF. The P200 material can be adjusted by controlling the amount of dust returned from dust collection system. The second step, if necessary, is to adjust the asphalt content. Finally, it may be necessary, to adjust the amount of material passing other sieve sizes (the amount of fine aggregate) which practically amounts to redesigning the mix.

The following are regression models which relate VMA and VTM to the best predictive variables. These models estimate the magnitude of adjustment needed to reconcile the differences between mix design and production.

VMA Regression Models -- The regression model recommended to predict the effect of the material passing #200 sieve (P200) on VMA is given as :

$$\Delta VMA = \beta_1 \times \Delta P200 \qquad (1)$$

where ΔVMA = difference from project VMA
ΔP200 = difference from project P200

Regression analysis was performed on projects with high VMA variation (δ more than 0.47) to increase the sensitivity of the regression model. These projects were then divided into three groups based on their VMA levels (> 16%, 14-16%, and < 14%) and analyzed separately. The results of the analyses are shown in Table 4.

Table 4 shows that VMA is expected to decrease when the P200 material is increased (based on the negative value of β_1). The VMA of the mixes in high VMA range is expected to decrease more than mixes in the low VMA range. Overall, for every percent increase in P200 material, VMA is expected to decrease by an average of about 0.3 percent.

The fine sieve sizes (#200, #100, #50, #30, #16, #8) were combined to produce another predictive variable, Area Enclosed. Area Enclosed is defined as the area enclosed by the aggregate gradation and the MDL from #8 sieve down to #200 sieve. An example of how the variable Area Enclosed is calculated and the associated regression model are given elsewhere [3]. The relationship between VMA and Area

Enclosed was found to be very dependent on the presence or absence of natural sand in the HMA mixes. A decrease in the Area Enclosed increased the VMA of mixes with natural sand. Since the aggregate gradation of mixes with natural sand are generally above the MDL (at #16, #30, and #50 sieves), reducing the amount of natural sand in these mixes decreases the Area Enclosed and thus increases the VMA. This is logical because generally sand particles are round, pack densely and, therefore, decrease the VMA.

An increase in the Area Enclosed increased the VMA of mixes with no natural sand. If the gradation is above the MDL, increasing the amount of fine aggregate increases the Area Enclosed. For gradation below the MDL, decreasing the amount of fine aggregate also increases the Area Enclosed. In both cases, when the aggregate gradation deviates from the MDL, it increases the Area Enclosed and, therefore, the VMA.

The average slope β_1 of Equation 1 (Table 4) is relatively flat, about 0.3. As mentioned earlier, adjusting the P200 material by one percent caused an average of 0.3 percent change in VMA. Therefore, the P200 adjustment can be used if the VMA correction to be made is minor. HMA mixes that need a significant amount of VMA correction have to be adjusted by varying the coarse-fine aggregate proportions (Area Enclosed). Consequently, it is recommended that adjusting the P200 is more appropriate for fine tuning the VMA while changing the aggregate gradation by adjusting the coarse-fine aggregate proportion (Area Enclosed) is more suitable for larger changes in VMA. Since the required adjustments are mix specific no quantifiable change in coarse-fine aggregate proportion can be recommended other than directional changes (increase or decrease coarse-fine aggregate proportion).

<u>VTM Regression Models</u> -- There is a strong relationship between VTM and VMA. All VTM regression models, therefore, will have VMA terms as predictive variables. Also, all predictive variables for VMA are also applicable to VTM. The best regression model which relates VTM to P200 is given as:

$$VTM = -8.3932 + 0.8793(VMA) + 0.9632(P200) - 0.07579(VMA)(P200) \quad (2)$$

$$R^2 = 0.42$$

Differentiating Equation 2 with respect to P200 results in:

$$\frac{\Delta VTM}{\Delta P200} = 0.9632 - 0.07579(VMA) \quad (3)$$

Equation 3 shows that the effect of P200 on VTM is dependent on VMA. Table 5 which is based on Equation 3 shows VTM is expected to decrease when the P200 is increased (negative value of Equation 3). The VTM of mixes with high VMA is expected to decrease more than mixes with low VMA. Table 5 deceptively shows that the VTM increases with the increase in P200 for mixes with 12 percent VMA. This has been caused by insufficient data points in the low VMA region to generate a reliable model.

TABLE 5 -- Changes in VTM caused by changes in P200 at different VMA level.

VMA	12%	13%	14%	15%	16%	17%	18%
ΔVTM/ ΔP200	0.054	-0.022	-0.098	-0.174	-0.249	-0.325	-0.401

The best regression model to relate asphalt content (AC) to VTM is given as:

$$VTM = 8.7802 - 3.552(AC) + 0.1420(AC)(VMA) \qquad (4)$$

$$R^2 = 0.63$$

Differentiating Equation 4 with respect to asphalt content results in:

$$\frac{\Delta VTM}{\Delta AC} = -3.552 + 0.1420\ (VMA) \qquad (5)$$

Equation 5 shows that the effect of asphalt content on VTM is also dependent on VMA. Table 6 which is based on Equation 5 shows that an increase in asphalt content decreases the VTM (negative value of Equation 5). This decrease is more severe for mixes with lower VMA.

TABLE 6 -- Changes in VTM caused by changes in AC at different VMA level.

VMA	12%	13%	14%	15%	16%	17%	18%
ΔVTM/ ΔAC	-1.351	-1.209	-1.067	-0.925	-0.783	-0.641	-0.499

No statistically satisfying model to predict VTM using the variable Area Enclosed could be constructed. However, increasing the Area Enclosed (deviating from the maximum density line or MDL) will increase the VTM of mixes with no natural sand but decrease the VTM of mixes with natural sand. Natural sands usually make the HMA mixes over sanded (too much deviation from the MDL and therefore, increased Area Enclosed) and tend to have relatively low VMA because natural sand particles pack densely. This change in VTM, therefore, reflects the change in VMA.

The slope values in Table 5 are comparatively smaller than the slope values in Table 6. Adjusting the P200, especially if it is excessively higher than the JMF, is more appropriate for fine tuning the VTM. Adjusting the asphalt content is more suitable for larger changes in VTM. It is expected that Equation 3 (or Table 5) will be used first, if the P200 deviates from the JMF, in any attempts to reconcile differences in mix design's VTM and production's VTM. If the production P200 is reasonably close to the JMF P200, the asphalt content should be adjusted.

Steps Recommended to Reconcile Differences between Mix Design and Production -- The values tabulated in Tables 4, 5 and 6 are derived from different mixes and thus represent average values for these mixes. Since each mix is unique, the values presented here may not accurately predict its behavior.

Figure 1 is a flow chart which shows the recommended steps to reconcile differences between mix design's VMA and mix production's VMA, after it has been verified that the composition (asphalt content and gradation) of the produced mix is reasonably close to that of the designed mix (JMF).

If the composition of the produced mix meets the JMF and the VMA of the produced mix has a minor deviation (less than 0.3%) from the JMF, it has been suggested to adjust the amount of P200 material in the mix. A one percent decrease in the P200 material to cause an average increase of 0.3 percent in the VMA, can be used as an approximate guide to determine the quantitative adjustment required for the P200 material to effect the desired change in VMA value. As an alternate, an extended laboratory mix design can include using two additional P200 contents (JMF $\pm$ 2%) in the HMA mix and plotting the curve of P200 content versus VMA. The percent decrease in VMA from the corresponding increase in the P200 content (which is mix specific) can be obtained from this curve and is likely to be more accurate than the approximate guide mentioned above.

If the VMA of the produced mix has a major deviation (more than 0.3%) from the JMF, the flow chart recommends different approaches depending on whether the HMA mix contains natural sand or not. If the HMA mix contains natural sand, the amount of natural sand will need to be decreased to increase VMA. If the HMA mix does not contain natural sand, the percentage of material passing the #8 sieve (that is, the relative proportions of coarse and fine aggregates) will need to be adjusted to move away from the maximum density line (MDL). Since this adjustment is mix specific, no quantitative recommendations can be made. However, an extended laboratory mix design which includes two additional percentages of the material passing #8 sieve (JMF $\pm$ 5%) is likely to be very helpful. The design curve obtained by plotting these percentages of passing #8 sieve versus VMA can indicate the quantitative adjustment needed to the #8 sieve to obtain desired VMA.

If the production VMA is not reconciled after the preceding efforts, the entire mix will need to be redesigned by changing the mix components and/or their proportions.

After the production VMA is reconciled, the next step is to check the VTM. Figure 2 is a flow chart to reconcile differences between mix design's VTM and production's VTM. Again, it is assumed that the produced mix has composition (asphalt content and gradation) close to the JMF composition. If the VTM has a minor deviation

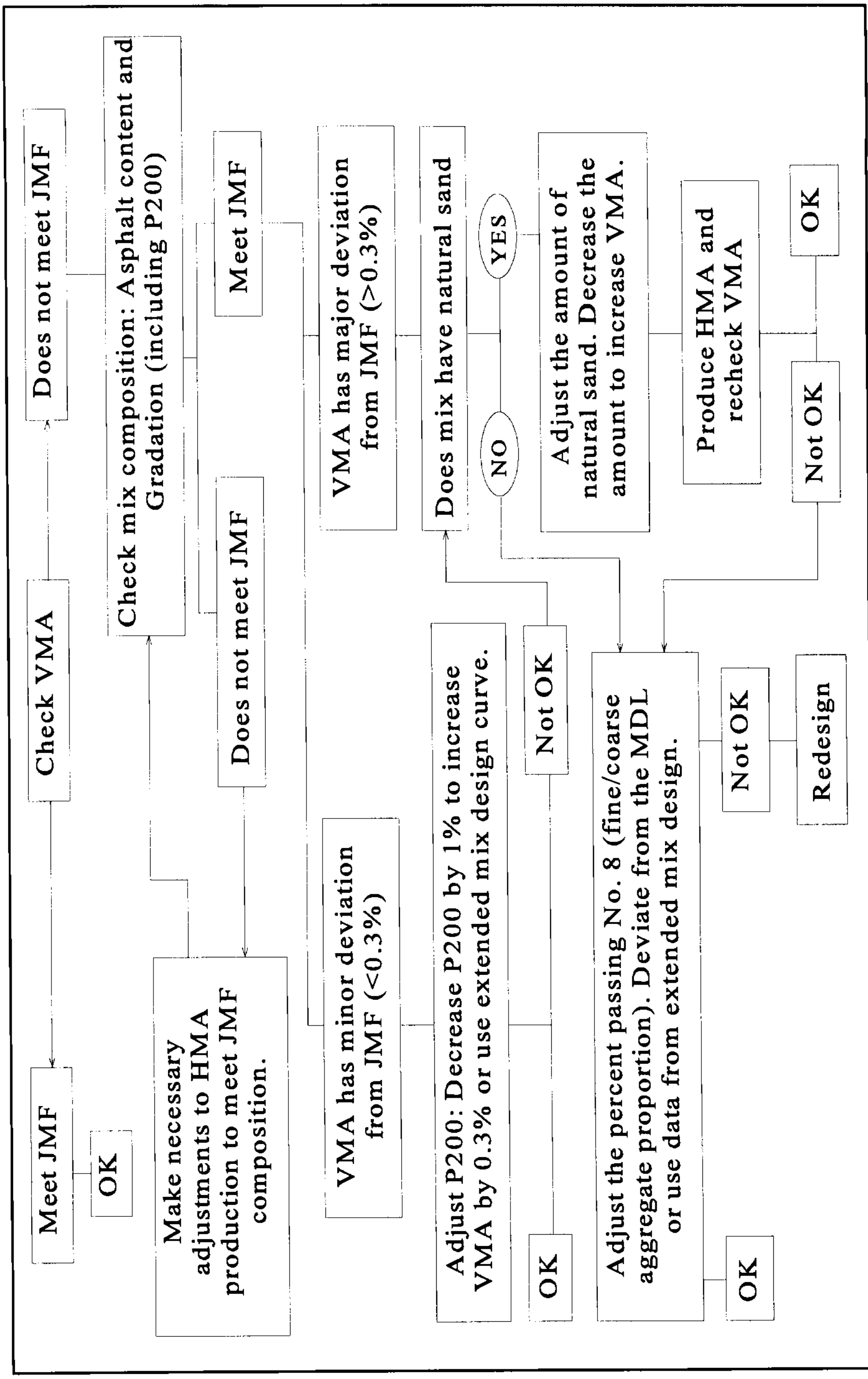

Figure 1. Flow chart for reconciling VMA.

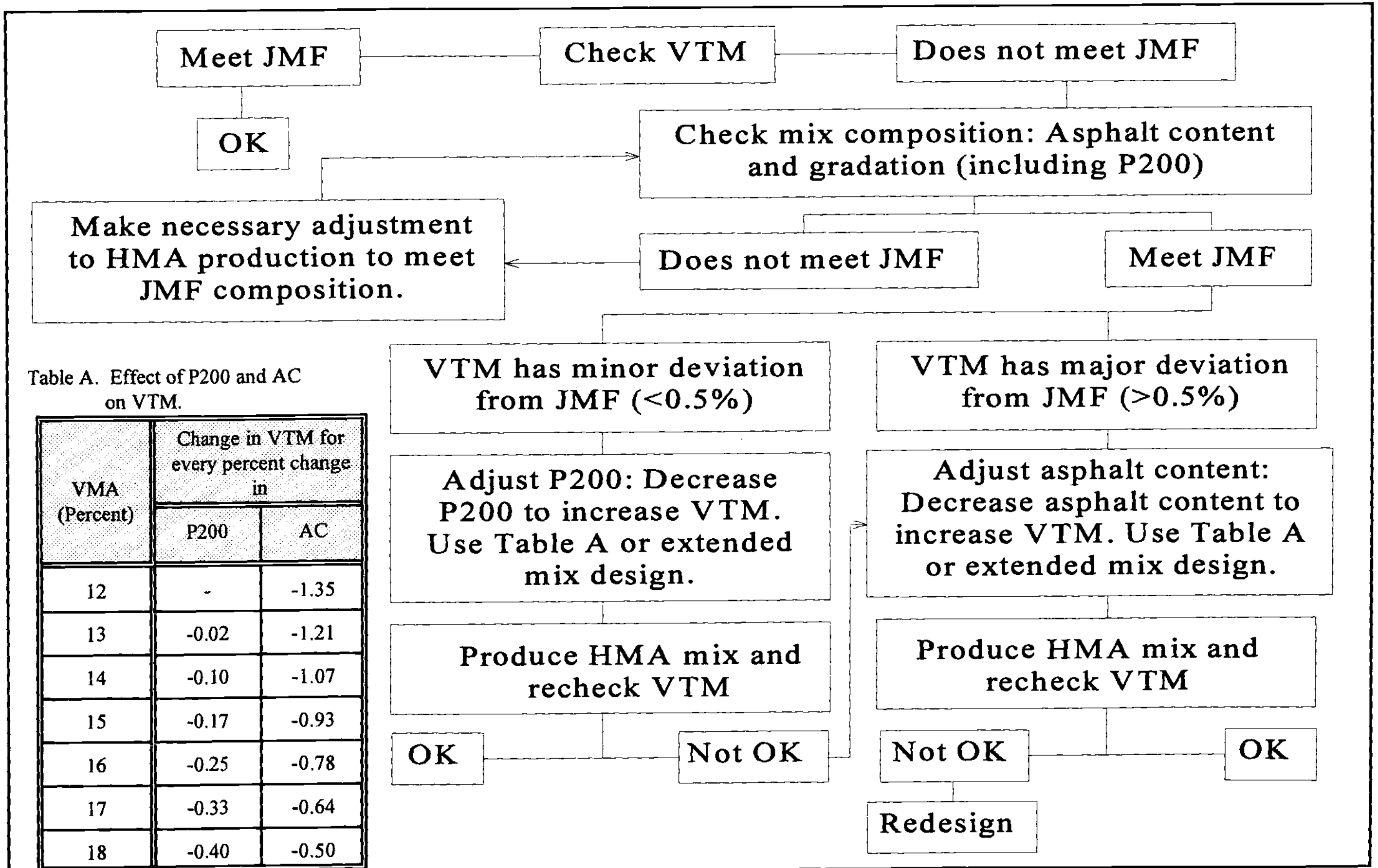

Table A. Effect of P200 and AC on VTM.

VMA (Percent)	Change in VTM for every percent change in	
	P200	AC
12	-	-1.35
13	-0.02	-1.21
14	-0.10	-1.07
15	-0.17	-0.93
16	-0.25	-0.78
17	-0.33	-0.64
18	-0.40	-0.50

Figure 2. Flow chart for reconcilinng VTM.

(less than 0.5%) from the JMF, it is recommended to adjust the P200 material. The P200 material will need to be decreased to increase the VTM. Table A (inside Figure 2) can be used as an approximate guide to determine the quantitative adjustment required to the P200 material to obtain the desired VTM. As an alternate, the extended laboratory mix design (mentioned earlier) curve of percent P200 versus VTM can be used for quantitative adjustment. If the VTM has a major deviation from the JMF (> 0.5%), it is recommended to adjust the asphalt content. The asphalt content will need to be decreased to increase the VTM. Table A (inside Figure 2) can be used as an approximate guide to determine the quantitative adjustment required for the asphalt content to effect the desired change in VTM. A better alternative is to use the asphalt content versus VTM curve developed during the routine laboratory mix design. The slope of this curve can give an indication of the quantitative adjustment needed to asphalt content.

TASK 4: FIELD VERIFICATION OF PROPOSED METHOD OF RECONCILIATION

It was deemed necessary to verify the proposed method of reconciling laboratory designed mix with the plant produced mix in the field. A paving project which was due to be visited by the FHWA trailer, was selected during the 1994 construction season. The HMA mix produced by the asphalt plant was a base mix with a maximum nominal size of 25 mm (1 inch). The details of this paving project such as JMF and production data (including volumetrics) are given elsewhere [3].

The JMF asphalt content of 5.6% gave a VTM of 3.0% (the state agency accepts the VTM as low as 3.0%) and a VMA of 16.2%. The amount of material passing No. 200 (P200) sieve in the JMF was 5.1%. However, when the HMA production began, a VTM close to 1.7% and a VMA close to 14.5% was obtained at an asphalt content of 5.6% and a P200 content of 5.0%. The produced gradation was reasonably close to the JMF gradation. Therefore, the HMA producer reduced the JMF asphalt content from 5.6 to 5.2%. Thirteen sublots of HMA were produced with the reduced asphalt content of 5.2%. An average production VTM of 2.67% and VMA of 14.5% was obtained.

It was evident that the mix composition needed to be adjusted further to increase the VTM to 3.0% or higher. The asphalt content was further reduced from 5.2 to 5.0% for three consecutive sublots. However, there was no improvement in the VTM value obtained with a limited number of tests. The contractor reduced the asphalt content again from 5.0 to 4.7% for the last 35 sublots of the project. This final decrease in the asphalt content increased the average VTM to 2.91% (closer to the target of 3.0%). Therefore, the following changes occurred during the entire paving period:

Change in asphalt content from 5.6% to 4.7% = 0.9%
Resulting change in VTM from 1.7% to 2.9% = 1.2%

This means that 0.9% reduction in asphalt content increased the VTM by 1.2%. This amounts to 1.2 ÷ 0.9 or 1.3% change in VTM by 1.0% change in asphalt content. The value of 1.3% compares reasonably well to the average value of about 1% corresponding to a VMA value of 14.5% in Table 6, based on all FHWA projects. In summary, this paving project had the problem of lower VTM in the produced mix compared to the laboratory designed mix. This was despite the fact that the produced mix was reasonably close in mix composition to the laboratory designed mix. This problem was resolved by lowering the asphalt content. The asphalt content could have been reduced drastically in one step if the proposed method of reconciliation was used, but the contractor chose to reduce it in three steps over the period of paving.

CONCLUSIONS AND RECOMMENDATION

The following conclusions can be drawn based on the statistical analysis of field data from 24 FHWA demonstration projects.

1. Significant differences existed between the volumetric properties of the laboratory designed and plant produced hot mix asphalt.
2. VMA is affected most by the amount of P200 material and the relative proportions of coarse and fine aggregates.
3. VMA can be increased by reducing the amount of P200 material or natural sand in the HMA mixes. VMA can also be increased by moving the aggregate gradation away from the maximum density line (MDL) especially for HMA mixes with no natural sand.
4. VTM is affected most by asphalt content, P200 material and the relative proportions of coarse and fine aggregates.
5. VTM can be increased by reducing asphalt content or P200 material or both.

The following recommendations are made to reconcile differences between the volumetric properties of the laboratory designed and plant produced hot mix asphalt.

1. Use the flow charts in Figures 1 and 2 as general guidelines for reconciling the VMA and VTM differences between the laboratory designed and plant produced HMA mixes.
2. Perform an extended mix design which will be useful in providing additional quantitative information for reconciling the differences in void properties that may arise during production. This information being mix specific is likely to be more reliable for making adjustment to the HMA mix. The recommended extended mix design consists of:
    a. Conventional mix design with a specific gradation used in JMF.
    b. Two additional levels of the material passing No. 8 sieve (JMF ± 5%).
    c. Two additional levels of P200 material (JMF ± 2%).
    d. Three levels of asphalt content (JMF ±0.5%).

The extended mix design requires a total of 27 combinations (3 levels of No. 8 material × 3 levels of P200 × 3 asphalt contents) of which 9 will be taken care of already by the conventional mix design. If three briquettes are made for each combination, an additional 72 briquettes would be needed for the extended mix design (24 combinations × 3 replicates).

3. Attempt to reconcile the differences between the volumetric properties of laboratory designed and plant produce mixes during first day's production by testing at least 4 sublot samples and using the average test values.

4. After the differences in the volumetric properties are reconciled, maintain control charts for mix composition (asphalt content and gradation) and volumetric properties (VMA and VTM) during the entire production period.

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DESIGN AND IMPLEMENTATION OF A DYNAMIC QUALITY MANAGEMENT SYSTEM FOR HMA: A CASE STUDY

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ABSTRACT
One of the items identified during the AASHO Road Test, constructed in Ottawa, Illinois in the late 1950's, was the variability of materials, the effects of this variation on material properties and, subsequently, the performance of various construction items. These activities had a marked influence on the development of assurance specifications during the last 30 years. These specifications, while recognizing variability in sampling and testing and establishing means to evaluate their effects, also clearly delineate the quality management responsibilities of the contractor during the construction process and the acceptance procedures of the agency.

The objective of this paper is to document an effective quality management system for an HMA contractor that has been used since 1989 on numerous projects and the steps taken to design and implement such a program.

This paper discusses the essential aspects of the QM Program and the actions required by the contractor's key management personnel in implementing the program. These include planning, budgeting, equipment acquisition and training. The program was intentionally designed to be dynamic so that changes that occur because of job conditions can be easiily handled.

Specific attention is given to the unit costs associated with the implementation process and the elements of an effective company-wide training effort.

KEYWORDS
Quality Management, Quality Assurance, Quality Control, Hot Mix Asphalt, Variability

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INTRODUCTION

The notion of managing quality during the construction of highway and transportation facilities in the United States is not new and is generally included in the specifications for a project. Most materials and methods specifications, the type used since the earliest specifications were developed, require control of materials production and the construction process, albeit, by the specifying agency. This methodology is vastly different from most major industries where the responsibility for day-to-day quality control is placed in the hands of the supplier [1]. The modern benchmark for the evolution of highway specifications in the U.S. was the American Association of State Highway Officials (AASHO) Road Test constructed near Ottawa, Illinois from 1956-1958 [2]. The test road was constructed to evaluate the design and construction practices for Hot Mix Asphalt (HMA) and portland cement concrete pavement systems, and short span bridges. There were numerous findings from this effort and the ones that best fit the context of this paper are:

- Variability of construction materials and processes was not fully understood and not adequately accounted for in the specifications

- Statistical methods can, and should, be used to determine compliance with specification requirements in any sampling and testing program used to evaluate project quality.

As the data from the Road Test began to be disseminated and discussed, [3], [4], State Highway and Transportation Departments began to develop and use what was at the time, known as End Result Specifications (ERS) [5]. In ERS, the responsibility for quality control is typically assigned to the contractor with the agency assuming the role of accepting the product or process on the basis of a statistically-based acceptance sampling and testing plan. These responsibilities are sometimes referred to as Process (Quality) Control and Acceptance Sampling and Testing. The American Association of State Highway and Transportation Officials (YACHT) defines Quality Control (QC) [6] as "the sum total of activities performed by the seller (producer, manufacturer, and/or contractor) to make sure that the product meets contract specification requirements."

The specification development process continued to evolve during the next 30 years and terminology changed as well. The most prevalent term used to describe the latest version of these types of specifications is Quality Assurance, which is defined [6] as "all those planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy given requirements for quality".

Total Quality Management (TQM) is a term frequently used in U.S. management circles today to describe an effort within an organization, regardless of type or size, to continually improve upon a wide spectrum of activities ranging from education and team building to customer relationships [7]. Like most other systems, it can be composed of various parts and generally the organization chooses those parts that are essential to their operating needs. Quality Management (QM) is used in this paper to be synonomous with TQM. In the case study of a highway material supplier and contractor which we will describe, this would include technical and administrative staff, facilities such as field offices and laboratories and operational activities. The effective management of these activities, with an emphasis on quality, is central to the financial well-being of any modern contracting organization. Payne and Dolan, Inc. Is a large highway contractor with operations in Wisconsin and Michigan that initiated a concerted effort in 1987 to implement a Quality Management (QM) Program throughout their organization, in part to react to negative employee feedback and to respond to the need for continuous organizational improvement to remain competitive. The steps taken by the company and the results to date are presented below.

ELEMENTS OF A QUALITY MANAGEMENT SYSTEM

ORGANIZATIONAL APPROACH

Payne and Dolan, Inc., a family-owned company founded in 1918 by the father of the current President, operates over 40 quarries and gravel pits, 30 HMA plants, numerous paving, grading and milling crews and asphalt cement terminals in Wisconsin and upper Michigan. During the peak of the construction season, they employ nearly 1,700 people. They began their quality initiative eight years ago when the President recognized the need to implement a "quality culture" in every facet of the organization in order to continue to be an industry leader. Although operating efficiently, the organization has decentralized into regional offices in order to better respond to customer needs. While appearing to increase efficiency, the company actually began to note a decrease in employee satisfaction and harmony because management had not provided the training necessary for regional office employees to acquire the required knowledge and skills to effectively manage their operation and maintain the high standards of the company.

Recognizing in 1987 that changes needed to occur, the management undertook a 5-step process that resulted in a major cultural change in the organization focused on quality and people. Since the pursuit of quality is a neverending venture, the company continues today to evaluate internal "systems" to detect if changes are required. The steps are as follows:

Assessment of the Company's Culture

From the time that the company was founded, it was organized with a top-down management style, the day-to-day operations were very autocratic and, while attempting to operate in a decentralized manner, decisions were sometimes delayed. The autocratic style is prevalent in the highway construction industry where a majority of firms are family-owned businesses and this may be perceived to be the most effective management approach. The President recognized that this style was not responsive to the needs of the company and began an undertaking to restructure the organization.

Evaluation of the Management Structure

Many different layers of management existed from the President to the Project Foreman. For change to occur, all the levels had to recognize and understand the need for and the value associated with change. In order to move ahead, a shift to a participatory management style was required. By including all levels of management and employees in the development of the quality program, and initiating an effective management information system, the change in management style was accomplished and has evolved to the point where the "boss" is now more of a "coach" in all areas of the company.

Communications

The company recognized that it had both short and long-term objectives in any revisions that took place and that it was important to have all employees "buy" into the real reasons for modification, not just change for the sake of changing. This had to be communicated to the entire organization so that everyone knew and understood what was going on at all times. Effective communication is the goal of every organization and is something the company continues to emphasize. It is not easy and has not been easy for the company to implement.

The company recognized early on that communication is not an easy process to implement and demanded continued attention. Communication in the aggregate and HMA industry environment was viewed not only as internal communication, but communication with the external customers and suppliers. To be effective, a communication system was planned that required good reporting mechanisms and distinct opportunities for face-to-face meetings between groups internally and externally. Examples of the internal systems that were used are:

- A company-wide newsletter
- Personal letters to employees from top management
- Open forum regional, group, and individual meetings between employees and management
- An open-door policy of communication between individual employees and Managers

Any or all of these methods are used, depending upon the circumstances.

For external customers, a job satisfaction evaluation form was used. This is filled out and returned by the customer. The returned information is evaluated and a follow-up personal contact is made. For suppliers, a written policy of procedures and expectations is provided. Mandatory meetings of similar providers are held annually to discuss this policy, clear up previous problems and suggest modifications. This system was planned to help prevent communication "breakdown" and internal/external miscommunication. These planned processes effectively enable for the timely transfer of proper information to the right people.

Customer Focus

Determining who the customer is, their wants, needs and expectations, was the fourth step taken to evaluate the status quo. This assessment lead to the realization that there were two types of customers: internal as well as external. Evaluating external customer needs, although extremely important, was "easy" when compared to the objective self-evaluation required to assess the internal customer and determine how to better serve them. Actually, the internal review provided a unique insight into how to better serve the external customer. We learned that our internal customers have similar wants and needs as our external customers. They both look for uniformity of product whether it be raw aggregate or finished pavement. They both have high expectations of product reliability and serviceability. We learned that if we could provide a high level of quality and consistency to our internal customers, it would make satisfying the expectations of our external customers much easier.

Development of a New Company Philosophy

Once the above 4 steps were taken, a new approach to business emerged which emphasized an "if it is working well, how can we make it better", instead of the prevalent, "if it ain't broke, why fix it" attitude that previously existed in the organization.

The system changes noted above resulted in a paradigm shift in the organization and led to the realization that anything is possible if the desire for doing things better, perhaps sometimes differently, is encouraged in the organization. For example, Payne and Dolan, Inc. recently teamed up with the Wisconsin DOT and the YMCA [8], in a pilot program to train women and minority construction workers in the Milwaukee, Wisconsin area where there is a need for skilled employees.

DESIGN OF A QUALITY MANAGEMENT SYSTEM

As noted above, the direction taken in the development of specifications since the AASHO Road Test has been the separation of responsibilities for quality control and acceptance testing between the contractor and the specifying agency. What is not explicitly stated are the actions that the contractor needs to perform, before and after the contract to assure quality. Quality needs to be viewed as a continuum, an attitude that exists before the contract is awarded and one that continues after the contract is completed. One cannot "turn" quality on and off like a faucet. Additionally, quality needs to be viewed from the customers' viewpoint as well as within the company.

IMPLEMENTATION OF A QM SYSTEM

To some extent, Payne and Dolan, Inc. has responded to outside stimuli in the development of a QM Program since their major customers, the Wisconsin and Michigan DOTs, have specified that contractors should have Quality Control systems in place prior to commencing work on specified DOT Contracts. As noted above, however, the company responded to their own internal demands for a QM System and developed a program that is all inclusive. Their approach is to control the process at the beginning, as well as throughout the entire process.

For example, in the production of aggregates for HMA, they examined the raw aggregate sources not only for the gradation of material that are produced, but the total quarry operation is evaluated including the characteristics of the material that is blasted, the loading sequence of the operators, and the handling procedures. This is accomplished for both permanent and portable crushing operations. The company is currently evaluating non-conformance with procedures, sources of variation and identifying areas that need improvement. They have acquired the assistance of a Statistician to aid them in the study of overall variation in each of their crushing operations and he has recommended specific actions that need to be taken to control a variety of products. Recognizing the need for technical expertise and having the resources to contract with professionals outside of the company if needed, is an integral part of the management plan.

EXPERIENCES

As one should expect with the implementation of any new management system, some things exceeded expectations and some did not. One item that was attempted and discarded early was the Quality Circle concept. This involved bringing together groups of 8-12 people to work on company-wide problems. Membership of the circle groups was determined by employee interest in a specific problem and from any location within the company. Standard quality circle principles were employed for problem solving. It worked well initially and served to launch the program, but because of the geographical distribution of the company, it could not be sustained and was discarded for a more regional, team-oriented approach that had greater autonomy but served the regions better. The most important lesson from the Quality Circle experience is that it gave us a much better understanding of what quality is and how each individual within an organization play an important role in the achievement of quality. It became a stepping stone for growing and promoting quality within the company.

A successful venture has been employee education. This is not new to the organization and is an activity carried out during non-construction periods for some time. Payne and Dolan, Inc. Has participated in sending its people to training sessions sponsored by various national organizations as well as in-house schools. In 1995, the company sponsored a "Payne and Dolan, Inc. College" in which a facility was rented for two weeks and trained over 550 employees in such diverse subjects as First Aid, CPR and Union Contracts. Along with the "college", a mini-trade show was staged to "showcase" different areas of the company and to acquaint employees with new innovations in the industry.

Problem Solving

Problem solving is a specific area in which the company has had good experiences. Figure 1 illustrates the company's QC management flow diagram followed at its quarries and HMA plants. The Quality Control Technician has direct responsibilities for sampling and testing. The test results are plotted on the quality control charts. When plotted data shows a trend toward the QC limits or are out of QC limits, production may or may not be stopped depending on the severity of the problem. The Project Manager, Plant Foreman, Senior Quality Control Technician, Quarry Foreman and Paving Foreman are immediately notified. An immediate meeting is held at the plant Quality Control Laboratory. The team specifically reviews the problem, determines the possible causes and recommends appropriate corrective action. The recommended corrections are made and the results verified by the required QC tests prior to continuance of full production.

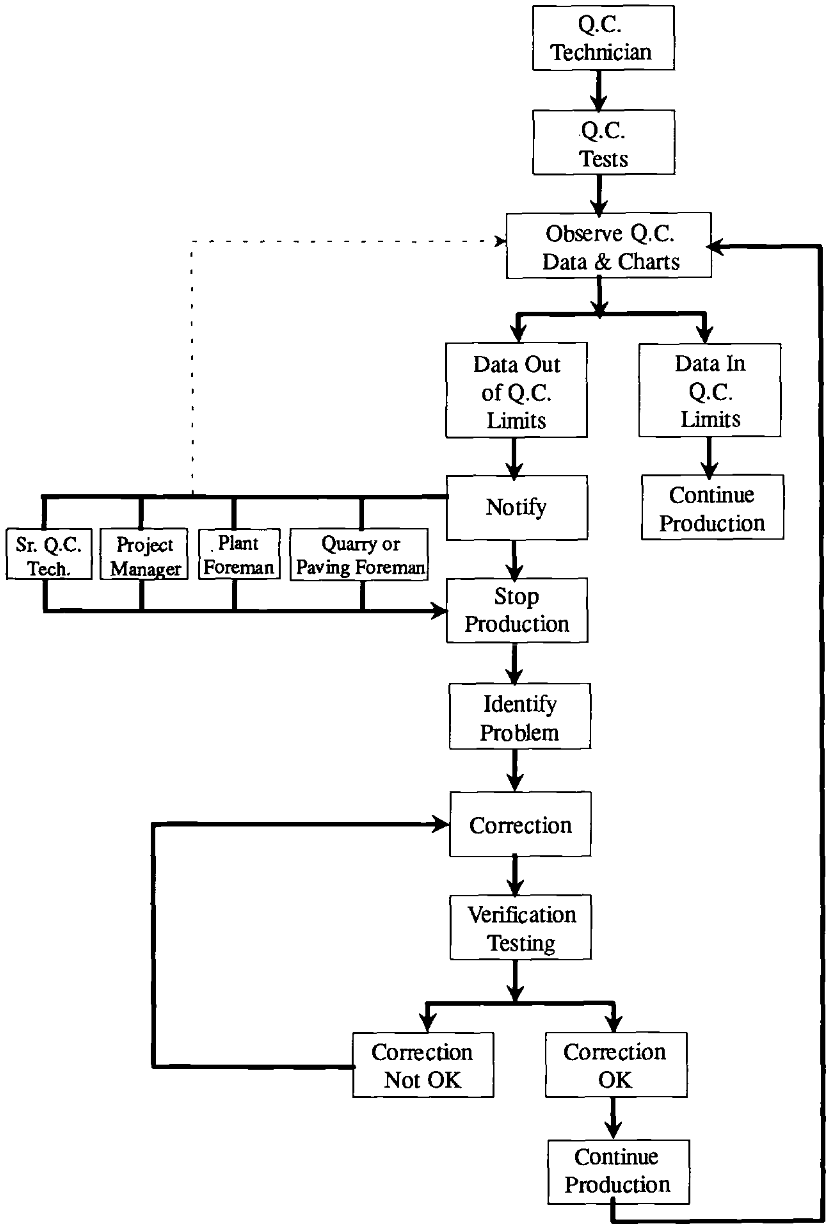

Figure 1 - Quality Control Management Diagram

All members of the team are encouraged by Top Management to monitor the data and control charts as part of their daily job functions. From the training we have received, and the experiences derived from decentralization, the employees have learned that it is much more efficient (and rewarding) to tackle smaller problems early because of the complexity of larger problems. By segmenting large problems into a series of small ones, they become much easier to evaluate and solve. In order to ensure compliance to customer specification, Payne and Dolan, Inc. Set internal tolerances tighter than those of the customer. This enables the company to react to problems faster and ensure that customer specifications are met.

Acceptance by Top Management

Top management in the organization has been very active in initiating most of the changes that have occurred. They have recognized that there are costs to Quality Control. These costs are dependent on the project location, size and estimated completion time. These costs generally range from $0.50/ton for rural projects to $1.50/ton for urban projects. However, Top Management through both support and money, have demonstrated their commitment to the success of the program. Resource allocation to the QM Program has been consistent and is exemplified continual support of all QC activities and training as illustrated by the "college" sponsored last year, which was a significant expenditure.

Agency Perceptions

For the most part, State Highway Agency acceptance of contractor process control has been well accepted. While agency upper management has embraced this concept, some individuals at the Project Manager and Inspector levels were initially somewhat skeptical. Perhaps there was concern how a contractor could know more about producing and controlling their own product than them. Fortunately, that type of skepticism was overcome by the total success of the Quality Management Program.

In Wisconsin for example, the contractor's quality control data is used for product acceptance provided that the agency acceptance testing verifies the contractor's testing. What this means for the agency is more control testing than was possible in the past. The responsibilities for mix design and quality control are the contractor's, freeing agency personnel for other assignments. Both contractor and the State Highway Agency have seen significant improvement in their organization through partnering the product.

The Wisconsin DOT has nominated Payne and Dolan's construction projects on I-894/43 (Milwaukee Bypass) for the 1995 National Quality Initiative (NQI) Achievement Award. The Wisconsin DOT believes that this project specifically reflects the values of partnership and quality being promoted by the NQI Steering Committee.

CONCLUSIONS

Quality Management seeks to improve product quality and increase customer satisfaction by restructuring traditional management practices. The application of QA is unique to each company or organization that adopts such an approach. Several features are deemed essential - customer-driven quality, strong quality leadership (top management), continuous quality improvement, action based on facts, reliable data and analysis and active employee participation.

Payne and Dolan, Inc. has implemented the QM process achieving a high degree of success. A basis for measurement of this success is the 1995 nomination of the company's I-894/43 construction project for the NQI Achievement Award "Promoting Partnerships to Improve Highway Quality".

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QC/QA SPECIFICATIONS-A TEXAS PRODUCER'S EXPERIENCES

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Abstract: The Texas Department of Transportation (TxDOT) has adopted QC/QA specifications for hot mix asphalt (HMA) projects. Under these specifications, the contractor is responsible for the HMA design and testing for pay-factors. The testing and pay-factors are broken into three areas: mixture, pavement density and smoothness. The contractor is also required to have a QC program to monitor the non-pay items of the job mix design. The contractor uses the data to make the decision to proceed, make corrections or shut down. The area TxDOT office is responsible for testing split samples taken by the contractor for acceptance. The TxDOT district laboratory is responsible for independent assurance samples. TxDOT, Division of Materials and Tests in Austin has been designated as the referee laboratory to settle any testing disputes not solved at the area office level.

This paper will summarize the construction of three QC/QA projects across Texas. The projects include Highway projects in Abilene and San Antonio and a project on I-20 near Eastland. The HMA used on these projects included a number of asphalt types and mixture designs. The projects used both polymer modified and conventional asphalts. The mixes used included both a dense graded surface mix as well as a coarse matrix high binder (CMHB) mix. The paper will also cover the problems and successes of mix design, testing which included using a nuclear asphalt content gage and communications.

Keywords: Quality Control, Quality Assurance, certification, pay-factors, gradation, asphalt content, density, hot mix asphalt, nuclear asphalt content gage.

The Texas Department of Transportation (TxDOT) initiated a new program to maintain and improve the quality of pavements being built in Texas. This program was started to handle the reduction in TxDOT staffing. The philosophy was that by involving the contractor in the mix design and testing phases innovation would be encouraged. Most importantly the adversarial relationship between the TxDOT and the contractor would be replaced by partnering. The partnering was initiated by a joint industry and agency QC/QA committee. The charge of this committee was to develop the controls TxDOT

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needed to ensure themselves a good quality project as well as give the contractor the freedom to construct a quality project. The committee was composed of an equal number TxDOT and industry representatives from the Texas Hot Mix Asphalt Pavement Association (TxHMAPA). The committee was co-chaired by a representative from TxHMAPA and TxDOT. This committee worked with consultants to develop the QC/QA specification. Representatives from the committee visited other states with quality control programs to see what was working and what was not.

The corner stone of the Texas QC/QA program is partnering. Partnering is building a team composed of the contractor and TxDOT whose goal is to build a quality pavement. The joint industry and TxDOT QC/QA committee developed a specification that made the contractor responsible for quality control (QC) and quality assurance (QA). The QC portion was to return process control to the contractor. With the proposed cutbacks to TxDOT, TxDOT would no longer have the staffing to control every aspect of the plant production and laydown of the hot mix asphalt (HMA). The quality assurance was to have the contractor buy into the quality of the in-place HMA. The incentive for the contractor is the pay-factors, bonuses for excellent quality work and penalties for substandard work.

The key to excellent work is timely and accurate testing. To ensure accurate testing the QC/QA Specification Committee developed a certification program. This program is administered by TxDOT and run by the TxHMAPA. TxDOT did not want to enter the training and testing market. The TxHMAPA established a training and testing center in Austin. This center tests the applicants for their practical skills in running the tests and their knowledge of the specifications. In a week long certification program, the applicant must demonstrate how to run each test as well as pass a written test on the specifications and the applicable calculations. A passing grade of at least 80% is needed to be recommended for certification. TxDOT reviews the recommendations and certifies the QC specialists.

The QC specialists are divided into three levels. The classes are divided to give TxDOT 50% of the available class space. Contractors and consultants make up the remainder of each class. The contractor's level 1A specialists are required to be at the HMA plant at all times during production. They take and test the samples for process and assurance control. The contractor's level 1B specialists are required to place the HMA on the roadway. They take cores to check for roadway density and also measure roadway smoothness. The final level of QC specialists are the level II specialists. These specialist must already be level 1A specialists. The level II specialist is responsible for developing and certifying the HMA mix design. TxDOT's specialists primarily conduct independent assurance testing. The certified QC specialists in TxDOT's Materials and Test Division are responsible for conducting the referee testing to settle differences between the contractor's and the TxDOT area engineer's QC specialist's test results. The contractor's tests are used to determine the pay factor for each lot. If a sample goes to referee testing, then the results obtained by the Materials and Test Division are used to determine the pay factors.

The TxDOT program was developed over a 5-year period and is still undergoing small corrections, and thus is an active program. Approximately three years after the process was started, the training center opened its doors in 1992. The first five trial projects were constructed in 1993. The QC/QA specification went into full implementation in September 1994.

MIX DESIGN

The development of the job mix formula (JMF) is divided into three initial stages. The first is JMF1. This is the lab design and establishes the gradation limits. The contractor's level II specialist is responsible for developing each of the JMF's. The corresponding TxDOT level II specialist then approves the JMF1 based on the mix volumetrics, air voids and VMA. The area engineer in charge has the option to request moisture susceptibility testing. After the JMF1 is approved, the contractor runs a trial batch to establish what the plant will run compared to the lab design. The trial batch results are used to establish JMF2. TxDOT tests this mix for compliance with all the mix design specifications. After this mix passes, the contractor then can move to first day of production. The results from the first day's production are used to set JMF3. The first day's production allows the contractor to make final adjustments to the mix design based on a production run. These results are considered one lot and are given a pay factor of 1.0.

The contractor has the option to set JMF3 based on the trial batch or a previously used successful design. When this option is used, pay factors are calculated for the first day's production permitting a bonus or a penalty to be accrued for that lot. Using an previously approved design made with the same materials permits a contractor to start a new project without the delays of running trial batches.

The contractor can change the JMF3 at the beginning of each subsequent lot to adjust for changing plant (continuous production), material or construction conditions. The contractor's and TxDOT's QC specialists usually meet between lots to establish any new JMF's. However, these changes must be within the master gradation based on JMF1 or a new mix design must be developed. The master gradation is based on JMF1 plus or minus 5% for sieves larger than the No. 10, plus or minus 3% for the sieves larger than the No. 10 sieve, plus or minus 1.6% for the No. 200 sieve and 0.3% for the asphalt content. For this paper each JMF used after JMF3 is established will be referred to as JMF3 for convenience.

The HMA samples are typically truck samples. Sample times are determined randomly by production for each sublot. Large samples of around 60 pounds are taken. These samples are split into the production, verification, referee and backup samples.

Sometimes the gradation control is established by correlating cold belt aggregate gradations to HMA extraction gradations. In all cases the asphalt content is determined by a calibrated nuclear asphalt content gage.

PAY FACTORS

Pay factors are based on the premise that consistency is key to making a good product. Testing is conducted on each sublot. A sublot is defined as being between 250 tons and 750 tons. Small production runs of less than 250 tons are not included in the pay factor calculations and are given a pay factor of 1. A lot is defined as four sublots. The contractor has the option of using daily productions lots (option 1) or running lots (option 2). The first option requires the contractor to take both primary and backup samples at randomly chosen production tonnages. Four of these samples will be used to define a lot if four full sublots are not produced. The second option accumulates sublots over time until four sublots are obtained. The first option is good for starting jobs and when conditions are changing because each day starts a new day. The second option is good when the project and weather conditions are consistent. The QC specialists like the second option since they do not have to sample or test as much. The contractor is allowed to switch options once from 1 to 2 or vice-versa during the project.

The pay factors are based on the mean absolute deviation between the JMF3 and the production sample test results for each sublot. The average or mean deviation is then determined for each lot. A pay factor from Table 1 is assigned to each lot based on the mean absolute deviation.

The pay factors for construction are presented in Table 2. These factors are based on absolute deviations based on the average air void content of two cores per sublot. The extra core sample is taken to reduce the effects of sampling variation from the roadway. The cores are cut from the compacted pavement at random locations determined for each sublot.

Table 1- Pay Factors for Plant Production

	Mean	Absolute	Deviations
Pay Factor	**No. 10**	**No. 200**	**%AC**
1.05	0-0.99	0-0.5	0-0.19
1.02	1.00-1.90	0.51-0.90	0.20-0.24
1	1.91-3.00	0.91-1.50	0.25-0.30
0.95	3.01-4.00	1.51-2.00	0.31-0.35
0.9	4.01-5.00	2.01-2.50	0.36-0.40
0.85	5.01-6.00	2.51-3.00	0.41-0.45
0.8	6.01-7.00	3.01-3.50	0.46-0.50
0.75	7.01-8.00	3.51-4.00	0.51-6.0
0.7	8.01-9.00	4.01-4.50	0.61-0.65
Remove	>9	>4.50	>0.65

Table 2 - Pay Factors for Roadway Construction

Pay Factor	Ave. Air Voids-%
1.05	4.0-5.9
1.02	5.0-6.9
1	7.0-9.0
0.95	3.5-3.9 or 9.1-9.5
0.9	3.0-3.4 or 9.6-10.0
0.85	2.5-2.9 or 10.1-12.0
0.8	12.1-13.0
0.75	13.1-14.0
0.7	14.1-15.0
Remove	<2.6 or >15.0

The pay factors are calculated for both production and placement lots and averaged. If all the pay factors for placement are 1 or better, then the highest pay factor is used. If any of the pay factors are less than 1, the lowest value is used to calculate the pay factor. The total pay adjustment for each lot is then calculated on the basis of the contractor's in-place bid price as shown:

TPA=B x Q x (A+B)/2

where: TPA=total pay adjustment

B=In-place bid price
Q=In-place lot quantity
A=Production pay factor
B=Placement pay factor

Quality Acceptance Testing

The area engineer's QC specialist is required to test at least one sublot out of 12 sublots split samples provided by the contractor. During the initial phases of the project the TxDOT specialist usually tests each sublot along with the contractor. The goal for both is to obtain test results that are within the tolerances presented in Table 3. The contractor has the option to accept all TxDOT's test results if the verification samples do not meet the tolerances shown in Table 3 and vice-versa. There is also a tolerance of 2% on any sieve with 100% passing. This was added to the specification to account for the effect of one or two large aggregate pieces from RAP or large stone mixes retained on a sieve.

During production if the contractor's QC test results indicate that a sieve or other parameter such as asphalt content is out of specification on three consecutive samples, the plant must be shut down until corrections are made to bring the process under control. The key to making this specification work is partnering.

Table 3 - Test Result Tolerances

Test	Tolerance-+/-
Gradation	
Production >No. 10	5%
Verification > 5/8 in	5%
No. 200<sieve< 5/8 in.	3%
Asphalt Content-Nuclear Gage	0.3%
Air Voids:	
Ave. 2 Pavement Cores	1.0%
Laboratory Molds	2.0%
Rice Specific Gravity	0.02%
Bulk Specific Gravity	0.02%

PARTNERING

Before starting their first QC/QA specification project, each contractor was required to have a partnering session with his suppliers and TxDOT These sessions, conducted by a independent consultant using TxDOT guidelines, lasted anywhere between a half-day to three days. The partnering sessions helped establish lines of communication so that problems could be solved at the lowest level. One of the goals of each partnering session was to develop a mission statement for that project. A typical mission statement follows with the key bolded:

MISSION STATEMENT

> The members of the Jones County US 83/277 QC/QA Highway Project, TxDOT, Contract Paving Co. and Vulcan Materials Co., are committed through **Teamwork** and **Pride** to build a **Quality Project** with priority on **Safety** to the traveling public and project personnel, within **Budget** for the contractor and TxDOT, with **Timely** and **Cooperative** resolution of issues, and be **Environmentally Sensitive** to produce a quality project that serve the citizens of Texas.

And most importantly build **TRUST** in each other. This was set up in the partnering plan. The partnering plan established lines of communication and responsibility. This set the lines of communication for problem resolution at the lowest level.

CASE STUDIES

The original goal of this paper was to analyze each project as it was completed. However, after finishing these projects there are a number of similarities. So the case studies on the three projects described in the abstract will be reduced to the areas that were common to all projects. This next section is based on Hwy 83, a four- lane highway west of Abilene that was produced with AC-20. The resurfacing of Hwy 83 was one of the first projects in Texas to use a new gap-graded mix called coarse matrix high binder (CMHB), a low cost SMA without fibers or other modifiers. This was produced in a drum plant with a scrubber. The next project used a conventional dense HMA coarse graded Texas Type C mix for resurfacing on Hwy 90 outside of San Antonio using a batch plant with a bag house. The last project was I-20 in Eastland. This resurfacing project used AC-45P in a fine graded Texas Type D mix produced in a batch plant with a scrubber.

TESTING

The first step in all these projects was certifying the certified. An important part of the partnering plan was to ensure that everyone's equipment was working and properly calibrated. This was handled by comparing test results between the contractor's and the TxDOT lab all through the mix design. Differences were eliminated one at a time. Equipment problems were handled by recalibrating. Differences in technique were resolved by split sampling and the specialists testing each other samples and compacted lab molds.

One problem on a later project was not resolved by recalibration. This problem concerned sample compaction. Both Texas gyratory compactors were found to be in standard calibration and each QC specialist could reproduce the other's test results on their compactor. The problem went up the resolution chain before the project started. The problem turned out to be a difference in pump stroke between machines made by different manufacturers. Both pumps produced the same pressure under one stroke on the solid calibration specimen, but the longer stroke produced the limiting pressure sooner. The molds in that device did not receive as many compaction gyrations and produced molds with lower densities. After adding a shim to correct the stroke length, densities were not a problem the rest of the project.

The nuclear density gage is a very reliable device to determine asphalt content. However, on the project using CMHB the asphalt contents starting varying. Calibration and sample preparations were checked and rechecked. A cooperative effort between the contractor, TxDOT and the device manufacturer determined a larger calibration range was needed. On a three point calibration curve with CMHB the gage was most accurate +/- 0.5% of the middle of the calibration curve. Extending the calibration by expanding the range of asphalt contents for more calibration points solved the problem.

A problem encountered on a couple of projects was temperature. Once everyone agreed on a test temperature, the problems disappeared.

Production

During production the essential item was that QC/QA was not a shortcut to getting paid. The contractor has to manage his business. The process starts with stockpile management. Good stockpile control in building piles with consistent gradations made achieving the maximum pay factor for mix production a regular occurrence. However, to reach that state required training of all the plant personnel in how they all effected the final quality of the mix. Consistency in stockpiling, in feeding the cold bins, and in plant production rates was essential to producing quality HMA. This consistency extended to the lay down operations as well. Truck loading and timely delivery of the mix to the paver so that the paver did not have to stop are the first steps in the field. With the paver moving at a consistent pace, the rollers were able to establish uniform rolling patterns, which in turn, resulted in good pavement densities. Control of mix temperature was key at all phases of the project.

A typical bonus report for production and placement is presented in Table 4. These results show that the production samples achieve the maximum bonus except for start-up and small tonnage (less than 250 tons) days. The bonus for placement was difficult to achieve on all products. A pay factor of 1 or 100% pay was usually achieved for compaction using three rollers, usually a combination of vibratory and static.

SUMMARY

The key points of a QC\QA program can be summarized as T^3:

Training, Testing and Trust

CONCLUSION

QC/QA programs with bonus and penalty pay factors work to promote better relations between contractor and state as well as improve road quality and value.

FORM H Table 4 MONTHLY BONUS/PENALTY WORKSHEET (QC/QA)

PROJECT: IM 20-2(177)295 COUNTY: CALLAHAN HWY.: IH 20
CSJ: 0006-07-069 ITEM: 3007 MEASURE: TONS

LOT	(a) PAY QUANTITY	(b) BID PRICE	(c) AMOUNT DUE (a X b)	(d) PAY FACTOR PLANT	(e) PAY FACTOR ROAD	(f) PAY FACTOR AVERAGE (a+b)/2	(g) ADJUSTED PAY (c X f)	(h) BONUS/ PENALTY (g - c)	(i) CUMULAT. BONUS/ PENALTY
1 "B" (1-12)	891.40	$26.62	$23,729.07	1.00	1.00	1.000	$23,729.07	$0.00	$0.00
2 "B" (1-13)	690.05	$26.62	$18,369.13	1.05	1.05	1.050	$19,287.59	$918.46	$918.46
3 "B" (1-16)	469.95	$26.62	$12,510.07	1.00	1.00	1.000	$12,510.07	$0.00	$918.46
1 "C" (1-17)	2126.75	$24.12	$51,297.21	1.00	1.00	1.000	$51,297.21	$0.00	$918.46
2 "C" (1-19)	1549.40	$24.12	$37,371.53	1.05	1.00	1.025	$38,305.82	$934.29	$1,852.74
4 "B" (1-20)	515.10	$26.62	$13,711.96	1.00	1.00	1.000	$13,711.96	$0.00	$1,852.74
3 "C" (1-20)	440.50	$24.12	$10,624.86	1.00	1.00	1.000	$10,624.86	$0.00	$1,852.74
5 "B" (1-21)	705.00	$26.62	$18,767.10	1.05	1.00	1.025	$19,236.28	$469.18	$2,321.92
4 "C" (1-23)	1379.75	$24.12	$33,279.57	1.05	1.00	1.025	$34,111.56	$831.99	$3,153.91
5 "C" (1-24)	1862.65	$24.12	$44,927.12	1.05	1.00	1.025	$46,050.30	$1,123.18	$4,277.09
6 "C" (1-25)	1332.45	$24.12	$32,138.69	1.05	0.95	1.000	$32,138.69	$0.00	$4,277.09
7 "C" (1-27)	1966.80	$24.12	$47,439.22	1.05	1.00	1.025	$48,625.20	$1,185.98	$5,463.07
8 "C" (1-28)	1928.35	$24.12	$46,511.80	1.05	1.00	1.025	$47,674.60	$1,162.80	$6,625.86
9 "C" (1-30)	1524.20	$24.12	$36,763.70	1.05	1.00	1.025	$37,682.80	$919.09	$7,544.96
10 "C" (1-31)	1630.80	$24.12	$39,334.90	1.05	1.00	1.025	$40,318.27	$983.37	$8,528.33
JMF#3 CMHB	2143.20	$27.30	$58,509.36	1.00	1.00	1.000	$58,509.36	$0.00	$8,528.33
1 CMHB (5-18)	2461.95	$27.30	$67,211.24	1.05	1.00	1.025	$68,891.52	$1,680.28	$10,208.61
2 CMHB (5-19)	1715.40	$27.30	$46,830.42	1.05	1.04	1.045	$48,937.79	$2,107.37	$12,315.98
3 CMHB (5-22)	2097.65	$27.30	$57,265.85	1.05	1.05	1.050	$60,129.14	$2,863.29	$15,179.27
4 CMHB (5-23)	2390.95	$27.30	$65,272.94	1.05	1.01	1.030	$67,231.12	$1,958.19	$17,137.46
5 CMHB (6-5)	1953.80	$27.30	$53,338.74	1.05	1.01	1.030	$54,938.90	$1,600.16	$18,737.62
6 CMHB (6-6)	2400.00	$27.30	$65,520.00	1.05	1.02	1.037	$67,911.48	$2,391.48	$21,129.10
7 CMHB (6-7)	2400.00	$27.30	$65,520.00	1.05	1.05	1.050	$68,796.00	$3,276.00	$24,405.10
8 CMHB (6-8)	2400.00	$27.30	$65,520.00	1.05	1.05	1.050	$68,796.00	$3,276.00	$27,681.10
JMF#3 "D" (6-9)	604.30	$32.94	$19,905.64	1.00	1.00	1.000	$19,905.64	$0.00	$27,681.10
1 "D" (6-12)	2000.00	$32.94	$65,880.00	1.05	1.05	1.050	$69,174.00	$3,294.00	$30,975.10
2 "D" (6-14)	2000.00	$32.94	$65,880.00	1.05	1.05	1.050	$69,174.00	$3,294.00	$34,269.10
						ERR	ERR	ERR	ERR
						ERR	ERR	ERR	ERR
						ERR	ERR	ERR	ERR
						ERR	ERR	ERR	ERR
						ERR	ERR	ERR	ERR
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						ERR	ERR	ERR	ERR
						ERR	ERR	ERR	ERR
						ERR	ERR	ERR	ERR

** Calculations based on Stephens-Martin Paving Company bid price.

Total Tons:	43580.40
Total Amount Due:	$1,163,430.11
Adjusted Pay:	$1,197,699.21
Bonus/Penalty:	$34,269.10
Average Pay Factor:	1.029

Sameh M. Zaghloul[1] and Nasser A. Saeed[2]

THE USE OF FALLING WEIGHT DEFLECTOMETER IN ASPHALT PAVEMENT CONSTRUCTION QUALITY CONTROL

REFERENCE: Zaghloul, S. M. and Saeed, N., **''The Use Of Falling Weight Deflectometer In Asphalt Pavement Construction Quality Control,''** Quality Management of Hot Mix Asphalt, ASTM STP 1299, Dale S. Decker, Ed., American Society for Testing and Materials, 1996.

ABSTRACT: Good quality control (QC) practices are essential to obtain satisfactory pavements. Typical QC tests for asphalt pavements include: asphalt content, mixture properties of laboratory samples, density, ..., etc. Results of these tests are used to ensure that the constructed pavements comply to specifications. However, quality of compliance to specifications and quality performance are two different things and are not always directly related to each other. The ultimate goal of QC is to have high quality of performance. However, efforts are made to achieve this goal by using laboratory based specifications, which are empirically related to field performance.

Current specifications are based on standard conditions which can be easily controlled in the laboratory but never exist in the field. Also, laboratory tests are run on samples representing individual layers (such as surface, base, etc.). In real life, a pavement structure performs as one unit and failure in one layer could happen because of another layer. Therefore, a performance-based specification that describes how a pavement must perform under the actual field conditions should be considered.

A study is underway in the Dubai Municipality (DM), U.A.E., to develop a procedure in which the falling weight deflectometer (FWD) is used to evaluate the in situ structural capacity of new pavements. FWD testing is conducted on each layer before constructing the next layer. Comparisons between the FWD test results and target deflection values are made to evaluate the construction quality of layers, as well as to identify weak spots. In this paper, the outline of this procedure is presented. Also, the results of a pilot study conducted to evaluate the procedure are presented.

INTRODUCTION

The strength of an asphalt pavement is the result of building up thick layers and, thereby, distributing the load over a large area of the subgrade. These layers interact together and behave as one system. A problem in one of the pavement layers affects the whole pavement system and may lead to a complete failure. Current QC/QA practices deal with the pavement layers on an individual basis and ignore the interaction between them. Also, it is always assumed that meeting the

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specification requirements will lead to a pavement that will perform satisfactorily over its design life. However, many pavements that satisfied the specification requirements prematurely failed.

Pavement performance has two components, functional and structural performance. Pavements could functionally fail (i.e. develop high surface roughness) or structurally fail (i.e. develop high deflection or structural related distresses). Smoothness acceptance testing is commonly performed on new pavements to ensure their functional performance over their design life. However, no deflection testing is performed on new pavements to ensure their structural performance.

Nondestructive testing (NDT) is commonly used to evaluate a pavement structural capacity. The falling weight deflectometer (FWD) is the most recent and popular device in this category of NDT. The FWD generates a loading cycle similar to that of a truck moving at a speed of 45 to 60 mph. Also, the FWD productivity is very high, which allows testing long pavement sections in a few hours.

EVALUATION OF THE IN SITU STRUCTURAL CAPACITY

The main objective of this procedure is to ensure that the new pavement under consideration has an acceptable structural capacity and the variation in its structural capacity is not significant. Fig. 1 shows the flow chart of the procedure. This procedure should be applied on each layer of the pavement structure, including the compacted subgrade. Construction of the next layer should not be started until the previous layer is checked and approved. The following are the main steps of the procedure:

1. Divide the pavement section under consideration into homogenous segments.
2. Test each segment with the FWD.
3. Determine the target deflection.
4. Conduct statistical analyses.
5. Repeat the FWD testing for the unsatisfactory segments.
6. Report any problems and investigate their possible causes.
7. Approve the satisfactory segments.

Sectionalization

Long pavement sections are divided into homogenous segments according to the following factors :

1. Traffic lanes
2. Construction day
3. Changing the construction equipment, such as using a heavier roller
4. Changing equipment operators
5. Changing source of materials

As an example, if the base course of a 2-lane pavement section is constructed in 2 days with the same construction equipment, operators and source of materials, then the pavement section can be divided into 4 homogenous segments as follows :

Segment #	1	2	3	4
Construction Day	1	1	2	2
Lane	1	2	1	2

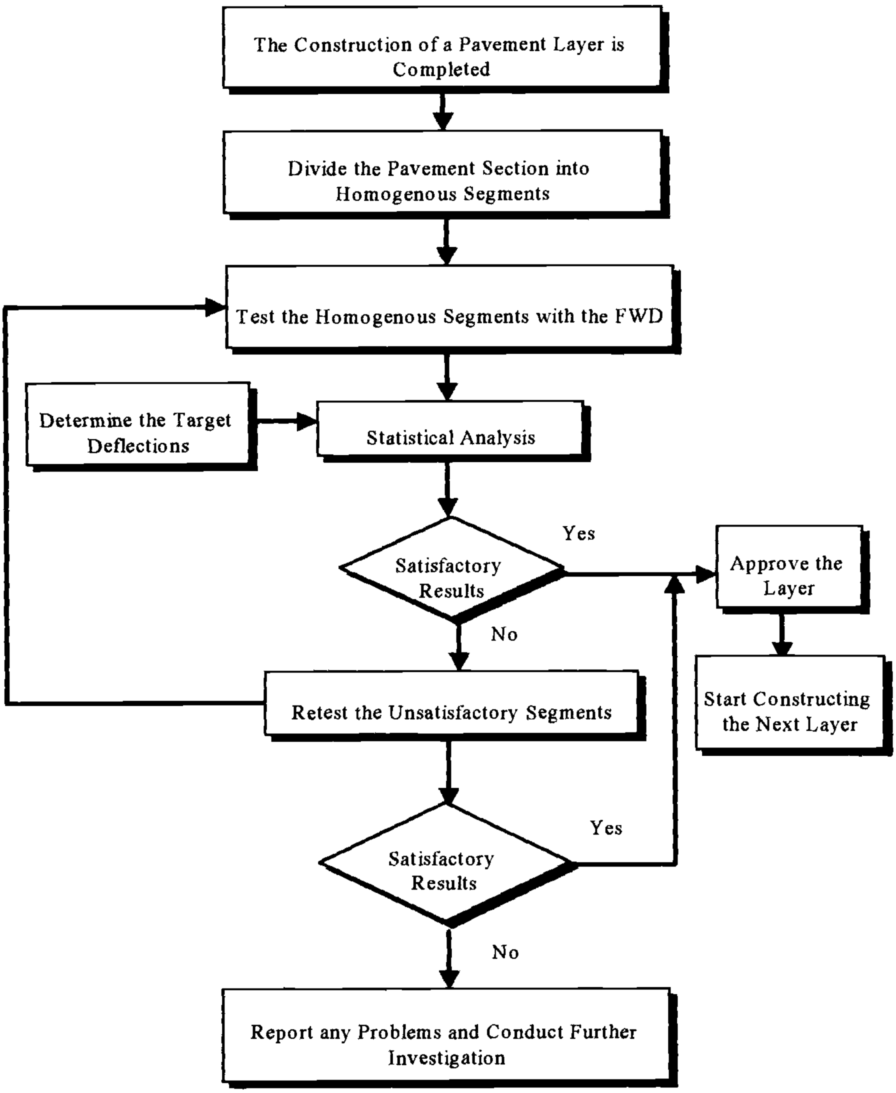

FIG. 1--Flow Chart of the Proposed Procedure.

FWD Testing

Tests are performed according to the ASTM D 4694 alternative procedure. In this procedure, three load drops are used. The result of the first drop are always rejected and the results of the last two drops are considered. The target load is recommended to be in the range of 45kn. However, for soft subgrades lower load levels can be used. Several geophones are used to measure the surface deflection at different offsets. However, only the readings of the first geophone (Do) located at the center of the load plate are considered in the analysis.

Because of the nondestructive nature of the FWD testing and because of its high productivity, tests are performed at short intervals (10 to 20 m). This frequency of testing allows an accurate evaluation of the in situ structural capacity. Test frequencies are selected based on the segment length. Efforts should be made to test as many points as possible to allow enough degrees of freedom for the statistical analysis.

Target Deflections

One important step in this procedure is to compare the measured deflections with target deflections. These target deflections are functions of thickness and material characteristics. Multi-layer analyses are commonly used to predict pavement deflection. These analyses assume static loading and linear elastic material properties. The FWD loading cycle is a dynamic loading cycle with a duration of 30 to 40 ms. Also, pavement materials and subgrades are not linear elastic material and their responses to static loads are different than dynamic loads. For example, asphalt mixtures are viscoelastic materials. The response of this type of material is highly dependent on loading time and rate of loading. The difference between the multi-layer analysis assumptions and the actual loading of the FWD and material conditions is significant [1]. Therefore, it is not recommended to use multi-layer analyses to predict the target deflections required for this procedure.

Two approaches are available to predict the target deflection: empirical measurements and three-dimensional, dynamic finite element analyses (3D-DFEA).

Empirical Approach

Field density tests are conducted routinely to ensure the in situ density of different layers. FWD tests can be performed at the locations which show acceptable density levels to determine the target deflections. Also, the specifications of some highway agencies require that trial sections be built to establish a relationship between the number of compaction passes and the resulting density, as well as to determine the target density of asphalt layers [2]. These trial sections can be tested to determine the target deflections.

Three-Dimensional Dynamic Finite Element Analysis (3D-DFEA)

The 3D-DFEA analysis has been previously used to conduct a non-linear dynamic analysis of FWD tests on asphalt pavements [1]. In this analysis, the FWD dynamic loading cycle was simulated and the actual material properties were considered. Results of the analysis show an excellent agreement between the measured and predicted deflection. Also, the same 3D-DFEA was verified in a number of studies [3, 4] using actual field measurements. Results of these verification studies show that there is no significant difference between the pavement response predicted using the 3D-DFEA and the measured response.

The 3D-DFEA can be used to predict target deflections, however, this type of analysis is quite complicated and required additional material testing to determine the required input parameters. Therefore, the empirical approach is used in this study to determine the required target deflections.

Statistical Analysis

Two types of statistical analyses are involved in the procedure:

1. Comparisons of two populations
2. Development of control charts

Comparisons of two populations

In this analysis piecewise comparisons are made between the deflection measurements of different segments, as well as between the deflection measurements of each segment and the target deflections. Hypotheses are made that:

$H_0 : \mu_1 - \mu_2 = 0$
$H_1 : \mu_1 - \mu_2 \neq 0$
or
$H_0 : \mu_1 - \mu_0 = 0$
$H_1 : \mu_1 - \mu_0 \neq 0$

Where μ_1 and μ_2 are the means of the peak deflections at the center of the FWD load plate (D0 measurements) of two pavement segments, while μ_0 is the mean of D0's of the target deflections. Assumptions are made that the two populations are normally distributed and the samples drawn from the two populations are independent random samples [5]. The purpose of the first test is to evaluate the construction quality and to determine the effect of changes in the process, while the purpose of the second test is to accept or reject the segment.

Development of Control Charts

Control charts for the process mean can be very helpful in detecting when a change in a process occurs that may require managerial action. For example, if the roller has been changed during the construction of a layer and this layer shows significantly higher deflections, then more passes of the roller may be required. Two methods are used to develop control charts:

1. Using the mean of the target deflection population (μ_0) and its standard deviation (σ_o). In this case, the upper and lower acceptance limits (UAL and LAL) are :

$$UAL = \mu_0 + n\sigma_0$$
$$LAL = \mu_0 - n\sigma_0$$

2. Set the UAL and LAL to the range of the target deflection population.

Both approaches are statistically valid and the selection between them is made based on the size of the sample drawn from the target deflection population [4].

APPLICATION OF THE PROPOSED PROCEDURE

A pilot study was conducted to evaluate the proposed procedure. In this study, three highways under construction (H_1, H_2, and H_3) were considered.

H1 Road

H1 Road is a 5-km, dual 4-lane rural road. The pavement structure of this road, as shown in Fig. 2.

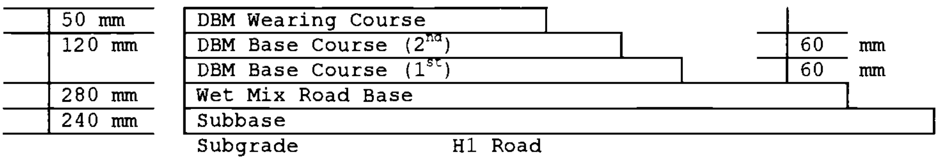

FIG. 2--Pavement Structures of H1 Road.

At the time of the study, the subbase and wetmix layers were completed for the whole project length. Also, a few hundred meters of the DBM layers and the wearing surface had been constructed. The finished surfaces of the wetmix layer, the DBM layers and the wearing surface layer were available for testing. A full-width section of each layer (total of four sections) was selected and included in the pilot study. The section length varied from 200 to 450 m depending on the length ready for testing. Each of these sections was further sectionalized according to the criteria mentioned earlier. FWD tests were performed on each segment at 10 - 20 m intervals. Locations of density tests conducted on each layer were tested with the FWD to determine the target deflections of each layer. Results of these tests are shown in Figs. 3 to 6.

Three statistical tests were conducted on the measured deflections of each layer: a comparison between Segments 1 and 2 (Lanes 1 and 2) deflections, a comparison between Segment 1 deflections and the target deflections, and a comparison between Segment 2 deflections and the target deflections. Results of these tests are summarized and shown in Table 1. The following can be concluded from Table 1 :

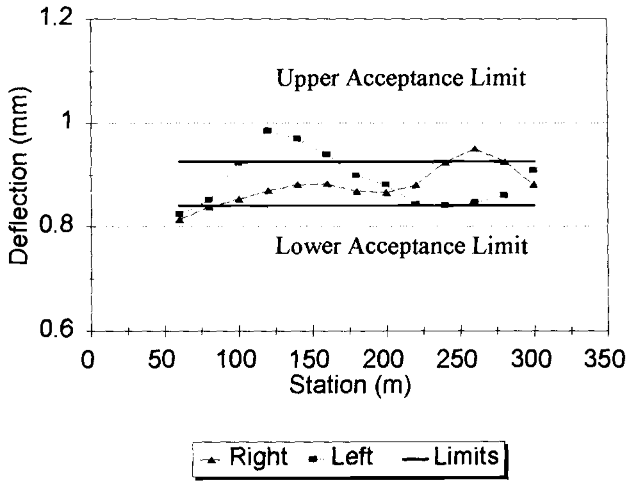

Fig. 3--Wetmix Layer (H1 Road).

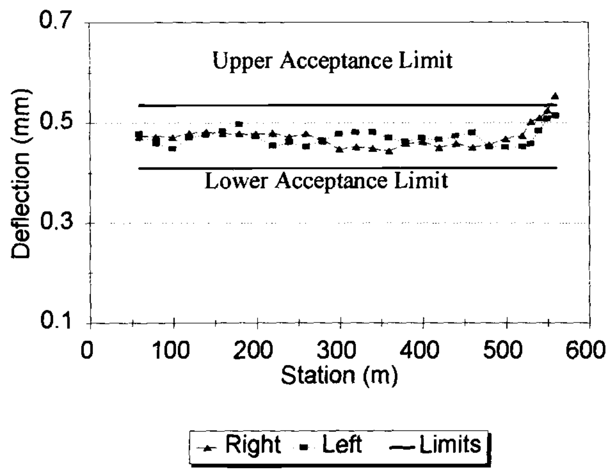

Fig. 4--First DBM Layer (H1 Road).

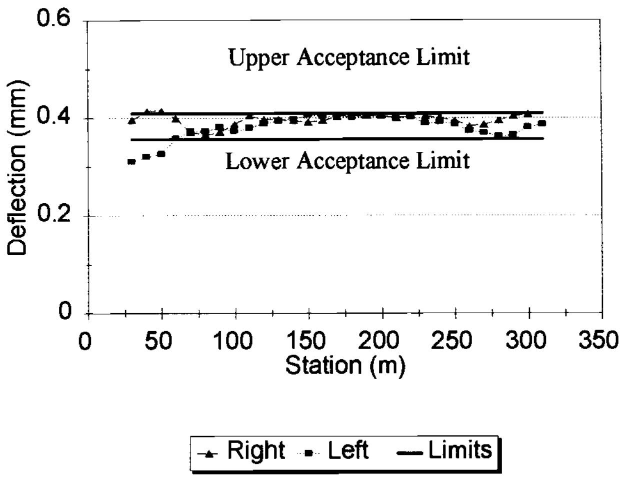

Fig. 5--Second DBM Layer (H1 Road).

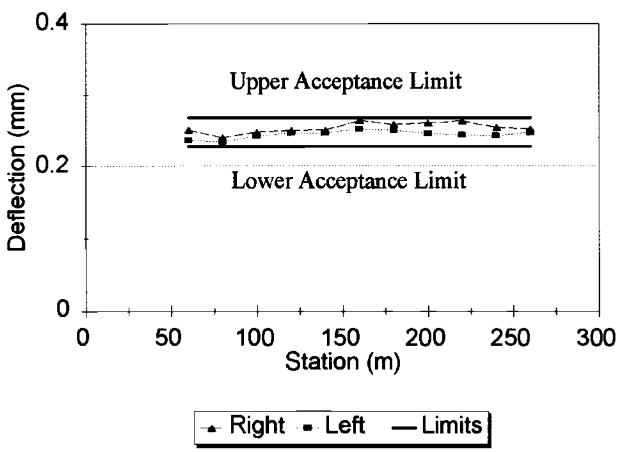

Fig. 6--Surface Layer (H1 Road).

Table 1– Results of the Statistical Tests of Road H1.

Case	Road	Layer	Mean 1	Mean 2	n1	n2	Sigma	Sigma	Decision*
S1 vs S2	H1	Wetmix	0.8641	0.8860	16	12	0.0726	0.0889	Acceptable
S1 vs Target	H1	Wetmix	0.8641	0.8827	12	16	0.0726	0.0142	Acceptable
S2 vs Target	H1	Wetmix	0.8827	0.8860	31	31	0.0142	0.0889	Acceptable
S1 vs S2	H1	Base (1)	0.4788	0.4752	31	13	0.0378	0.0339	Acceptable
S1 vs Target	H1	Base (1)	0.4788	0.4774	13	31	0.0378	0.0483	Acceptable
S2 vs Target	H1	Base (1)	0.4774	0.4752	31	31	0.0483	0.0339	Acceptable
S1 vs S2	H1	Base (2)	0.3954	0.3772	15	32	0.0260	0.0337	N/A
S1 vs Target	H1	Base (2)	0.3967	0.3772	31	15	0.0049	0.0337	Acceptable
S2 vs Target	H1	Base (2)	0.3954	0.3967	32	23	0.0260	0.0049	Acceptable
S1 vs S2	H1	Surface	0.2533	0.2443	32	13	0.0146	0.0113	Acceptable
S1 vs Target	H1	Surface	0.2533	0.2490	13	23	0.0146	0.0086	Acceptable
S2 vs Target	H1	Surface	0.2490	0.2443	23	13	0.0086	0.0113	Acceptable
S1 vs S2**	H1	Base (1)	0.5507	0.5298	31	13	0.0389	0.0391	N/A
S1 vs Target**	H1	Base (1)	0.5507	0.5411	13	31	0.0389	0.0133	Acceptable
S2 vs Target**	H1	Base (1)	0.5298	0.5411	31	32	0.0391	0.0133	Acceptable

*Based on 95% confidence level

** The same section of the wetmix layer

Deflections are in mm's

1. **Wetmix Layer, First DBM Layer and Wearing Surface:** There is no significant difference between Segments 1 and 2 (i.e., good construction quality control). Also, there are no significant differences between the target deflections and those of Segments 1 and 2 (i.e., segments are acceptable).

2. **Second DBM Layer:** There is a significant difference between Segments 1 and 2 (poor construction quality control). However, both segments are acceptable. Tests were repeated for these segments and the same results were obtained. Investigations were made to find out the possible reasons for the significant difference between Segments 1 and 2. It was found that the first stretch (50 m) of Segment 1 was over compacted, while the corresponding stretch of Segment 2 was under compacted, as can be seen from Fig. 5. When the deflection measurements of these stretches were excluded, the difference between Segments 1 and 2 became insignificant. The over and under compaction problems were reported to the project engineer and the proper action was taken. More compaction was applied on the under compacted stretch, while the over-compacted stretch was removed and replaced. It should be noted that both segments satisfied the project technical specification, which requires QC tests to be conducted every 200 m. It was found that no QC tests were conducted on these 50-m stretches.

Control charts are developed for each layer and shown in Figs. 3 to 6. The following can be concluded from these figures:

1. **Wetmix Layer**: Some high deflection spots (weak spots) are found on both segments of the wetmix layer (Fig. 3). More compaction was applied on the wetmix layer before constructing the next layer (the first DBM layer). Recall Table 1; no significant differences between the target deflections and those of Segments 1 and 2 are found, even with these high deflection spots. This happened because the low deflection spots exist toward the end of the segment (Fig. 3).

2. **First DBM Layer**: None of the first DBM layer segments have outliers, except the last part of the segments. The reason for the increased deflection at the end of the segments is related to the existence of a construction joint.

3. **Second DBM Layer**: Other than the first 50 m stretches, no outliers are found (Fig. 5).

4. **Wearing Surface**: No outliers are found (Fig. 6).

Another round of FWD testing was performed on the first DBM layer constructed on the wetmix segments. Results of this testing are shown in Fig. 7. As can be seen from this figure, both segments are marginally acceptable. A comparison between Figs. 3 and 7 shows that the deflection lines of the first DBM layer follow the same trend of the deflection lines of the wet mix layer. This finding highlights the importance of repairing each layer before constructing the next layer. Statistical tests were conducted on the segments of this DBM layer. A significant difference is found between the deflections of Segments 1 and 2 (i.e., poor construction quality control). However, both segments are acceptable.

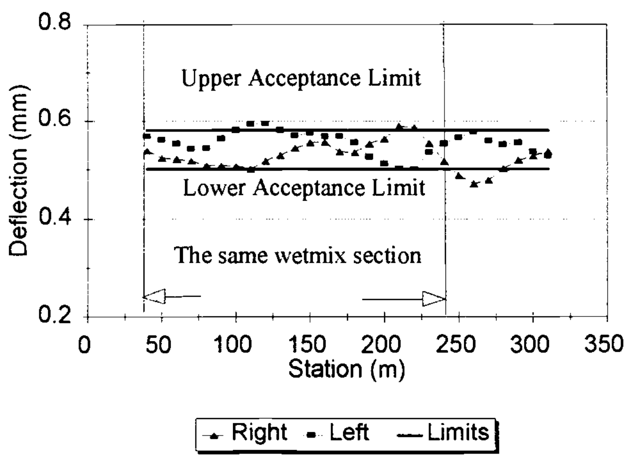

Fig. 7--First DBM Layer (H1 Road).

H2 Road

H2 Road is a 3-km, single 2-lane urban road. The pavement structure of the road, as shown in Fig. 8.

50 mm	Wearing Course
150 mm	Aggregate Roadbase
300 mm	Subbase
	Subgrade H2 Road

FIG. 8--Pavement Structures of H2 Road.

At the time of this study, the subbase layer was completed for the whole project length. Also, a few hundred meters of the aggregate road base and the wearing surface layers had been constructed. The finished surfaces of the subbases, base course and wearing surface were available for testing. A full width, 200-m section of each layer (total of three sections) was selected and included in the pilot study. Sections were further sectionalized according to the criteria mentioned earlier. FWD tests were performed on each segment at 10- to 20-m intervals. Also, the density test locations were tested to determine the target deflections. Results of the FWD tests are shown in Figs. 9 to 11. Also, the upper and lower acceptance limits are shown in the same figures. Results of the statistical tests performed on the measured deflections of each layer are shown in Table 2. It was found that:

1. A large area of the subbase layer has deflection values higher than the upper acceptance limit (weak spots). The FWD test was repeated for this area and the same results were obtained. Therefore, the Project Engineer was notified about the problem and more compaction was applied on this area.
2. No significant differences between segments were found in any of the layers, i.e., good construction quality control and acceptable layers.
3. No outliers were found in any of the layers. Therefore, all layers were approved.

H3 Road

H3 Road is a 8-km, single 2-lane rural road located in an industrial area. The pavement structure of the road, as shown in Fig. 12. At the time of this study, the compaction of the subgrade was completed for the whole project length and 30% of the subbase layer had been constructed. Two, 250-m sections were selected and included in the pilot study. The procedure applied on H1 and H2 Roads was followed for this road. Results of the deflection measurements are shown in Figs. 13 and 14, while the results of the statistical tests are shown in Table 3. It was found that:

1. Most of the subbase layer deflections are within the acceptance limits.
2. The first 100-m stretch of the right lane of the subgrade requires more compaction. The FWD test for this area was repeated and

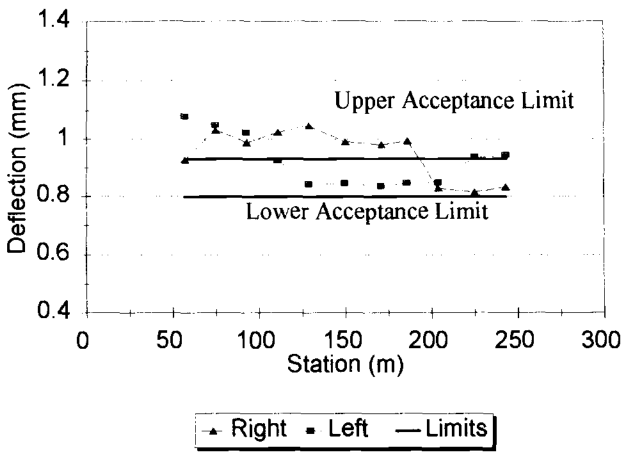

Fig. 9--Subbase Layer (H2 Road).

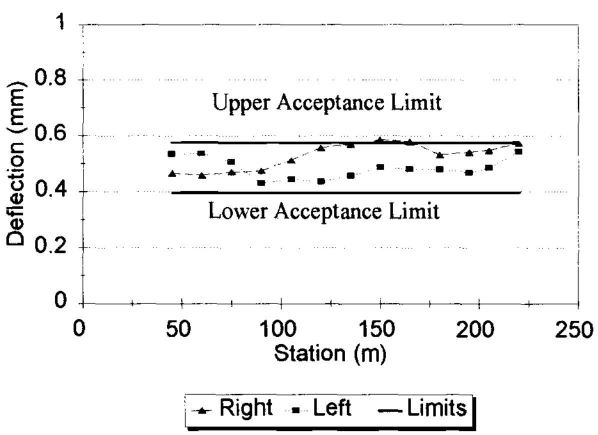

Fig. 10--Base Course Layer (H2 Road).

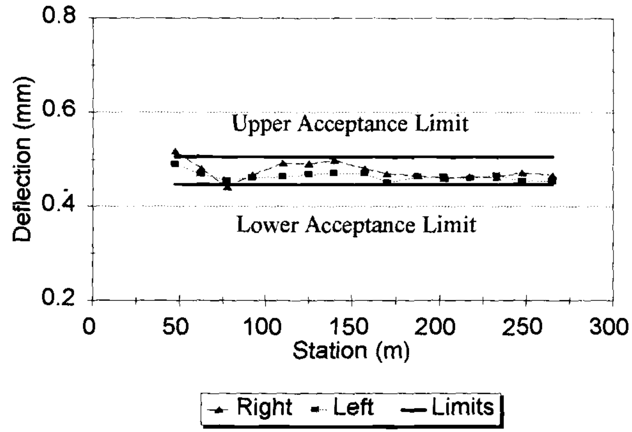

Fig. 11--Surface Layer (H2 Road).

Table 2-- Results of the Statistical Tests of Road H2.

Case	Road	Layer	Mean 1	Mean 2	n1	n2	Sigma	Sigma	Decision*
S1 vs S2	H2	S.base	0.9299	0.9332	14	14	0.1680	0.1705	Acceptable
S1 vs Target	H2	S.base	0.9299	0.8418	14	7	0.1680	0.0522	Acceptable
S2 vs Target	H2	S.base	0.9332	0.8418	14	7	0.1705	0.0522	Acceptable
S1 vs S2	H2	Base	0.5325	0.5003	16	16	0.0778	0.0801	Acceptable
S1 vs Target	H2	Base	0.5325	0.5098	16	8	0.0778	0.0939	Acceptable
S2 vs Target	H2	Base	0.5003	0.5098	16	8	0.0801	0.0939	Acceptable
S1 vs S2	H2	Surface	0.4838	0.4659	18	18	0.0561	0.0253	Acceptable
S1 vs Target	H2	Surface	0.4838	0.4722	18	8	0.0561	0.0208	Acceptable
S2 vs Target	H2	Surface	0.4722	0.4659	8	18	0.0208	0.0253	Acceptable

* Based on 95% confidence level
Deflections are in mm's

the same results were obtained. Therefore, the Project Engineer was notified.

50 mm	DBM Wearing Course
80 mm	DBM Base Course
250 mm	Wet Mix Road Base
300 mm	Improved Subgrade

Subbase H3 Road

FIG. 12--Pavement Structures of H3 Road.

Table 3- Results of the Statistical Tests of Road H3.

Case	Road	Layer	Mean 1	Mean 2	n1	n2	Sigma	Sigma	Decision*
S1 vs S2	H3	S.grade	1.3614	1.2024	19	28	0.5052	0.1990	Acceptable
S1 vs Target	H3	S.grade	1.3614	1.2046	19	15	0.5052	0.1030	Acceptable
S2 vs Target	H3	S.grade	1.2024	1.2046	28	15	0.1990	0.1030	Acceptable
S1 vs S2	H3	S.base	1.0903	1.0384	33	31	0.1651	0.2037	Acceptable
S1 vs Target	H3	S.base	1.0903	0.9934	33	16	0.1651	0.2400	Acceptable
S2 vs Target	H3	Subbas	1.0384	0.9934	31	16	0.2037	0.2400	Acceptable

Based on 95% confidence level
Deflections are in mm's

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A procedure was developed to evaluate the in situ structural capacity of new pavements using the FWD. In this procedure, long pavement sections were divided into homogenous segments. FWD tests were conducted on each layer of the segments at 10- to 20-m intervals. Statistical tests were conducted on the measured deflections to evaluate the construction quality, as well as to identify weak spots. A pilot study was conducted on three roads. Results of this study show that:

1. The deflection of a layer is highly dependent on the deflection of the previous layer. Therefore, it is very important to repair any weak spots before constructing the next layer.

2. The current QC testing is conducted at long intervals (e.g. 200 m) which makes it unable to identify problems between the testing points.

3. The proposed procedure is fast and easy to implement. Most of the segments were tested in less than an hour.

Advantages of using the Procedure :

1. FWD testing is nondestructive and simulates moving truck loads.

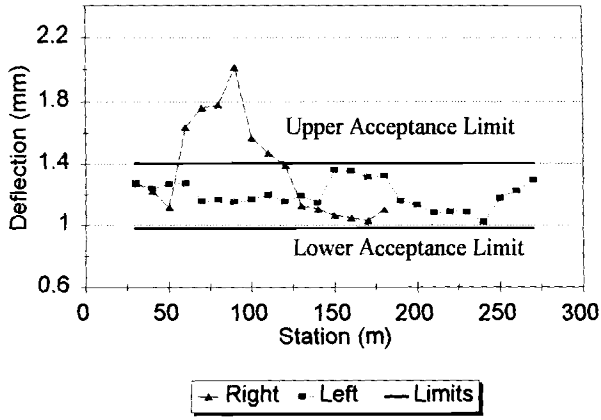

Fig. 13--Compacted Subgrade (H3 Road).

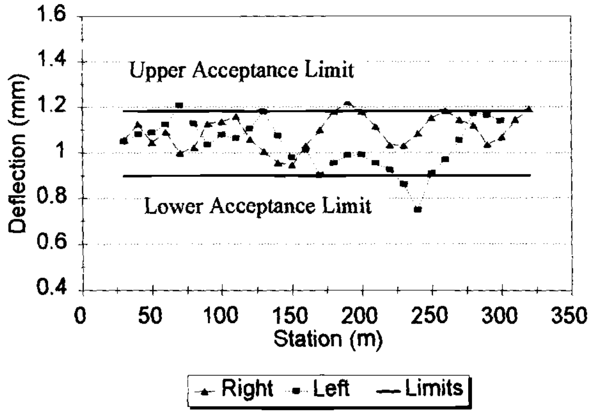

Fig. 14--Subbase Layer (H3 Road).

2. Pavements are tested under the actual field conditions. Sample, size, shape, boundary conditions, etc. have no effect on the results.

3. A pavement is tested as one unit and the actual interaction among layers is considered.

4. Testing each layer will make it possible to identify weak spots early and repair them before constructing the following layer.

5. FWD testing will provide a continuous profile of the pavement structure.

6. Savings in the QC cost could be made by eliminating some of the current laboratory tests. Also, savings in maintenance and rehabilitation costs could be made by identifying weak spots in each layer and repairing them immediately.

7. The performance of pavements can be easily and accurately monitored by conducting FWD tests regularly and comparing the results with the as-built deflections.

8. A computer program will be developed to implement this procedure. Results of the analysis will be obtained a few minutes after completing the FWD testing.

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QUALITY MANAGEMENT IN ASPHALT PAVEMENT CONSTRUCTION

REFERENCE: Davis, R. L., **"Quality Management in Asphalt Pavement Construction,"** Quality Management of Hot Mix Asphalt, ASTM STP 1299, Dale S. Decker, Ed., American Society for Testing and Materials, 1996.

ABSTRACT: The concept of identifying and controlling the processes that are essential to quality is at the heart of Total Quality Management (TQM) The best path to quality lies in making the product right the first time. Not by sorting out and rejecting the bad, but by reducing the bad by concentrating on the control of the core process where quality is obtained at minimum cost to both the buyer and the seller. The buyer is not protected from loss by inspection and rejection. In the long run he pays for the bad material as well as the good for he has to pay for the entire cost of manufacture. There will be no suppliers or contractors if there is no profit. The cooperation of buyer and seller in the control of the process has been shown to be the optimum method of realizing the benefits of TQM in numerous instances in the revolution in quality in the private sector. While there has been much enthusiasm for Quality, Quality Assurance, and even for Total Quality Management in the construction field, the changes necessary to achieve real progress are so difficult that most transportation agencies will not even give serious consideration to them. Transportation agencies are not faced with decisions that mean life or death to their organizations that is part of everyday life in the private sector and can afford a more relaxed attitude toward their problems. The benefits and cost reductions which have been shown to follow the introduction of Total Quality Management in the private sector should be an incentive to transportation agencies to undertake the difficult organizational changes required to realize TQM.

KEYWORDS: quality, management, total quality management, customer satisfaction, statistical probability, statistical methods, precision, testing, sampling, acceptance, top management leadership, continual improvement, knowledge, research, cooperation, teamwork, process control, training, benchmarking, strategic planning, profitability, reduced costs.

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QUALITY

Quality as used in this paper has a special meaning that is not ordinarily found in most dictionaries. For instance, the American Heritage Dictionary gives a number of definitions for quality. Among these are "The essential character of something" and "Degree or grade of excellence" which are related to the meaning of quality as used in this paper, but a clearer definition of quality as used in this paper would refer to the degree or grade of excellence of customer satisfaction. This paper is an attempt to explain what constitutes quality, what are the best tools for obtaining quality, and how they relate to the quality of asphalt pavement construction. The goal of quality management is to increase the level of satisfaction of all people. This has been a primary goal of human beings since the dawn of history, and therefore is of fundamental importance.

QUALITY THROUGHOUT HISTORY

Recognition of the importance of quality goes back to ancient times. A big improvement in quality was realized when prehistoric man began to exchange products instead of attempting to produce all of his family's needs himself. This specialization allowed those who were especially good at producing a given product to devote their full time to producing it and to becoming expert in producing a better product.. In the 13th and 14th centuries craft gilds or guilds had as one of their principle objectives the improvement of quality.The craftsman of this period was able to charge a higher price if he had a reputation for supplying a better more satisfying product. Therefore, it was important that each craftsman maintain his reputation for quality so he could justify a higher price and profit than his competitors through the greater satisfaction of his customers. So superior were the violins of the Italian violin maker, Stradivarius (1644-1737) that they still bring the highest prices in today's market. Then as now, increased customer satisfaction is probably the soundest basis for increased prices and profits.

KNOWLEDGE

Knowledge has always been a cornerstone in the attainment of quality. It is the heart of improved quality. Quality does not stand still. It must be continually improved or it fades away over time. Without continuing increase in knowledge, quality is lost. Continual improvement and increasing knowledge are essentials of the quality process. Such improvement and increase in knowledge is usually termed research and effective research is an important part of the quality effort. Many people have lost faith in the rewards of research since it has often been poorly directed. There is nothing automatic about reaping the benefits of research through investment in laboratories and scientific personnel. For research to yield its optimum value it must have wise and inspiring leadership and the fruits of innovation must be utilized in as short a time as is possible in order to ensure maximum profitability. The true benefit of research is lost if it is not implemented quickly.

TOTAL QUALITY MANAGEMENT

In recent years there has been increasing recognition of the importance of quality in coping with competition in both domestic and international markets. A number of plans and programs have been put forward to aid manufacturers in instituting a quality program. The Total Quality Management (TQM) concept has received increasing recognition as the key to U. S. industry's ability to compete in the world of the 1990's. At the heart of this concept is the idea of maximizing customer satisfaction with increasing awareness of the many customers that each of us has. Every stage in a manufacturing or service organization has both internal and external suppliers and customers. Minimizing fear and increasing trust, understanding and teamwork among those engaged in a project is basic to the process of assuring quality. Total is supposed to denote an understanding of the importance of a complete devotion of everyone in an organization to the improvement of quality.

The following six key elements of TQM help to form a suitable definition in the view of the author.

1. The maximum progress in quality comes from the identification, improvement, and control of those processes which are essential in producing the desired product.

2. Statistical analysis is necessary in achieving true TQM.

3. Continual and never ending improvement in quality is a critical part of TQM. This is efficient research.

4. Top management must recognize that TQM is of fundamental importance and that they must be actively involved in it if maximum profitability or efficiency is to be achieved.

5. Teamwork and cooperation for quality of all involved in producing a product is important to achieving TQM.

6. The customer is the sole and final arbiter of what constitutes quality and it is important to recognize the importance of customers inside the organization as well as those outside. Customer satisfaction is the ultimate goal of TQM since customer satisfaction maximizes profitability.

To give an idea of what TQM ordinarily encompasses some important characteristic terms are listed below

CUSTOMER SATISFACTION

EFFICIENT RESEARCH

STATISTICAL ANALYSIS

SAMPLING AND TESTING

REDUCED COSTS

INCREASED PROFITABILITY

TOP MANAGEMENT LEADERSHIP

EMPLOYEE INVOLVEMENT

PROCESS CONTROL

NEVER ENDING IMPROVEMENT

CONTINUAL TRAINING

BENCHMARKING

STRATEGIC PLANNING

All of these terms are essential to TQM. Their position on the list should not be taken as an indication of their relative importance.

STATISTICAL ANALYSIS

While most of the terms are self-explanatory, some people find it hard to understand why statistical analysis is important to TQM. This is because many people think of statistical analysis and the calculus of probability as being abstract and removed from practical problem solving. The origin of the calculus of probability was due to an eminently practical effort to bet on dice so as to ensure winning in the long run. The French mathematician, Pascal was consulted by a gambler as to how he should bet in order to maximize his winnings. Out of Pascal's studies came the calculus of probability and later statistical analysis. Large gambling casinos such as those at Monte Carlo, Atlantic City, and Las Vegas are monuments to the correctness of the calculus of probability and statistical analysis. The accumulation of money is often considered to be the best evidence of practical wisdom. Not only are the gambling casinos evidence of this practical wisdom, but also many other major business enterprises such as insurance companies and banks which use statistical methods to estimate their risks.

STATISTICAL ANALYSIS IN INDUSTRY

The early introduction of statistical methods into industrial quality control is associated with Walter A. Shewhart, G. D. Edwards. Howard Dodge, and W. Edwards Deming, all of the Bell Telephone Laboratories. The great improvement in industrial quality due to these gentlemen came about through their introduction of statistical analysis into the control of quality which enabled the separation and evaluation of the factors which make up the total variation of the quality measurement process. The numerical basis for this variation is usually measured in terms of test results from a test method. While a numerical result is not always required for a statistical analysis, the analysis is enhanced if the test method results are in terms of numbers. As Lord Kelvin is quoted as saying; "When you can measure what you are speaking about and express it in numbers you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind".

In many instances in the highway industry it has been difficult to get a numerical answer of any kind. Numerical thinking is not only desirable but is convincing. It has led highway engineers to go to great lengths to get numerical answers. While such efforts fill us with admiration, we must realize that in some instances the numerical answers are so imprecise that they are more misleading than helpful. It is important that we not only get numerical answers but also determine their validity and precision.

Statistical analysis of numerical data makes it possible to separate the total variation into variation due to a number of factors. Learning the major sources of variation is a great aid in analyzing and reducing the total variation. It is important to recognize that every process has a large number of sources of variation. This means that most of them are small relative to the total variation. Reduction of the effects of one of the small sources of variation may be as expensive and difficult as reduction of one of the major sources of variation. Reduction of one of the minor sources may not result in any discernible improvement in the process while reduction of a major source will result in an important advance in quality. It should be noted that a source of variation is never eliminated, merely reduced, and the essence of effective quality improvement is determining the major sources of variation and reducing their size.

TEST METHOD PRECISION

Statistical analysis has helped to measure the variation in test results due to the test method itself. If the imprecision of a test method is large, it can be useless in the determination of the properties of a material. The world in which we live is extremely complex. Most of us realize that we can not cope with every detail of our complicated environment so we resort to simplifications by ignoring many details. Theories usually do not attempt to explain everything, but restrict themselves to the explanation of the more important or central principles of a process. Engineers recognize, when closely questioned, that the numerical results from the testing process will vary when the test procedure is repeated with test specimens as nearly identical as they can be made They usually prefer to treat this variation as small enough to be neglected. In the highway field we have many test methods whose precision is such that this comfortable practice results in serious errors. It is important that highway engineers recognize the necessity of the careful evaluation of test method variation and the high cost of ignoring it.

HISTORY'S WARNING ABOUT TEST PRECISION

Knowledge of the existence of testing error goes back to ancient times. Aristotle warned that there was always error in information that was obtained through the physical senses. These warnings were taken so seriously that for almost 1500 years philosophers made little use of physical measurements. Galileo and Bacon founded scientific methods when they started using physical observations to develop theory and then refined the theory by comparing it with additional physical observations. The success of the use of the scientific method in solving mankind's problems has led to well earned respect, but this does not change the validity of Aristotle's warning. All physical measurements do have error and until we have some estimate of the size of this error we cannot make effective use of a test method since the variation in test results may be due more to the test method rather than any real change in properties of a material.

FOR EXAMPLE

An example may help to clarify the fundamental importance of test method precision and the great complexity of the measuring process. The determination of asphalt content in mixtures has been a fundamental paving measurement since the earliest pavements were laid. The solvent extraction test has been used since the very beginning of construction involving the asphalt binder. Fifty years ago it was shown that the test method was capable of measuring the amount of asphalt in a test portion of asphalt concrete with good precision. However, it was also shown that the amount of asphalt in a test portion could vary widely due to the distribution of the aggregate.

This variation is easily illustrated by taking a sample portion of well mixed HMA with a top size aggregate of 0.04 m (1 1/2 in.) and separating out the aggregate retained on the 0.025 m (1 in.) sieve and determining the asphalt content by means of the extraction test. Separating out the HMA passing the 0.006 m (1/4 in.) sieve from this same sample and comparing that asphalt content with that obtained by running an extraction test on this finer test portion. The asphalt content of the large aggregate extraction typically might run about 2 % while the asphalt content of the fine aggregate would be much higher say about 6.5 %. It is apparent that if an extra piece or two of large aggregate gets into the sample portion the asphalt content will be low while if by chance there are fewer pieces of large aggregate than usual in the test portion the asphalt content will be high. It is evident that we can have large variations in measured asphalt content that are independent of the percentage asphalt put into the mix.

This is true even if both portions are taken from the same well-mixed batch. There is nothing mysterious about this, since the asphalt is a surface coating on the aggregate and the surface area divided by the volume becomes higher as the size of the aggregate becomes smaller. This leads to a higher asphalt content for fine aggregate than coarse aggregate which means that if the size of the test portion is small in relation to the size of the largest pieces of aggregate the asphalt content can fluctuate considerably from test portion to test portion within the same batch of HMA. The test method precision can be very poor if proper attention is not given to ensuring that a large enough test portion exists to reduce the variation due to the large pieces of aggregate.

Since early rock asphalt deposits consisted of mostly fine aggregate mixes and therefore, early pavements were also fine aggregate mixes, early test methods tended to have test portions too small to measure the asphalt content of mixes containing stone with the proper precision. Large test portions increase the cost of the testing program so there is continuing incentive to keep the test portions small. Much of the equipment is not designed to cope with test portions large enough to accurately measure asphalt contents where large aggregate is present and many agencies do not want to test portions that are of sufficient size because of the increased cost for equipment, materials, and health considerations. The author has found that a good rule of thumb for the solvent extraction test is that a test portion should be at least 125 times larger than its largest pieces of aggregate to maintain good test precision.

The futility of trying to evaluate the quality of HMA with test methods of poor precision should be emphasized at this point. Not only is much money wasted in operating an inefficient sampling and testing process, but much more money is wasted in rejecting good pavement and accepting bad pavement. Statistical analysis clearly shows the inefficiency of the solvent extraction test where test method precision is not properly maintained as it would for any other method that did not have the proper precision. TQM would emphasize the importance of teamwork and cooperation between buyer and seller in controlling the key process, the paving plant. Only the paving plant can produce a quality pavement and control of the paving plant is obviously the primary goal of insuring pavement quality. A system of testing and rejection, or of testing and penalties, has as its primary goal to provide incentive to the seller to control the hot plant. It has been demonstrated many times in private industry that the system of testing and rejection is inefficient where key processes are concerned and an attempt will be made in this paper to show the superiority of more direct methods after some discussion of how we have gotten to where we are.

TRADITIONAL HIGHWAY PRACTICES

The traditional approach of many highway departments has been to test or inspect the finished highway. When the author first started work in the highway field many, many years ago, it was explained to him that the test results for highway test methods had absolutely no error in them. This was especially true if the testing was done in the Central Laboratory. Other laboratories might make mistakes, but not the Central Laboratory. These test results could be calculated out to any number of decimal places and be absolutely correct. In addition, it was thought that the sample was entirely representative of the materials from which it was sampled.

These comfortable assumptions made it quite easy to make decisions involving the quality of highway materials. They served as a reasonable basis for completely rejecting material or pavement since it was certain that out of specification material had been produced and the highway department had no obligation to pay for such material. The contractor was responsible for all costs involved in bringing the roadway up to specification requirements so there was no cost to the highway department in the rejection of pavement or materials. Exceptions were sometimes made if the point was brought up that humans are prone to error, and maybe the operator had not performed the test method correctly. In such cases, it was thought to be proper to make another determination to find out if an error had been made. If the next test result was inside the specifications, the first value was dubbed erroneous and completely forgotten. If the second value was outside the specifications and if the contractor was a "good guy" who had a reputation for doing good work or if he was a "bad guy" who screamed bloody murder, another sample was obtained. The end result was that in many highway departments it was, indeed, a rare event for any material to be declared outside the specification limits.

The result in far too many agencies was that the testing procedure had little or nothing to do with the quality of the finished road. Most contractors realized that the highway department was merely paying "lip service" to quality since no bad material was eliminated by it and little effort went into ensuring the production of good material..

At the heart of this problem were several misconceptions, one was that the supplier or contractor paid for all rejected material so the highway department paid nothing. Another was that the test method was always precise so a clean separation between good and bad could always be made. A third was that the test sample was absolutely representative of the material being tested, and a fourth was that all test methods measured properties that were important to the quality of the pavement. Suppliers and contractors are seldom in business for philanthropic reasons so if their business does not yield a profit including rejected material, they do not remain in business. Of course, some contractors who are unable to produce quality material may be eliminated from competition for contracts at little cost to the buyer through vigilant scrutiny of the product which he produces. The buyer should not lose sight in this process of the importance of retaining as many good bidders as possible. The buyer can rest assured that he is paying for nearly all material produced in the long run and he has an important interest in reducing rejected material to a minimum. In other words, to see that it is made right the first time.

The author was consultant to a major highway department over thirty years ago. In summing up his analysis of the department's material acceptance program to the state materials and testing engineer he pointed out that due to such practices as cited above that there was little relationship between the laboratory's test results and the quality of the pavement in the state. This did not seem to bother the state materials and testing engineer very much as he pointed out that it was very comforting to him to have row on row of file cabinets of test results to show those who complained about pavements in the state. These test results were convincing evidence of the department's diligence in protecting the tax payer from inferior roads. When the engineer could show test results from the very pavement from which the complaints arose, it had a very beneficial effect on the governor or legislative delegation who was making the inquiry. His statement made it clear to the author that state highway testing programs have other purposes than the control of quality.

While recognizing that the traditional highway acceptance program has a multiplicity of uses and that past approaches cannot be set aside overnight, let's take a look at a program designed to achieve the highest quality at the lowest cost, a TQM program. TQM emphasizes the importance of building a pavement "Right the First Time" rather than trying to inspect or to test it right. A concentrated, well managed effort in process improvement should result in a continuing improvement in the end product. Certainly, the author found this to be the cost effective way to assure quality many years before he ever heard of TQM. In contrast, the inspecting and testing program took attention away from the primary task of making a good product and directed attention to evaluating the end product. Even though this is usually a very expensive process, it would be much easier to justify if there were little or no error in the test methods used. Since many of the prominent highway test methods are known to have sizable errors (poor precision), it is inevitable that there will be increased costs due to rejecting good and accepting bad product which may dwarf the costs of the testing process. The traditional highway acceptance program was a very expensive and ineffective method of assuring quality.

MORE ABOUT TQM

Early in his career as a chemical engineer, the author worked with a variety of different processes to maximize the quality of production and he had complete freedom to employ any method he chose to obtain maximum quality levels. Many approaches were tried. One of the things that became quite clear in these efforts is that it is much more cost efficient to build quality into a product during the manufacturing process than it is to try to inspect or test quality into it through reworking or rejection of bad production. On entering the highway field the author could not help but marvel at the high costs and inefficiencies of the acceptance program. It was evident that the acceptance program was so intertwined with traditional and legal principles to the point where, even with the best intentions, the quality of product was practically lost. Highway authorities, who have not already done so, should examine their acceptance practices with the intent of making them more efficient and economical. While Total in TQM emphasizes the complete dedication to the assurance of quality at the lowest possible cost, it includes increased knowledge gained from a number of old familiar statistical techniques, such as, the analysis of variance, the design of experiments and statistical quality control. Knowledge has always been a cornerstone in the attainment of quality. It is the heart of TQM.

We have stated that customer satisfaction is the central point to TQM, but let's explore customer satisfaction in a little more depth. While higher prices and profits bring increased incentives to the manufacturer, higher prices do not bring increased satisfaction to most customers. The manufacturer may earn higher prices through the increased satisfaction which he brings to the customer, but the customer would get even greater satisfaction if he could get the same product at a lower price. Lower price contributes to a buyer's satisfaction and therefore, contrary to traditional thought, increases quality, since quality is measured by the degree of customer satisfaction. A product of the highest quality brings little satisfaction to those who can not afford it. The manufacturer can be trusted to keep his price high enough to ensure his own satisfaction and if his return on investment does not satisfy him he can get out of the business of producing HMA. The buying agency is usually aware of the importance of competition in reducing construction costs, but it sometimes loses sight of the importance of using precise test methods and a fair evaluation system in attracting more bidders to the bidding process, which would lower their costs.

One of the major tenets of TQM is that it is better to build quality into a product or service rather than to inspect or rework it into a quality product. This is because it nearly always lowers the cost of producing quality products and the lower costs increases the level of quality. The measurements that are necessary to control the manufacturing process are paid for by the buyer and buyer's testing costs can be reduced if these test results are substituted by the buyer for those tests used to establish the quality level of the finished product. If it can be established at the point of manufacture that the product has acceptable quality, further inspection of materials can be greatly reduced. Therefore, it is important that the buyer satisfy himself of the validity of the tests made during manufacture and make use of them in establishing quality. It should be stated though that TQM requires that everyone should always be vigilant in the pursuit of quality and quality can never be taken for granted. What this means is that the buyer should recognize that his major interest is in controlling the process that produces the HMA rather than to accept or reject the finished product. Everyone's interest, that is the buyer, the seller, and the general public, is best served by making a product right in the first place. Testing and reworking, given the inherent variation in the sampling and testing process in the highway field, costs so much more than controlling the process that it can no longer be justified.

APPLICATION OF TQM

How will the TQM method differ from the traditional approach? First, test properties which are closely related to the quality of the product are selected for measurement. Precise test methods for these properties will be developed since it is recognized that imprecise test methods obscure the purpose of testing. The number of these test properties will be held to as low a number as possible while still controlling the quality of the chosen product. These measurements will be made on a continuous or a frequent basis with a minimum time between measurement and correction of the process. This nearly always means computerized controls. Since the buyer pays for all measurements, they should be the basis for determining the acceptability of the product.

The validity of these measurements should be a primary concern of both the supplier and the buyer. The supplier should recognize that his reputation for quality and his future profits are dependent on the effectiveness of the quality process. The buyer should realize that controlling the process is the most efficient way for him to insure a quality pavement and the best way to control the process is for him to cooperate with the supplier in that control. Cooperation between the buyer and the seller is essential to assuring the highest quality, but both have, in addition, an individual responsibility for the quality of the process. Since the number of measurements will be large, both the average and the standard deviation of the process will be very precise which is very important to a proper understanding of the process. To make this discussion more specific and understandable the control of a HMA plant will be covered. The program consists of very carefully choosing the truly important quality characteristics of the mix, reducing the number to as few as can be shown to be related directly to the performance of the HMA, and then controlling the process through them.

TQM FOR HMA

What are the key processes in the production of HMA? The author after some study separated the production of HMA into two processes, the hot mix plant and pavement laydown. It is important to the control of a process to establish those characteristics that will lead to a quality product. It is also basic that only the most important characteristics should be chosen. Ideally, only one characteristic should be chosen. Quite often processes are too complicated to be properly controlled with just one characteristic but it is important to always look for ways to reduce the number of chosen characteristics. The difficulty of control of the process increases exponentially with an increasing number of measurement characteristics and should only be attempted with precise test methods for the important characteristics. The selection of processes, test characteristics, and test methods are of fundamental importance to the quality program and the quality program is only as good as their selection.

What are the quality characteristics of the hot mix plant that need to be controlled to produce quality HMA? A properly functioning hot mix plant heats the mix to the proper temperature and grades the aggregate according to size, controls the proportion of asphalt in the mix, and thoroughly mixes the HMA. To help us find what is important to the performance of HMA, let's look back at those problems that could not be ignored from the past. From these, gradation of aggregate and control of asphalt content, were selected as the most important requirements for the control of HMA plants. The extraction test has validity as a research tool if the test portion is properly chosen, but it should not be used for routine control of a HMA plant. The author believes that an inspector's time is better spent in seeing that the plant is operated properly than in running extraction tests. Since plants vary considerably, there will be no attempt to give a detailed plan for calibrating them. Calibration by either weight or volume should be relatively easy with most plants. Plant volumes are much larger than those possible in standard extraction tests and this leads to asphalt content determinations of potentially much greater precision than is possible with the standard extraction tests. The accuracy of the measurement devices of a hot mix plant should be checked before allowing the plant to start producing HMA on a new project and a regular program of check ups instituted. Computerized controls make it possible to have a running record of the percentage asphalt content of the HMA. It is important that the buyer determine the validity of these determinations. They can be very accurate, but they must be verified before much credence can be attached to them.

The author selected as the two most important pavement laydown characteristics, pavement smoothness and pavement density. Smoothness of the pavement is the most important characteristic for driver or customer satisfaction. The driver is pleased as long as the pavement remains smooth and the traction is good. Frequent or continuous measurement of smoothness is an essential quality requirement. Proper compaction is important to the durability of the pavement and therefore to its continued smoothness. Modern truck tires are being operated at much higher pressures than was customary in the past. This requires much greater attention to the compaction process than was necessary when tire pressures were much lower. Frequent density determinations are necessary to control compaction.

Determination of asphalt content, smoothness, and density have been discussed , but no mention has been made of aggregate gradation control. The best way to check aggregate gradation control is to carefully calibrate the HMA plant. Where a quick test is required, it should be remembered that aggregate gradation is closely related to the volume concentration of aggregate (VCA) [1]. If asphalt content is closely controlled, density is closely related to (VCA) for properly compacted specimens. Density measurements are a measure of gradation variation for properly compacted specimens. In those instances where the contractors rolling operation is achieving uniform density in the pavement these density determinations can be used as a measure of aggregate gradation control.

Control charts of the important variables, asphalt content, smoothness, and density should be maintained and studied to control and to improve the plant operation. Much of the drudgery can be avoided through the routine use of the computer and computerized data recording. Where problems are revealed by the control chart, a designed experiment may be indicated in the never ending quest for improved quality.

CONCLUSION

Quality is a never ending search for increased satisfaction for all people. Highway engineers can make a big contribution to the satisfaction of the motoring public through continuing improvement of pavements and roadways. Good management and low cost are an integral part of quality since they make significant contributions to the driving public's satisfaction. A good measure of the success of a TQM program is the reduction in over-all costs. A program which does not result in significantly lower costs cannot be considered a success even if the top officials spend half their time singing its praises. If highway administrators were aware of the large savings that were possible through a properly implemented TQM program,.they would be more widely used. Improved quality results from increased knowledge, so effective research results in continual improvement in quality. Improved HMA can make the pavements of the future smoother, lower cost, and more durable.

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John T. Harvey[1], Bernard A. Vallerga[2], and Carl L. Monismith[3]

USE OF SHRP-DEVELOPED TESTING IN QC/QA PROGRAMS ON ASPHALT CONCRETE FOR HIGHWAY AND AIRFIELD PAVEMENTS

REFERENCE: Harvey, J. T., Vallerga, B. A., and Monismith, C. L., **"Use of SHRP-Developed Testing in QC/QA Programs on Asphalt Concrete for Highway and Airfield Pavements,"** Quality Management of Hot Mix Asphalt, ASTM STP 1299, D. S. Decker, Ed., American Society for Testing and Materials, 1996.

ABSTRACT: Present-day test equipment and procedures in quality control (QC) and quality assurance (QA) programs, based on use of the Marshall and Hveem methods, are essentially limited to verification of the physical composition of the asphalt concrete mix and its compacted density to control and assure that the builder is supplying a product which falls within the constraints defined by the job-mix-formula. They do not answer the essential question as to whether or not the asphalt concrete mix will have the strength properties needed to resist the number and intensity of repeated wheel load applications for which it was designed, both at the as-constructed and the traffic-compacted stages. This paper presents a philosophical discussion of the requirements for an asphalt concrete QC/QA system, using performance-based measures as the criteria. The framework for a performance-based system is described based on use of the Repetitive Simple Shear Test at Constant Height (RSST-CH) for rutting prediction and the Flexural Bending Beam Test (FBBT) for the estimation of fatigue cracking.

KEYWORDS: asphalt concrete, quality control, quality assurance, rutting, fatigue, performance prediction, construction

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Present-day procedures in quality control (QC) and quality assurance (QA) programs are essentially limited to verification of the physical composition of the asphalt concrete mix and its compacted density to control and assure that the builder is supplying a product which falls within the constraints defined by the job-mix-formula (JMF). They do not answer the essential question as to whether the asphalt concrete mix will have the properties needed to resist the number and intensity of repeated wheel load applications under the existing environmental conditions, both in the as-constructed and during the traffic-compacted stages.

The Marshall and Hveem test equipment and procedures have been found to be inapplicable for this purpose because they define only laboratory-generated measurements that are empirically and indirectly related to performance under generic environmental conditions. On the other hand, the test methods and procedures developed under SHRP Contract A-003A for characterizing asphalt concrete mixes, in both the rutting and fatigue modes, provide test results that are expressed in engineering units (stress-strain relationships) under site-specific environmental conditions which can be used to verify the performance predicted by the same SHRP test procedures in the mix design phase. Moreover, they can be run on asphalt concrete cores or beams cut directly from the asphalt concrete paving at any stage of construction, or on laboratory-compacted specimens that duplicate field-compacted specimens.

CURRENT QC/QA SYSTEMS

The step-by-step procedure for application of the Marshall and Hveem methods for design and QC/QA of asphalt concrete mixes for highways and airfields is presented in Figure 1. In Step 1 of Figure 1 the mix design is based on the mix meeting certain criteria that have been generally associated with good performance based on past experience with similar mixes.

These criteria include aggregate characteristics, gradation limits, minimum air-void contents (AV) under standard laboratory compaction, other volumetric criteria such as voids in the mineral aggregate (VMA) and voids filled with bitumen (VFB), and strength tests under conditions (loading, temperature) that may or may not be applicable to anticipated traffic loading and environmental conditions. None of these criteria provides a means of predicting the in-situ rutting and fatigue performance of the mix. In addition, the mix is usually evaluated against these criteria as either passing or not passing, even if only just over or under the empirically-defined limit.

If the mix meets these design criteria, the JMF is accepted, as shown in Step 1 of Figure 1. Tolerances for the elements of the JMF are set based on variances observed in past process control; and, construction proceeds with quality control of the construction process based on maintaining the elements of the JMF within the tolerances, as shown in Steps 2 and 3 in Figure 1. Quality assurance is also based solely on meeting the JMF criteria.

If the mix fails to meet the JMF criteria, the decision must be made whether to adjust the construction process or adjust the JMF, as shown in Steps 4, 9, 10, and 11 of Figure 1. There can be tremendous pressure on both the builder and owner in this situation, with neither party having a means to quantify the effects on pavement performance of either decision.

Because the existing methods do not design the mix based on its ultimate performance in situ, there are also cases in which the JMF meets all criteria and construction quality is within the tolerances of the JMF, yet the constructed mix does not perform adequately. Within the existing QC/QA system there are no means to quantitatively evaluate changes in the JMF to provide the desired performance, other than by constructing costly and time-consuming pavement test sections and subjecting them to traffic, or by judgment based on past experience which may not be applicable for the project conditions. The designer, builder, owner, and maintainer of the pavement have scant information with which to make rational decisions if there is little past experience with the mix, e.g., such as those with modified binders or new gradations, or those exposed to different wheel load configurations, tire pressures, or loading times. Moreover, it is difficult to measure changes in the materials supplied, as will occur with changes in refinery crude sources or refining methods or with changes in an aggregate source or aggregate manufacture.

When the existing methods are used with end-result specifications it is very difficult to quantify changes in pavement performance caused by failure to meet the JMF, or the adequacy of the JMF to produce a mix that will meet design requirements for performance. Pay factors for non-compliance in the end-result specification are therefore difficult to establish and may not produce the desired result, namely to provide incentives that will result in improved pavement performance.

Changes in design or construction variables that reduce the life of the mix from 15 years to 10 years, or vice versa, are impossible to assess quantitatively within the time-frame in which pay factor decisions must be made. Instead, pay factors are often based solely on guesses as to the effect of "out of tolerance" variables on performance, or are set at a level that "makes the builder pay attention." For example, the pay factor for a gradation that is outside the specification tolerance by two percent may be the same as that for an air-void content that is two percent higher than the specification, although the effect on the fatigue life of the pavement of the higher air-void content may be much more severe.

When used with pavements constructed under warranty, whether design/build/maintain or build/maintain, the predicted performance of the mix cannot be directly ascertained during either the design or construction processes using current methods. The methods therefore provide no feedback to the designer or builder regarding adjustments in design or construction in terms of the warranty criteria, usually rutting, ravelling, and cracking. Thus the JMF criteria or their minimum tolerances are the variables optimized, rather than pavement life-cycle cost, which depends on initial cost and maintenance/rehabilitation cost during the warranty period and, therefore, on performance.

The lack of feedback greatly increases the risk associated with undertaking the project. Greater risk generally results in higher bid prices.

PROPOSED QC/QA SYSTEM

Philosophy

The philosophy of the proposed system is to design the mix so that it provides the required performance level for rutting and fatigue resistance. This level is quantified in terms of equivalent single axle loadings (ESALs) based on laboratory tests in representative test specimens versus severity and extent considered as failure under the in-situ environmental conditions, namely temperature and exposure to water. The number of ESALs to failure required of the mix (N_{design}) is typically greater than the ESALs anticipated in the design period (N_{demand}) because it includes an adjustment for reliability in the form of a multiplier that accounts for the risk of premature failure the designer is willing to accept and the variance associated with both the laboratory test results and the estimate of future traffic, Figure 2 [*1*].

A framework for the proposed QC/QA system is shown in Figure 3. The results of the mix design are the performance predictions for rutting and fatigue (Figure 2), and the JMF for the mix, as can be seen in Step 1 of Figure 3. Construction of the pavement is then begun following the JMF as shown in Step 2.

To verify that the mix will provide the acceptable level of performance found in the mix design, the mix must be tested as it is spread and compacted in the field, using laboratory-compacted field mix specimens and/or field cores and beams, as shown in Step 3. The detailed procedures for rutting and fatigue are described later in this paper. Performance predictions for the failure modes selected are the criteria for quality control of the mix during construction, while the JMF and other materials characteristics and construction techniques are the means for adjusting the mix to meet the performance criteria, as can be seen in Steps 4, 5, 6, 9, 10, and 11 of Figure 3.

There are many construction variables that can affect performance, only some of which are part of the JMF, including those shown in Table 1.

Table 1—Materials/design/construction variables that can affect performance.

Materials/Design/Construction Variables	Distresses Strongly Affected by Variable	JMF Factor?
Binder Content	Rutting, Fatigue	Yes
Binder Homogeneity (modified and reinforced binders)	Rutting, Fatigue	No
Binder Aging During Construction	Rutting, Fatigue	No
Aggregate gradation	Rutting, Fatigue	Yes
Aggregate characteristics (surface texture, shape)	Rutting	No
Density/Air-Void Content	Rutting, Fatigue	Yes[a]

[a] In JMF may be specified in terms of field density relative to density under standard laboratory compaction, rather than measured air-void content, which can result in high air-void contents for mixes with reduced binder contents.

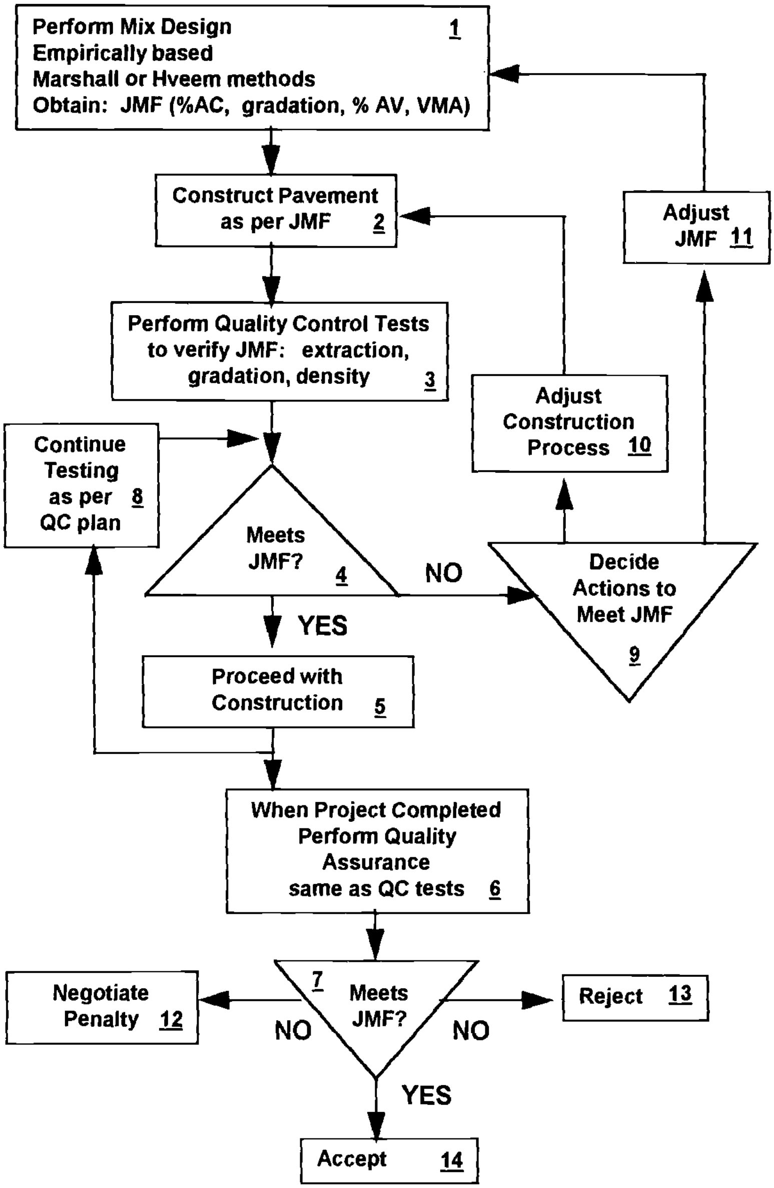

FIG. 1—Existing QC/QA systems.

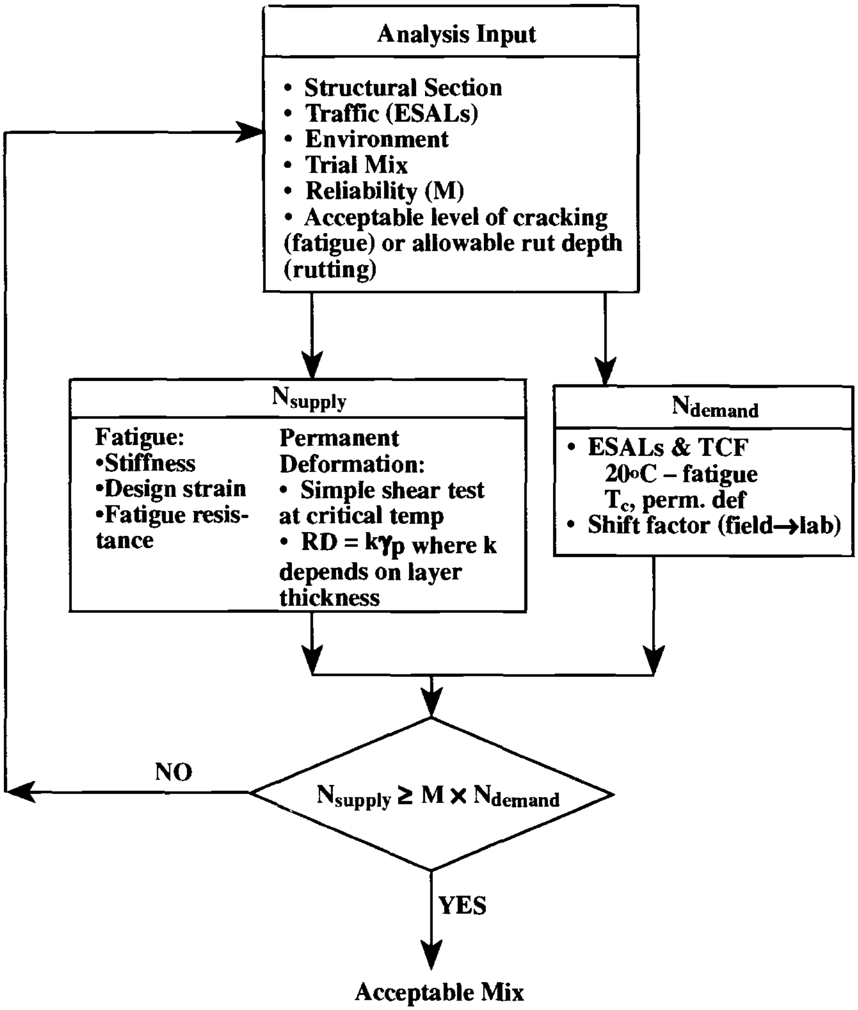

FIG. 2—Mix design and analysis system.

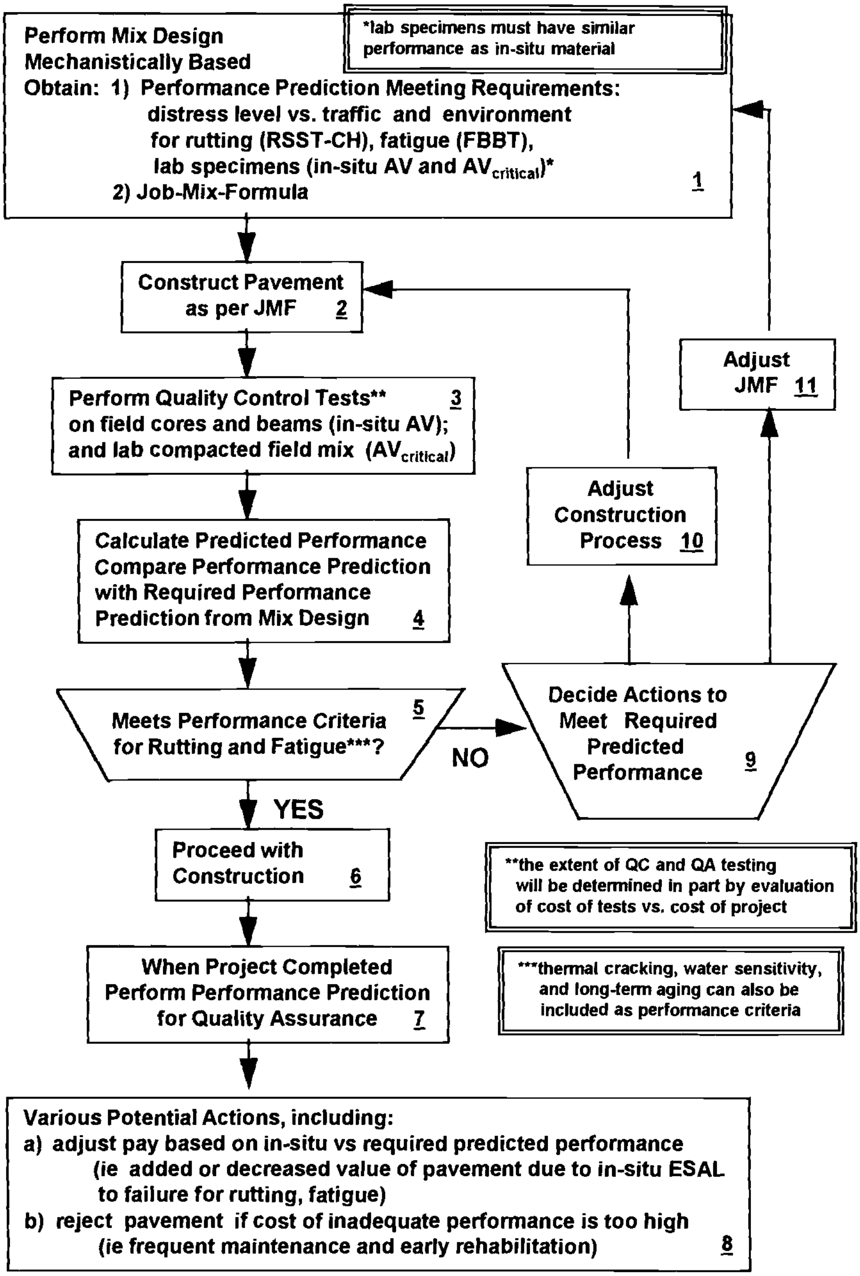

FIG. 3—Proposed QC/QA system.

If the predicted performance from the field specimens, including reliability, does not meet the criteria, these variables can be adjusted until the mix provides acceptable predicted performance, as shown in Steps 9, 10, and 11 of Figure 3.

While strict specifications can be set for all of these variables, individually, it would be better to test the mix directly for performance in terms of rutting and fatigue. The determination of appropriate standard specifications for each variable which influences performance and the obtaining of useful feedback would be nearly impossible because the quantitative effect of each on performance is not the same for different combinations of asphalt, aggregate, traffic, and environment. In addition, such specifications would require that each variable be tested to obtain quality control information, thus increasing the test effort required.

Quality assurance (QA) tests performed after construction would provide performance predictions that permit the quantitative evaluation of the completed work calculated in terms of life cycle cost, as shown in Steps 7 and 8. Consequently, reduced compensation can be objectively calculated if the predicted performance of the mix does not meet requirements. If the predicted performance of the mix shows a probability of such an early failure that excessive maintenance and/or rehabilitation would be necessary, replacement could be required based on readily understood performance criteria.

Test Methods for QC/QA Using Performance Prediction

To be practical, effective, and implementable, quality control and quality assurance methods based on performance prediction must meet the following requirements:

1. Provide fundamentally-sound and reliable predictions of mix performance for all cases, without exceptions that might result in loss of confidence in the method;
2. Have a variance in the performance predictions that permits a reasonably low number of specimens to be tested;
3. Duplicate the construction processes controllable by builder (Table 1);
4. Incorporate the use of field specimens (beams and cores) and/or provide a method to prepare realistic test specimens at the site from the loose field mix for QC/QA;
5. Include a mix design laboratory compaction method that produces specimens with performance similar to that of field specimens;
6. Provide rapid turnaround times to provide useful feedback for quality control; and
7. Be cost-effective in terms of equipment and staffing, in relation to the cost of the project. While the current Marshall and Hveem methods are low-cost, the maintenance, rehabilitation and user costs of early failures most likely are much greater than the additional cost of a performance prediction based design/QC/QA system. In some states the responsibility for QC testing is being passed to the builders and producers and is included directly in the cost of the project. The level of QC testing should be commensurate with the cost of the project.

The goal of the proposed QC/QA system is to meet these requirements.

Test Method for Rutting Resistance

Rutting in the mix is predicted using the repetitive simple shear test at constant height (RSST-CH). The RSST-CH is performed using the simple shear tester developed as part of the SHRP A-003A project and is reported in SHRP Report A-414 [2]. The simple shear tester includes two servo-hydraulic pistons that can apply loads or impose strains on the specimen simultaneously, one vertical (axial) and one horizontal (shear).

The cylindrical specimen, typically 150 mm or 200 mm in diameter and 50 mm to 75 mm in height, is fastened with epoxy to platens, which in turn are clamped to the pistons. After being brought to the project's critical temperature for rutting [3], a condition of constant height is imposed on the specimen using a linear variable displacement transducer (LVDT) which measures the distance between the top and bottom platens.

A repetitive haversine shear load of 68.9 kPa (10 psi) is applied to the specimen, with a 0.1 second loading time and 0.6 second rest period. The resulting shear deformations are measured using a second LVDT mounted horizontally on the specimen.

A method has been developed which relates the measured permanent shear strain and shear load repetitions data in the RSST-CH to vertical rut depth and equivalent single axle loads (ESALs) in the field [2]. This method allows determination of the number of ESALs (N_{supply}) that the mix will withstand in the field at the critical temperature before it reaches the maximum allowable rut depth.

The number of ESALs to which the mix will be subjected in the field is adjusted for the range of temperatures expected at the project site and differences between laboratory and field conditions. An adjustment for reliability, in the form of a multiplier, is also applied to the expected ESALs to provide a measure of the probability that the mix will perform satisfactorily for the design-period traffic and environmental conditions. The reliability multiplier accounts for variance in the future traffic estimate and in the laboratory test results. The resulting required number of ESALs (N_{design}) is then compared with N_{supply} to determine the acceptability of the mix. This process is illustrated in Figure 2.

The behavior of the mix during construction compaction and trafficking is considered to consist of the simultaneous processes of permanent compressive volume change (densification) and plastic flow at constant volume (permanent shear deformation).

Densification alone cannot be the primary mechanism for the excessive vertical rut depth found in pavements that fail by rutting of the mix. For example, if a 100 mm overlay was compacted to an initial air-void content of 8 percent, and under trafficking the entire mix densified to an air-void content of 1 percent, the total vertical rut depth that could be attributed to densification alone would only be less than 2.5 mm $(0.07 \div 3 \times 100)^4$, which would not be considered failure. It would be expected that an in-situ mix with 1-percent air voids after trafficking would likely have rut depths exceeding 2.5 mm.

The excessive rutting observed in failed pavements is caused by permanent shear deformation. If a condition of plastic flow under constant volume occurs under repetitive wheel loads, then large volumes of mix can be pushed out of the wheelpath by the shear stresses below the edge of the truck tires, resulting in the familiar "humps" of material that are found at the edges of the wheelpath in rutted pavements.

The RSST-CH allows evaluation of permanent shear deformation resistance under approximately constant volume because of the constant height condition imposed during shear loading. It has been shown that this resistance increases as the mix densifies under traffic, until a critical air-void content is reached ($AV_{critical}$), typically between 2.5 percent and 4 percent. Resistance in the RSST-CH decreases at air-void contents below $AV_{critical}$. As densification under traffic occurs, the mix is also accumulating permanent shear deformation. Resistance to permanent shear deformation is therefore evaluated at its peak, $AV_{critical}$. If the mix does not have adequate resistance at $AV_{critical}$ then it will not have adequate resistance at any other time during the densification process, resulting in rut depths that greatly exceed 2.5 mm.

Test Method for Fatigue Cracking

Fatigue cracking in the mix is predicted using the Flexural Bending Beam Test (FBBT). The FBBT uses a third-point, controlled-strain, flexural beam apparatus. The test was developed as part of SHRP A-003A and is described in SHRP Report A-404 [*4*]. The equipment incorporates several significant changes from the original equipment developed at UC-Berkeley in the 1960s [*5,6*] that greatly reduce testing time, and test result variance.

A 10 Hz haversine wave is typically used, with the deformation of the beam centroid calculated to produce the desired tensile strain in the extreme fiber at the bottom of the beam. Failure is assumed to occur when the stiffness reaches half of the initial stiffness.

Analysis performed during and after the SHRP A-003A project demonstrated that, when compared with the controlled-stress test method, the controlled-strain test method produces proportionally the same fatigue life for pavement structures greater than about 75-mm thickness [*7*]. The laboratory to field shift factors for both methods account for absolute differences in laboratory fatigue life versus stress or strain measured for a given mix using the two methods.

Tests are typically performed at 20°C, as recommended in the SHRP A-003A fatigue reports [*4*].

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[4] A reduction in volume of 0.07 amounts to a reduction in height of approximately $0.07 \div 3$, assuming uniform densification across each of the three principal directions. If densification occurred only in the vertical direction the rut depth would be 7 mm.

The analysis method for predicting fatigue life in situ requires knowledge of the underlying pavement structure, future traffic, and temperature data for the project site. In addition to an adjustment for in-situ temperature, and an adjustment, i.e. shift factor, to account for differences between laboratory and in-situ loading patterns, reliability concepts are applied to the future traffic estimate in a manner similar to that previously described for rutting, Figure 2.

The FBBT analysis method assumes that cracking will be initiated at the bottom of one of the asphalt concrete layers and propagate upwards. Analysis in the proposed QC/QA system assumes that the mix does not densify in the wheelpaths after construction.

Quality Control Procedures

Quality Control Procedures for Rutting

The quality control procedures for rutting in the mix begin with the mix design, e.g. compaction of laboratory specimens to the critical air-void content ($AV_{critical}$), RSST-CH tests, and establishment of the ability of the selected JMF to adequately resist permanent shear deformation for the traffic and temperatures expected at the project site. Quality control during construction involves RSST-CH testing of the mix as spread and compacted to determine whether it can adequately resist permanent shear deformation.

There are several options for preparing quality control specimens, shown in Table 2 and Figure 4.

Table 2—Options for specimen preparation and analysis of QC tests for evaluation of rutting performance at critical air-void content ($AV_{critical}$).

Steps in QC Tests	Option A	Option B	Option C
Method of Specimen Compaction	Field compact test strip at site to $AV_{critical}$	Collect field mix and compact to $AV_{critical}$ using lab rolling wheel (at site or in lab)	Field compaction as per specification (typically air-voids greater than $AV_{critical}$)
Coring of Specimens for RSST-CH	Rapid cooling of small area at test strip, take core	Take core from rolling wheel slab	Rapid cooling of small area, take core
Evaluation of Shear Resistance at $AV_{critical}$ from RSST-CH	Compacted to $AV_{critical}$	Compacted to $AV_{critical}$	Extrapolate results from as-built air-voids to $AV_{critical}$ based on mix design data

The preferred options for preparing QC specimens are Options A and B, or a combination of the two, because the specimens are compacted to, and tested at, the critical air-void content. Differences in permanent shear deformation resistance between specimens compacted to $AV_{critical}$ using rolling wheel compactors or field

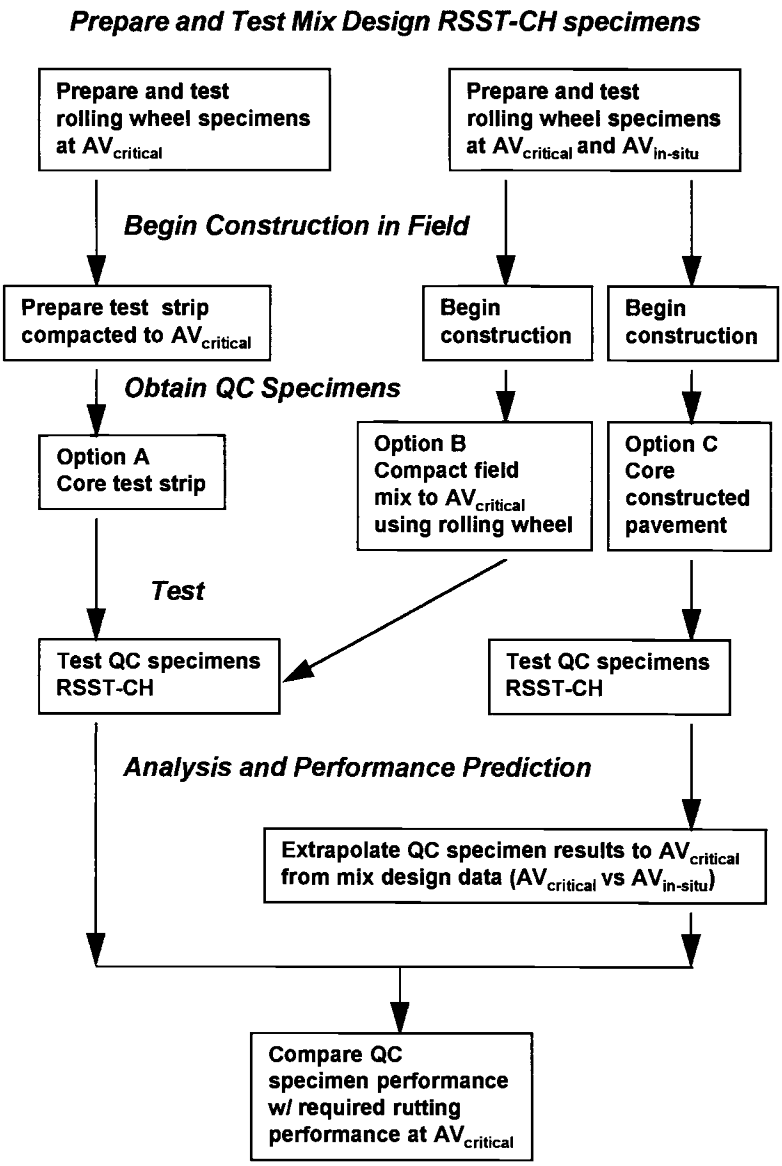

FIG. 4—Operations for QC control of rutting performance.

compaction equipment versus those compacted under traffic have not been definitively examined. Information available to date indicates that rolling wheel compaction and field compaction produce similar performance at low air-void contents [*8*].

Specimens from rolling wheel compaction have been cored and cut, which allows direct comparison between field cores and lab-compacted specimens. Compaction methods that produce specimens with some as-compacted (uncut) surfaces have aggregate orientation and air-void characteristics that differ between the interior and exterior of the specimen [*9*].

Option C involves compaction during the mix design to two air-void contents, namely $AV_{critical}$ and an air-void content at or slightly greater than that expected in the field. RSST-CH results for both air-void contents would allow results from field specimens compacted to the specified air-void content to be extrapolated to $AV_{critical}$. However, that extrapolation relies on the assumption that the improvement in permanent shear deformation resistance between the two air-void contents observed during the mix design will be the same for the mix in the field under traffic.

If specimens are to be prepared from field mix compacted in the laboratory (option B), it is important that there be minimal heating of the mix beyond that which occurs in the field. Extra heating will stiffen the binder which results in greater resistance to rutting in the laboratory compacted specimen. If laboratory rolling wheel compaction is to be used, as in Option B, a compaction mold can easily be transported to the site, and a sidewalk compactor can be rented to compact the mix as it is taken from the paver or windrow, thus eliminating the need to buy an expensive laboratory compactor for QC.

The QC specimens are tested using the RSST-CH to determine N_{supply}. The relationship between permanent shear deformation and shear load repetitions is transformed into a relationship of in-situ rut depth versus equivalent single axle loads (ESALs), as described previously. The ability of the mix to meet the design requirement (N_{design}) for maximum rut depth can then be assessed. If the mix is predicted to reach the design rut depth prior to the traffic expected during the design period ($N_{supply} < N_{demand}$), it can be determined whether the mix will be rejected until the JMF is adjusted, or a penalty pay factor will be implemented.

<u>Quality Control Procedures for Fatigue Cracking</u>

The quality control process for fatigue cracking requires either beams cut from the field compacted pavement or field mix compacted in the laboratory. Research has indicated that fatigue performance is not affected as much by compaction method as is rutting performance, provided that aggregate is not degraded by the compactor. Laboratory beams should be compacted to the air-void content obtained in the field, i.e. not in the test strip compacted to $AV_{critical}$.

The beams are then tested using the FBBT, and the ability of the mix to resist fatigue cracking for N_{design} is assessed. Again, if a mix is predicted to fail before the required design life ($N_{supply} < N_{design}$) it can be decided whether to replace the mix, or use a pay factor calculated in terms of percentage of design life obtained, or in terms of the increased life cycle cost.

A maximum 24-hour turnaround is typically required for timely feedback to the construction process. Within 24 hours, it is possible to obtain about 3 to 9 RSST-CH specimens from either field cores or laboratory compaction, trim and test them and obtain results using one simple shear device. It is possible to obtain up to 4 FBBT beams either from field cores or laboratory compaction, trim and test them, and obtain results using one fatigue beam device. One trained person is required for most of the tasks. A helper greatly increases efficiency for the current non-automated methods of laboratory rolling wheel compaction. A mobile trailer containing test equipment that can be stationed at the construction site will also increase efficiency and help reduce turnaround time.

Quality Assurance Procedures

Quality assurance (QA) tests are performed to establish the degree to which design objectives have been achieved and to determine pay factors. Under current QA systems pay factors are often associated with achievement of various properties, such as aggregate gradation, asphalt content, or air-void content. However, the relationships between these measured properties and performance are empirical, and, therefore, a rational basis for pay factors is not possible.

With the proposed QA system, pay factors can be calculated in terms of percent reduction in pavement life compared to the required design life, which is not possible under existing systems. A more sophisticated pay factor calculation can also be made of the increased life cycle cost caused by the predicted early failure which would include the costs of early maintenance and rehabilitation, and, for traffic-congested regions, an estimate of additional user delay and other external costs associated with early maintenance and rehabilitation.

For example, a gradation that is out of specification by 2 percent on the 4.75 mm sieve may not affect the rutting and fatigue performance of the mix, but the pay factor may be made severe for no other purpose than to make the producer take note. Alternatively, pay factors may not reflect the large decrease in pavement fatigue life that can result from an air-void content that is two or three percent higher [*4*].

USE OF THE QC/QA SYSTEM IN A WARRANTY PAVEMENT ENVIRONMENT

In a project development environment in which the builder is responsible for maintenance after construction, the builder must have a means of evaluating the performance of the mix in order to make rational decisions regarding the cost of the maintenance functions that will be required during the warranty period. If the design is performed by another entity, the builder/maintainer may wish to verify the ability of the design to meet performance requirements in the warranty agreement [*10*].

The existing QC/QA methods are based only on empirical relationships and are not likely to provide the performance data necessary to enter into a warranty agreement with confidence. The proposed QC/QA system outlined in this paper provides a fundamentally sound approach on which the builder can rely.

In a warranty pavement environment the extent of testing and analysis included in the QC plan will depend on an evaluation of testing cost, cost of delays, and reliability level desired.

IMPLEMENTATION PLANS

Elements of the QC/QA system have been implemented using a remotely located test center. Several highway and airport design and construction projects are planned in California for the near future that will include use of the proposed system. The initial projects will use the proposed system in parallel with a conventional QC/QA system based on use of the Marshall or Hveem methods.

CONCLUSIONS

1. Current systems (Marshall and Hveem) for quality control (QC) and quality assurance (QA) for asphalt concrete construction measure quality in terms of ability to meet the requirements of the job-mix-formula (JMF): aggregate gradation, asphalt content, and density relative to that of a standard laboratory compaction effort or an air-void content. The JMF is determined from purely empirical design procedures.

2. Use of the current QC/QA systems can result in inadequate performance or premature failure because meeting the requirements of the empirically designed JMF does not measure, control, or assure mix performance, in situ.

3. The framework for a QC/QA system based on performance prediction presented in this paper is based on the philosophy of testing the field mix immediately after construction and prediction of performance in terms of distress development, i.e. rutting and fatigue cracking versus expected traffic and environmental conditions at the project site. The predicted performance of the field constructed mix is compared with the required performance to determine quality after accounting for reliability of the prediction.

4. The repetitive simple shear test at constant height (RSST-CH) is used to predict rutting, and the flexural fatigue beam test (FBBT) is used to determine fatigue cracking. Methods are employed to ensure that laboratory compacted mix design specimens and compacted field mix have properties that duplicate those of the field-compacted mix. Case histories are being developed to demonstrate the ability of the RSST-CH and FBBT to meet the requirements for a performance prediction based QC/QA system, primarily quick turnaround time, adequately accurate and robust predictions of in-situ performance, and relatively low cost in terms of staffing and equipment.

5. This system appears to be ready to provide the builder with rapid feedback regarding the effects of changes in construction processes on pavement performance. The system provides the pavement owner a prediction of the life of the pavement, as-built, quantified in terms of the traffic versus fatigue cracking and rut depth. The

entity responsible for maintenance is provided with an estimate of when maintenance for fatigue cracking and rutting should be required.

6. In a warranty pavement environment, the proposed system gives the designer/builder/maintainer the means to develop rationally a product that will minimize life cycle cost, including an estimate of risk associated with the design and the traffic estimate.

7. The proposed QC/QA system assumes the use of similar performance prediction methods for mix design. Implementation of the performance prediction based mix design/QC/QA system presented in this paper will result in design and construction of asphalt concrete mixes to meet explicitly required performance in terms of quantified distress levels versus expected traffic and environment.

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PERFORMANCE BASED FIELD QUALITY CONTROL/QUALITY ASSURANCE FOR ASPHALT-AGGREGATE MIXES

REFERENCE: Sousa, J. B., Way, G., Bouldin, M. G. and Harvey, J. T., ''**Performance Based Field Quality Control/Quality Assurance for Asphalt-Aggregate Mixes,**'' Quality Management of Hot Mix Asphalt, ASTM STP 1299, Dale S. Decker, Ed., American Society for Testing and Materials, 1996.

ABSTRACT: The Arizona Department of Transportation in its continuing effort to improve pavement technology evaluated the use of the repetitive simple shear test at constant height and flexural bending beam test as part of the mix design and field quality assurance process. The results of the efforts, indicated that the use of those performance based tests and associated analysis procedures are feasible and implementable for routine use.

KEYWORDS: quality control, simple shear, flexural fatigue, quality assurance, performance based tests, field tests.

INTRODUCTION

As part of its program to improve the quality of its flexible pavements, the Arizona Department of Transportation (ADOT) is evaluating promising new concepts and test methods developed to evaluate mix performance as part of the Strategic Highway Research Program. The ADOT evaluation included placing two one-mile test sections, six miles north of Phoenix on Interstate 17 near the Pioneer Living Museum exit in November, 1993 and a long test section on Interstate Route 40 near Flagstaff in July of 1995.

ADOT is investigating use of new procedures for construction quality control and assurance, as well as mix design, recognizing that the two functions should be integrated in order to obtain the best product possible.

The primary purpose of the test sections was to evaluate new SHRP performance based tests and their applicability in the mix design and field assurance control stage.

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The paper is divided into two parts. The first, *Performance Based Mix Design Concepts*, describes concepts and analysis for selection of the asphalt content of the mix. The second, *Field Quality Control*, presents concepts for field quality control based on performance related tests and contains comparisons between performance predicted from laboratory specimens produced during mix design and from field cores.

The performance related tests used in this analysis were the repetitive simple shear test at constant height (RSST-CH) [1-4] and the flexural bending beam [3,5-7]. These tests have been developed by the SHRP A-003A project and are now part of the P-005 and M-009 test protocols as well as AASHTO TP7-94 and AASHTO TP8-94 protocols, respectively.

This design concept is based on measurements of physical properties in the mix which can be linked to its performance in the various distress modes. As such it provides a tie between mix properties and structural design. This aspect is particularly important because pavement thickness design requirements drives the construction cost. An approach based purely on volumetrics is incapable of providing sufficient information for cost effective overlay or pavement designs specially when modifiers and binder types can affect fatigue life.

Together with the implementation of performance based mix designs raises the need for adequate field quality control. The true benefits of a high quality design can only be realized when a performance based quality control and acceptance system is instituted in the field.

It has been argued that advanced mix design and field quality verification are not implementable because of their high cost. However with the new SHRP tests and procedures initial field results appear to indicate that the total extra cost in the design and quality control process is less than 2% of the total construction cost while potentially extending the pavement lifetime significantly. This cost is only likely to decrease with standardization while the potential benefits are only likely to increase with experience and added knowledge. In addition, such design and quality control procedures significantly reduce the probability of premature failure due to rutting.

Performance based mix designs with field Quality Control/Quality Assurance (QC/QA) programs have four distinct advantages over other mix design systems and over systems without QC/QA programs:

- Performance related field QC/QA programs provide a means of timely verification of the mix design. Also, field test results can be compared with laboratory test results, thereby giving the designer an estimate of how the two correlate.
- Performance related field tests provide a direct tie between the mix properties and the structural design, thereby providing an almost instant feedback to designers, who, if needed, can make necessary adjustments in the mix/structural designs without too much delay.
- Record of field test results in conjunction with laboratory tests and the mix/structural design data can provide an

important source of information and database for similar projects in the future

- As experience is gained and the pavements are subjected to traffic and environment effects comparisons between actual performance and predictions can be made leading to fine-tuning of the prediction models.

The QC/QA program being evaluated in Arizona involves the sampling of cores from different locations of the newly laid SHRP test sections and testing them on site for their fatigue and rutting performances. The SHRP field trailer is equipped with the required sample preparation and testing equipment along with the required software to run the tests and analyze the results. The trailer is equipped with a CS7200 Shear testing System and a CS7800 Axial testing system equipped with the four point bending testing fixture. The equipment is controlled by the ATS software. As such performance predictions can be done at the construction site and thus provide a timely feedback on the quality of the job.

PERFORMANCE BASED MIX DESIGN CONCEPTS

The objective of the Performance Based Mix Design method used in these projects was to establish the appropriate amount of asphalt content in a mix that will simultaneously satisfy the rut resistance and fatigue cracking requirements for a given set of conditions (i.e. traffic and environment). It was assumed that the thermal cracking problem was controlled by selecting the proper PG binder grade. Figure 1 depicts the process where three mixes A, B and C are evaluated and compared against the design requirements. The dashed lines represent the increase in resistance to shear deformation with a decrease in asphalt content while the solid lines represent an increase in fatigue performance with an increase in asphalt content. For MIX A the point where the lines cross (optimum AC content for a given mix) is below the design traffic, as such this mix should not be used at for those conditions. Fatigue life of a given pavement section is dependent not only on fatigue performance of the mix but also on the structural pavement capabilities. Consider two possible pavement structures **s** (strong) and **t** (thin and weak). Using a weak (str. **t**)structure Mix B would satisfy the design requirements. However Mix C with a stronger structure (str. **s**) would also satisfy the design requirements. The decision to use Mix C on a strong structure or Mix B on a thin (weak) structure could be made based on cost.

To evaluate rut and fatigue cracking resistance of the mixes, tests developed during the SHRP-A003A project are used. These tests are executed in conditions most critical for the distress mechanism they are trying to evaluate. The four point flexural bending beam fatigue test should be executed at temperatures between 15° to 30°C where the conditions that cause fatigue cracking are generally most severe [7]. The effects of aging and moisture on the mix are addressed as they affect performance. Furthermore, it is recognized that air void content changes due to traffic densification and tests are executed accordingly. For instance, for dense graded mixes, the RSST-CH should be executed at air-void contents of approximately 3 to 4 percent, where the mix is most resistant to accumulation of permanent deformation due to shear stresses. It is assumed that rutting is only likely to occur when the mix drops below that air void content range. However for performance based approaches to mix design to work it is required that compaction in laboratory yield specimens with performance properties identical to those obtained from field cores [8].

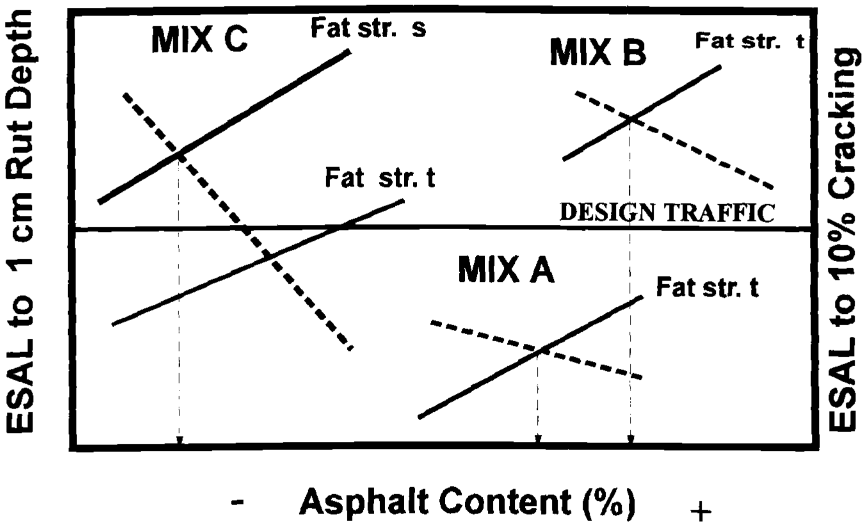

Figure 1 - Performance-Based Mix Design Concept

Using this performance-based approach [9] there is no need to set explicit limits on volumetric characteristics. If a mix does not meet a particular value of VMA (voids in mineral aggregate) or VFA (voids filled with asphalt), but still has the desired performance, at the expected in-situ volumetric characteristics, it would be acceptable. The selection of asphalt content is based on the desired level of performance for each mode of distress. For instance, in this framework a change of asphalt type, even within the same binder grade, can have a significant effect on the predicted fatigue life.

PERFORMANCE DESIGN CONCEPT USED IN THE SHRP SECTIONS IN ARIZONA

The concepts adopted in the mix design have already been extensively presented and as such they will only be summarized in this section. Both the performance based rutting evaluation and the fatigue evaluation follow similar approaches that can be summarized into four major steps:

1. Design Requirement definition.
2. Conversion of those design requirements into critical strain levels in the asphalt aggregate mix by means of Transfer Functions.
3. Evaluation in laboratory of the performance of the mix at the critical strain levels and environmental conditions (i.e.,

aging, temperature and moisture) identical to those expected in the field [10-12]

4. Conversion of the observed laboratory performance into expected field performance by means of shift factors calibrated based on previous experience.

In this approach reliability concepts can be introduced at any stage.

Rutting Evaluation

A summary of the Performance Based Rutting Evaluation Procedure is presented in Figure 2. Initially in the Design Requirement stage the number of ESALs required to reach a given rut depth is selected. Through the Transfer Function the permanent shear strain is determined for the rut depth selected. RSST-CH tests are executed in the laboratory at high temperatures representative of those encountered in the top 50 mm (2 in.) of the pavement during the warmest days of the year. Tests should also be executed at the selected aging and moisture condition protocols as they affect performance. It is recognized that air void content changes due to traffic densification and tests are executed accordingly. For instance, for dense graded mixes, the RSST-CH should be executed, at air-void contents of approximately 3 to 4 percent, where the mix is most resistant to accumulation of permanent deformation due to shear stresses. It is assumed that rutting is only likely to occur when the mix drops below that air void content range. Under those conditions the results of the test can be converted into Equivalent Single Axle Loads (ESALs) to a required rut depth using the appropriate shift factors. For instance in Figure 2 it can be observed that Mix A would be less resistant to permanent deformation than Mix B.

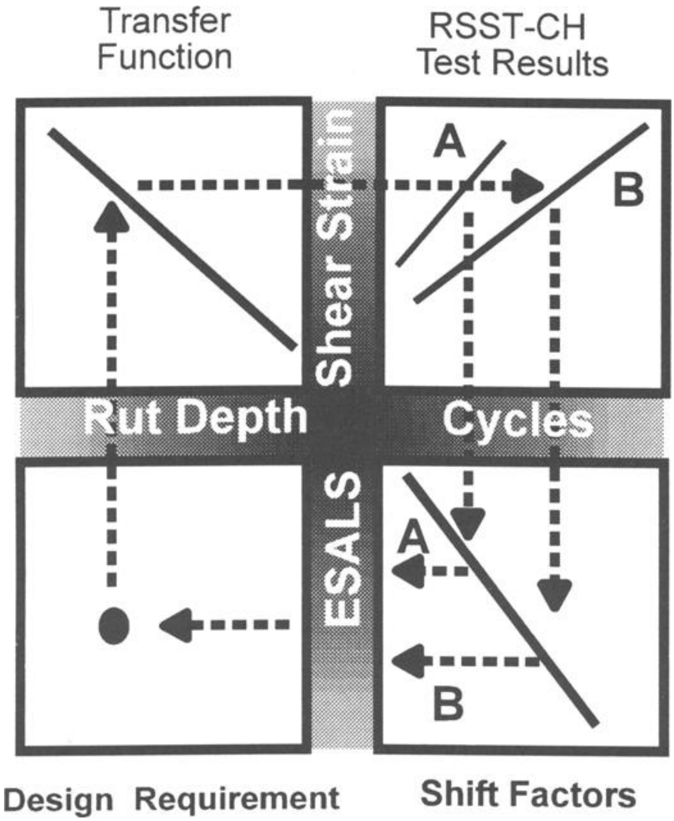

Figure 2 - Summary of the procedure to evaluate rutting propensity of the mixes in a given pavement condition and environment.

Fatigue Evaluation

A summary of the Performance Based Fatigue Evaluation Procedure is presented in Figure 3. Initially in the Design Requirement stage the number of ESALs of a Standard Load is selected (i.e. 80 kN or 130 kN). Through the Transfer Function the corresponding tensile strain level at the bottom of the asphalt layer is determined. The strain level is a function of pavement type and strength as well as mix stiffness. In Figure 3 the effect of different pavement types is depicted through the lines associated with the letters **s** , **t**, **u** and **v**. Pavement **s** would be stronger then pavement **v** thus it would be imposing lower tensile strain levels in the asphalt layer. The four point flexural bending beam test (AASHTO TP8) is then executed at selected temperatures and the tensile strain versus fatigue life relationship is determined for each mix. Those values are then converted to ESALS to % cracking by means of shift functions. Traditionally two levels of % cracking are used; 10% and 45% [13]. In Figure 3 it is demonstrated how mix fatigue resistance and pavement structure are interdependent. For the established design requirement if Mix A is placed in structure **t** it will exhibit premature cracking. However Mix B will satisfy the design requirement in the same structure. However if structure **s** is used then Mix A would satisfy the requirements.

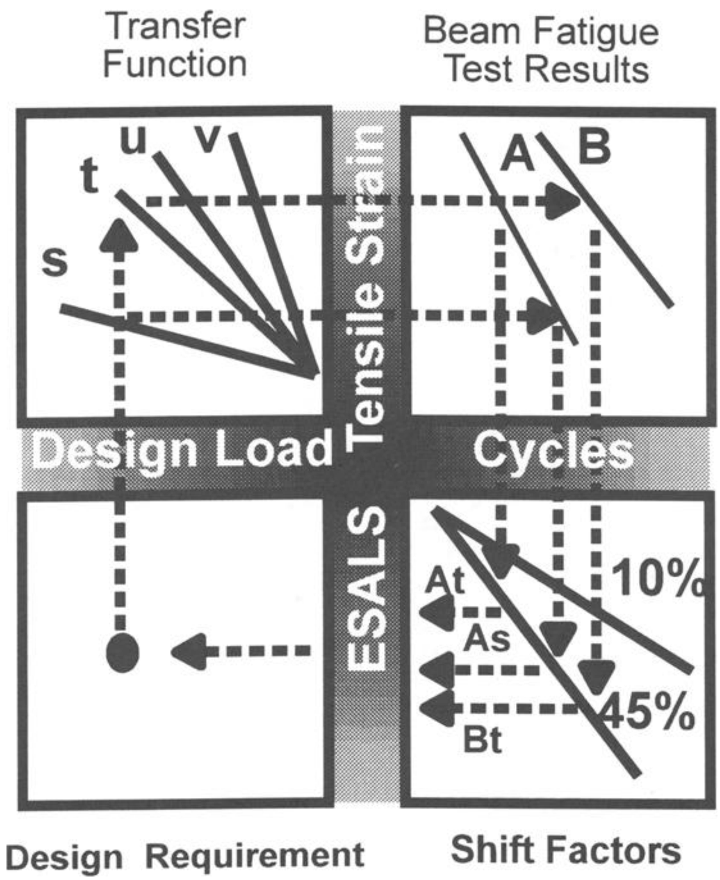

Figure 3 - Summary of the procedure to evaluate fatigue propensity of the mixes in a given pavement condition and environment.

FIELD QUALITY CONTROL

Objectives and Concept

The primary purpose of the quality control activities during these two projects was to demonstrate the feasibility of using performance based tests such as the RSST-CH and flexural fatigue tests as tools to enforce quality construction. The advantage of this new concept is that the performance can be directly measured on cores taken from the pavement. This means that, for example, if the binder content is too high but the aggregate is better than specified, then the contractor will not be penalized if the mix performs within the specified performance levels. It also ensures higher levels of compaction, which is one of the most critical parameters in obtaining high performance pavements.

It is recognized that air void content changes with traffic densification. In both fatigue and permanent deformation laboratory evaluations, in the mix design stage, the selected air void content of the specimens ranges between 3 and 5%. At these low air void contents tests are executed for the selection of the adequate asphalt content. However post-compaction air void content are generally higher. As such differences are encountered between field performance of cores of as compacted pavements and those obtained from the laboratory prepared specimens only due to air void content differences. To overcome this it is required that during the mix design stage, performance tests be conducted on specimens, with the design binder content, at higher air void contents thus covering the range of air void contents expected in the field.

As such in a performance related field quality control system the change of fatigue and permanent deformation performance with air void content should be determined in the laboratory during the mix design stage. Once that performance change is determined, field quality control becomes straight forward, accurate and relatively inexpensive. The performance of the field cores can be directly compared with expected laboratory mix design performance at any air void content. For either permanent deformation or fatigue expected performance at a given air void content can be expressed in terms of ESALs (such as ESALs to a given rut depth or ESALs to percentage area with fatigue cracking). Figure 4 demonstrates the QC/QA system. The **design** area is determined in the laboratory based on the tests over a range of air void contents usually between 3 and 4 and between 5 and 7 percent. The proposed **Penalty, Bonus** or **Rejection** areas could be selected, determined and imposed by a Department of Transportation based on experience and data variability. If performance from field cores falls within each of the areas then corresponding action would be taken.

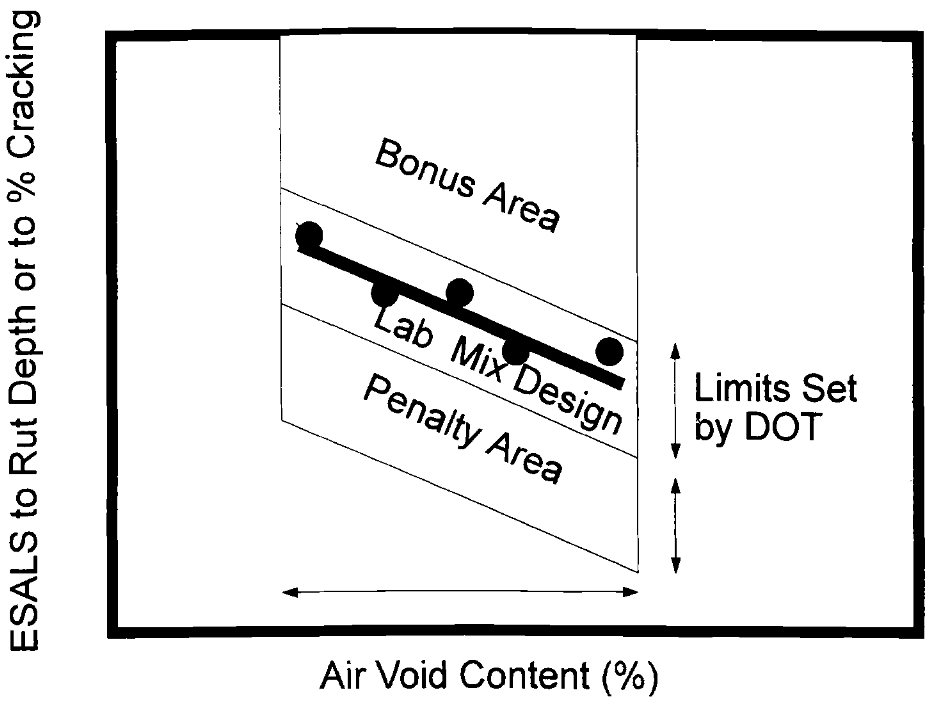

Figure 4 - Performance Based Field QC/QA concept

To improve applicability of these concepts potential problems had to be evaluated:

- Would it be possible to obtain beams or cores from the overlay without having to saw or cut all the way down to the subgrade?
- Would it be possible to cool the mix down with sufficient speed so that quality control activities could be executed within a time frame that would permit rapid adjustments to the construction process?

In order to address the first problem a double sheet of heavy duty aluminum foil was cut to the correct dimensions and placed on the pavement after applying the tack coat. The bottom sheet bonds to the tack coat while the top sheet bonds to the new overlay leaving no bond between the two aluminum sheets. The dimensions of the aluminum foil (see Figure 5) were chosen so that two cores and two beams could be cut from the overlay which debonded at the interface between the two sheets of aluminum. This concept worked very well in the field.

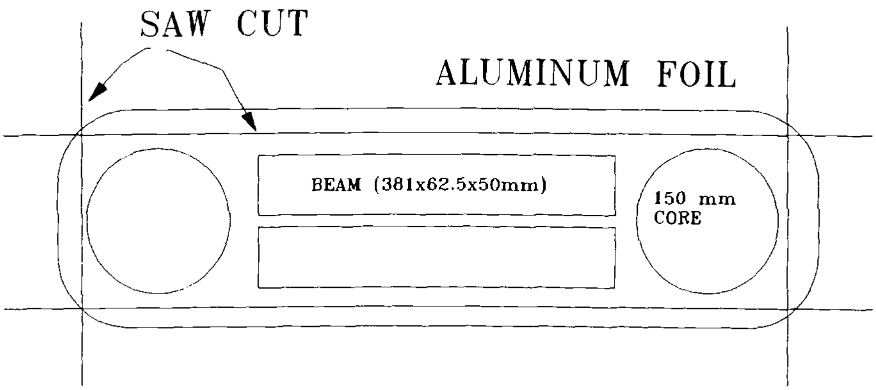

Figure 5- Concept for obtaining beam and cylindrical specimens for field quality control.

To address the second problem thermometers were placed in the mix at several depths and a 75 mm layer of "dry ice" over a 50 mm layer of ice was placed over a 1000*500 mm (40x20 in.) area. After two hours the section was sufficiently cool to permit coring and sawing. It is important to note that the "dry ice" is not in contact with the mix because this could induce micro-cracking, due to the extremely low temperatures (-180 °C), which could affect fatigue properties. The ice is used as an insulator between the mix and the "dry ice".

To improve turn around times during the field quality control stage and to insure that corrective measures can be taken in a timely fashion it was felt that specimens should be tested in the field. However the Superpave Shear Tester (SST) is too massive to bring to the field. In order to overcome this limitation of the SST a smaller simple shear system (SSS) capable of doing the RSST-CH was designed together with an integrated control system and frame that permits simultaneous testing of fatigue beams. This testing platform was placed on a trailer equipped with generator, hydraulic pump, ovens, incubator, freezer, saw and gluing device. This trailer, see Figure 6, permits execution in the field of all performance related tests presented here and can be used for routine testing where performance based field quality control is required.

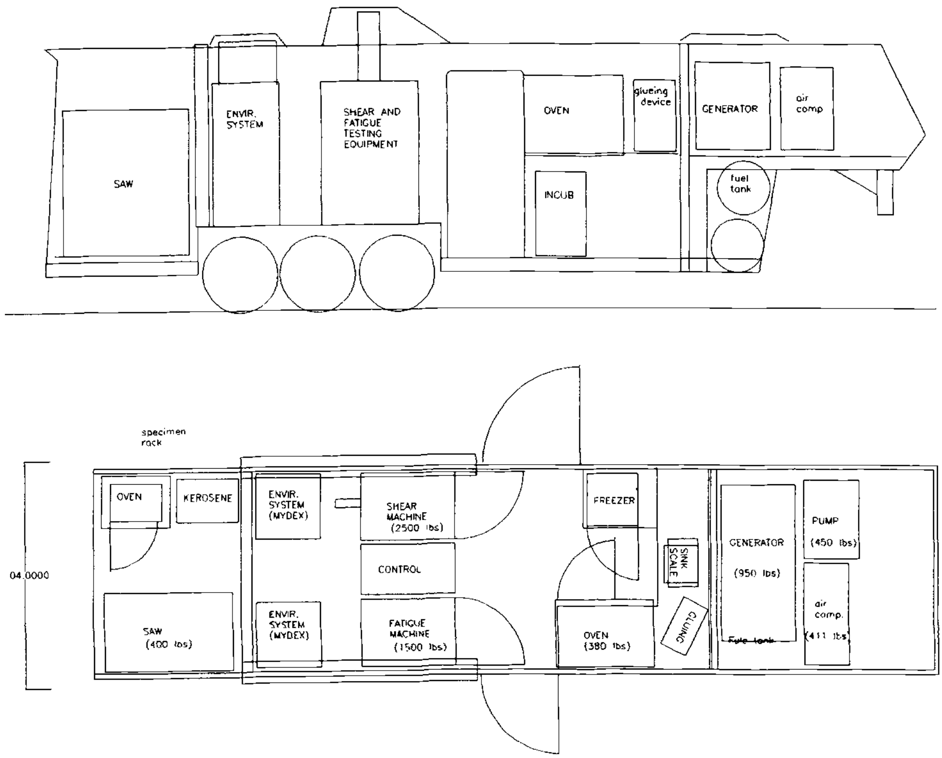

Figure 6 - Schematic Representation of the Field Quality Control Trailer developed by Cox and Sons, MTS and SHRP Corporation for APT.

CASE STUDIES

M-40 Case Study

Project IM-40-3(75), also known as the Williams-Riordon Project involves the mill and replace construction work in part of the Interstate Route 40, (I-40) near Falgstaff, Arizona. This construction was executed in July of 1995. The total length of the project, beginning at MP 166.6 and ending at MP 190.8 is approximately 24.2 miles. Several test sections were placed on this project. Among them one designed using the concepts that use the RSST-CH and the Flexural Beam Fatigue tests and another using a standard Marshall mix. The test temperatures were respectively 64°C and 15°C. The specimens were compacted in laboratory using the rolling wheel compactor.

Figure 7 shows a comparison between laboratory prepared specimens at the high air void content and from the field specimens at identical air void contents. It can be observed that the results are relatively identical indicating that the permanent deformation performance expected from the field mix will be approximately the same as predicted during the mix design stage. However the data shows that compaction was not uniform and it indicated that in some sections weaker resistance to permanent deformation exists. Data obtained from other test sections in California [14] suggests that the post-compaction air void content should be sufficiently low to impart a shear resistance in the mix capable of resisting at least the first three years of traffic to prevent catastrophic failure.

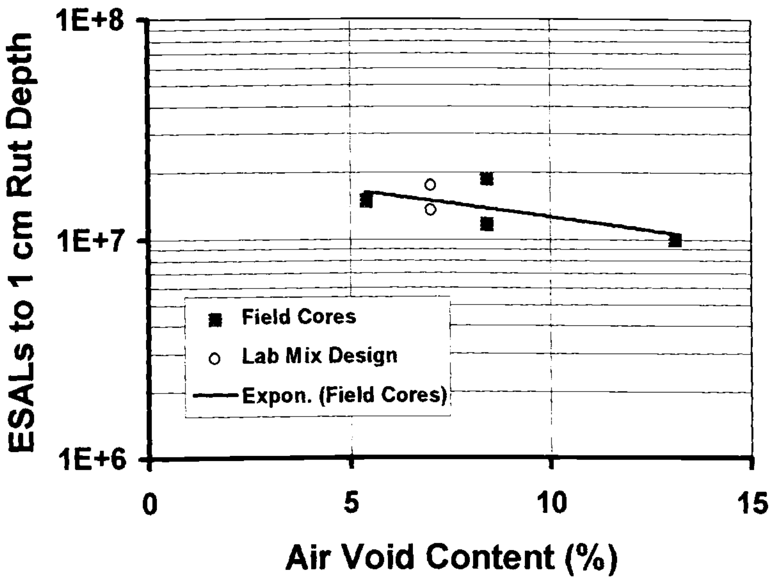

Figure 7 - Comparison between expected performance from field cores and rolling wheel laboratory prepared specimens.

Figure 8 shows an identical comparison made from the results of the fatigue tests. The tensile strains were determined based on FWD data and pavement layer thickness provided by the ADOT. Although no fatigue tests were executed at air void contents similar to those encountered in the field, it can be observed that the trend from the SHRP mixes is the same. For comparison a few fatigue tests were executed from the beams cut from the Marshall section and it can be seen that the expected fatigue performance of the two test sections is clearly different.

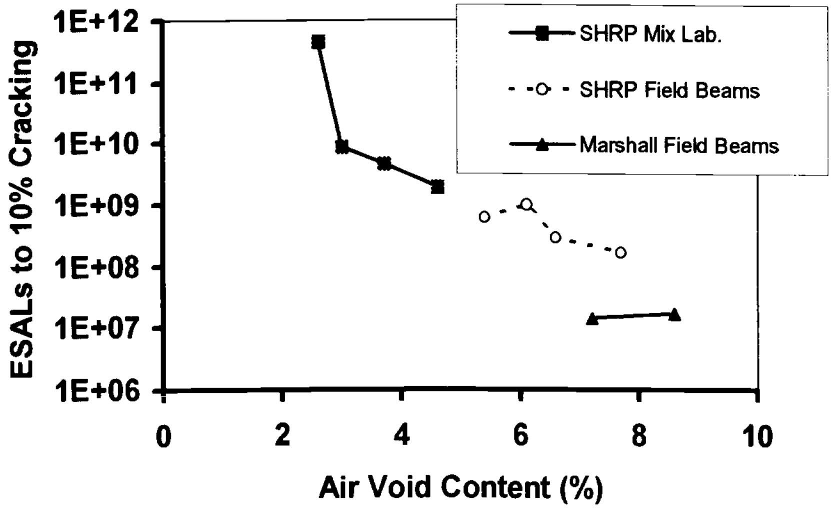

Figure 8 - Comparison between expected fatigue performance of field beams and beams obtained from the laboratory prepared specimens in the mix design stage.

These results indicate that the mix that was placed in the field is expected to have a performance in terms of fatigue and permanent deformation identical to that studied in the laboratory.

I-17 Case Study

An inlayed overlay was placed on I-17 near Phoenix in 1993. A modified binder was used in this project to satisfy the PG70-10 grade recommended for the location. The average 7-day maximum surface pavement temperature at the site is 68.1 °C with a standard deviation, based on 33 years records, of 1.7°C from the SHRP. From these values the temperature at the critical depth for shear deformation, 50 mm, was computed to be 61.3 °C. Considering that it is desired that there be a high reliability that this temperature not be exceeded, two standard deviations were added (approx. 0.95% reliability) to that value to yield the test temperature of 65°C.

All the tests in this project were executed in the University of California at Berkeley (UCB) laboratory. Cores were taken from the field and flown to UCB because the trailer was not yet available otherwise they would have been tested on-site.

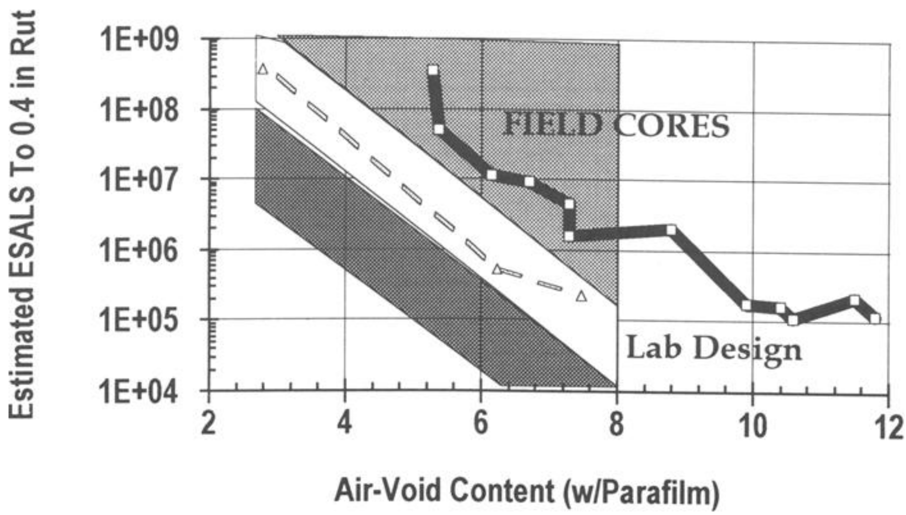

Figure 9 - Comparison between expected performance of field cores and that obtained during the mix design stage.

In this case the results presented in Figure 9 indicate that the field performance is expected to exceed the provisions made during the mix design stage. This was later attributed to changes in aggregate gradation and percentage of crushed faces in the aggregate.

SUMMARY AND CONCLUSIONS

This paper presents a concept for performance based field quality control sponsored by the Arizona Department of Transportation in which performance related tests were used in the mix design and construction quality assurance process. The repetitive simple shear test at constant height and the flexural four point bending beam test and associated analysis procedures were evaluated in this effort.

The field quality control and assurance procedures based on those tests recognize that mix performance is strongly dependent on air void content, and that air void content of asphalt-aggregate pavement layers near the surface decreases with trafficking. It addresses fatigue and permanent deformation considerations and could be extended to thermal cracking. Two of the key features of the approach are: first, quality control is based on the performance of cores and beams taken from the constructed pavement and, second, that performance is compared, at the appropriate air void content, with the design performance obtained from mix design testing of laboratory compacted specimens.

It was concluded that the integration of mix design with the field quality process proposed was feasible. For easier implementation a field quality control trailer was adopted which permits the execution of those fatigue and rutting tests near the job site in the field or at a mix plant, thus reducing turn around time to a minimum.

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This paper represents the views of the authors which may differ from those of the organizations with which they are associated.

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CONSIDERATION OF HOT MIX ASPHALT THERMAL PROPERTIES DURING COMPACTION

REFERENCE: Chadbourn, B. A., Luoma, J. A., Newcomb, D. E., and Voller, V. R., ''**Consideration of Hot Mix Asphalt Thermal Properties During Compaction,**'' Quality Management of Hot Mix Asphalt, ASTM STP 1299, Dale S. Decker, Ed., American Society for Testing and Materials, 1996.

ABSTRACT: A computer program was developed at the University of Minnesota to predict asphalt concrete cooling times for road construction during adverse weather conditions. Cooling models require extensive experimental data on the thermal properties of hot-mix paving materials. A sensitivity analysis was performed to determine which thermal properties affect pavement cooling times significantly. The results indicated that more information on asphalt thermal conductivity and thermal diffusivity is required. Two suitable test methods for determining these properties at typical paving temperatures and densities were developed, and preliminary results for dense-graded and stone-matrix asphalt (SMA) mixes agreed well with values reported in the literature.

KEYWORDS: cooling model, finite difference, hot-mix asphalt, late season paving, slab specimen, stone-matrix asphalt, thermal conductivity, thermal diffusivity, thermal probe

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INTRODUCTION

Background

High demand for new asphalt pavements often requires that paving be done in unfavorable construction conditions. Low air temperatures, high winds, and night construction create adverse conditions for hot-mix asphalt paving. These conditions, though most common late in the paving season, may occur at any time. This presents a risk for owners and contractors. To achieve optimum load-bearing and weathering characteristics, an asphalt mix must be compacted to a specific range of density, and the time required for hot-mix asphalt to reach the proper compaction temperature to achieve this density decreases with an increased rate of cooling.

Hot-mix asphalt compaction is generally begun as soon as the mix can support the roller weight. The roller operator determines the best time to begin compaction by means such as judging the depth of a heel imprint. This method works well when the ambient temperature is high enough. However, low ambient temperatures, high wind speeds, and night construction increase the rate of heat loss from the mix. During these conditions, the ability to predict mix temperature is more critical

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because the time available for mix compaction is decreased. A computer tool that will predict pavement temperature profiles from easily acquired mix design and weather information will increase the certainty of reaching the desired level of compaction by rapidly providing an estimate of the time to reach a temperature below which compaction cannot be achieved.

J. S. Corlew and P. F. Dickson [1] pioneered the use of computational methods in predicting pavement cooling profiles, and many researchers since have developed similar models. Most of these models take the form of an explicit or partially implicit finite difference scheme. Given the scarcity of experimental data on hot-mix asphalt thermal properties, constant pavement density and thermal properties are typically assumed. A sensitivity analysis was performed to determine the effect varying thermal properties have on pavement temperature profiles and cooling rates. It was determined that a pavement cooling model should incorporate thermal property variations related to mix type, temperature, and density.

Objective

The main purpose of this research was to lay the groundwork for the design of an interactive paving tool. The model required extensive experimental data on the thermal properties of various hot-mix paving materials, including information about how hot-mix thermal properties vary with mix type, temperature, and density. A search of the literature revealed a wide range of reported thermal conductivity values for asphalt concrete and limited information on the specific heat and thermal diffusivity of asphalt concrete. However, mixture types, temperatures, and densities were rarely reported in the literature. Two test methods were developed to measure the required thermal properties.

Scope

A sensitivity analysis was conducted to determine which thermal properties have a significant effect on hot-mix cooling rates. Thermal conductivity and thermal diffusivity tests for hot-mix asphalt were then developed. These tests were conducted on dense-graded and stone-matrix asphalt (SMA) mixtures at temperatures and densities typically found in a hot-mix asphalt lift from initial lay-down through final compaction.

COMPACTION OF HOT-MIX ASPHALT PAVEMENT

The compaction process has a great effect on the strength and durability of hot-mix asphalt pavement. The main objective of pavement compaction is to achieve an optimum density. This helps to ensure that the pavement will have the necessary bearing capacity to support the expected traffic loads and durability to withstand weathering.

In asphalt binders, viscosity changes with temperature. Research has shown a 1,000-fold increase in asphalt viscosity as the temperature drops from 135 to 57°C. There was also a ten-fold increase in resistance to compaction as mix temperature dropped from 135 to 63°C, due entirely to an increase in binder viscosity [2]. Attention to compaction is especially crucial in cold weather conditions, when air voids after compaction can be as high as 16 percent. Pavements with this level of air voids have shown signs of deterioration after two years [2].

Once a paving job has begun, temperature control is the principal means of controlling compactibility. A means of controlling temperature at the time of compaction is by adjusting the lag time between the paver and the roller. There is, however, a limit to the amount the lag time can be reduced. In 1971, contractors determined that 10 minutes was the absolute minimum allowable compaction time needed with the present equipment [3]. Cold air and base temperatures can reduce the lag time for a given lift thickness to the point where the mix cannot be adequately compacted. This can be rectified by increasing the lift thickness, allowing the mix to retain heat longer [4]. Another consideration is the lack of traffic densification during the winter months. Therefore, pavements constructed late in the season should be roller-compacted as close as possible to 100 percent of the laboratory-compacted density [2].

Assuming density affects pavement thermal properties, a pavement cooling model will require information on how the density and thickness of a hot-mix asphalt lift change with each pass of the roller. Tegeler and Dempsey reported that density changes in hot-mix asphalt have a much greater effect on the thermal conductivity of hot-mix asphalt than temperature changes. A paving mixture will typically leave the spreader with a density at 75 to 80 percent of the laboratory-compacted density. They estimated that thermal conductivity values range from 1.04 W/mK immediately behind the paver to 1.56 W/mK after final compaction [3].

THERMAL PROPERTIES OF PAVEMENT MATERIALS

A mathematical relationship that explains the cooling behavior of hot-mix asphalt is required to predict cooling rates. Cooling occurs by three modes: conduction, convection, and radiation. Although convection and radiation are necessary components of a pavement cooling model, they are not needed for the thermal calculations defined in this paper. Conduction theory describes the transfer of heat through a solid, and is the basis of the basic thermal properties required for a pavement cooling model. Conduction is described by Fourier's law, which states that the heat flux in a given direction, is proportional to the temperature gradient in that direction. The proportionality constant in this relationship is called thermal conductivity [5]. One-dimensional steady-state heat conduction is described by the following equation:

$$q_z = -k\frac{dT}{dz} \tag{1}$$

where

q_z = heat flux in the z (vertical) direction, W/m^2,

k = thermal conductivity, W/mK,

T = temperature, K

z = vertical distance, m

Describing transient heat flow requires two more thermal properties. Specific heat is a measure of the heat required to increase the temperature of a mass by one degree. Thermal diffusivity is a measure of heat propagation speed. These properties, along with density are related by the following equation:

$$\alpha = \frac{k}{\rho C_p} \tag{2}$$

where

α = thermal diffusivity, m^2/s,

ρ = density, kg/m^3,

C_p = specific heat, J/kgK.

Transient heat flow is represented by the following relationship, known as the diffusion equation:

$$\frac{d^2T}{dz^2} = \frac{1}{\alpha}\frac{dT}{dt} \tag{3}$$

where

t = time, seconds.

Although thermal conductivity was the most commonly reported asphalt thermal property, thermal diffusivity alone was required to predict pavement cooling rates. If thermal diffusivity values are not available, then thermal conductivity, specific heat, and density values are required to predict cooling times.

SENSITIVITY ANALYSIS

A sensitivity analysis was conducted on a spreadsheet program on a personal computer. Thermal conductivity, specific heat, and thermal diffusivity were varied according to the ranges reported in the literature. All other variables were held constant. The model was based on an explicit finite difference algorithm developed by Corlew and Dickson [1]. The model predicted a significant difference in cooling times for hot-mix asphalt pavements over the range of thermal properties reported in the literature. For example, the predicted time for a 60 mm lift to cool from 135 to 80°C ranged from about 10 minutes at the lower values of thermal conductivity and thermal diffusivity to over 60 minutes at the higher values. The effect of specific heat was less significant. These results indicated a need for further analysis of asphalt concrete thermal properties, especially thermal conductivity and thermal diffusivity.

COMPUTER MODEL

The final version of this computer tool will consist of a user interface, a pavement cooling model, and a knowledge-based expert system (Fig. 1). The user interface includes a keyboard and/or a pointing device such as a mouse. The pavement cooling model was based on an implicit finite element scheme utilizing transient heat flow theory. The expert system will be programmed using a commercially available expert system shell.

A pavement cooling model requires information on the densities and thermal properties of the pavement layers, as well as environmental conditions. Jordan and Thomas [6] recommended the following parameters:

1. Densities of pavement layers
2. Thermal conductivity values
3. Specific heat values
4. Ambient temperatures
5. Wind speeds
6. Convection coefficients
7. Incident solar radiation
8. Coefficients of emission and absorption of solar radiation for the pavement surface
9. Time and depth increments
10. Initial pavement temperature profiles

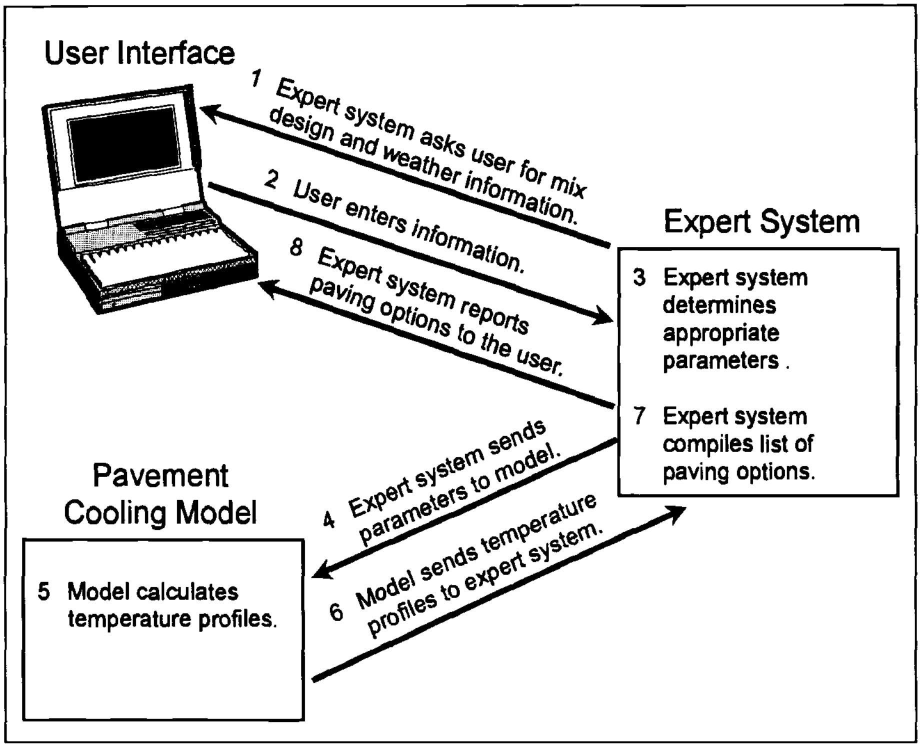

FIG. 1--Asphalt pavement cooling tool schematic.

Ambient temperatures and wind speeds are easily acquired at the site or estimated from local weather reports. The convection coefficient and incident solar radiation are difficult to determine exactly, but an adequate means of estimating the convection coefficient from wind speeds and estimating the incident solar radiation from location, time, and cloud cover information were included in the cooling model. The coefficients of emission and absorption used were those assumed by Corlew and Dickson [1]. Time and depth increments were chosen to optimize accuracy and computing speed. The initial temperature profile of the existing structure on which the hot-mix will be placed was assumed to be constant and equal to the measured surface temperature. The initial hot-mix temperature profile was assumed to be constant and equal to the mix temperature behind the paver.

The current version of the Asphalt Pavement Cooling Tool consists of an input screen that prompts the user for all necessary data, a finite element model, an output window that displays the cooling time, and a module that plots the cooling curve. The hardware requirements include an IBM compatible personal computer (386 or better), Microsoft Windows 3.1 (or later), at least 1 megabyte of free hard disk space, at least 4 megabytes of RAM memory, and a VGA 640 x 480 monitor. The final version of the program should be available in 1998. It will include an expert system which will provide the user with solutions to many of the paving problems encountered during adverse weather conditions.

THERMAL TEST METHODS

Although there are many standardized methods for determining thermal properties of materials, asphalt pavement presents problems relating to the specimen dimensions required (an assumption of homogeneity requires that the smallest specimen dimension be several times larger than the largest aggregate particle). Another complication involves the change in the asphalt binder as the mix is heated and then allowed to cool. Once a hot-mix specimen is heated above a certain temperature, it must be contained in order to maintain the desired shape. Most of the commercially available thermal property devices were not designed for the standard asphalt specimen sizes or for a loose-mix type of material. Although standard thermal devices can be modified for the purpose of measuring asphalt concrete thermal properties, the cost involved was prohibitive for this investigation.

A test for thermal diffusivity of asphalt concrete slabs was designed in order to provide the necessary thermal information for a pavement cooling model. It involved heating a slab specimen to a constant temperature, and measuring the temperature at several depths over a period of time as the slab cools. The ASTM Standard Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe (D 5334) was modified for use on asphalt concrete cylinder specimens so that experimental results could be compared to the thermal conductivity values reported in the literature. The specimen required for this test was a cylinder similar in dimensions to pavement cores used in triaxial testing of asphalt concrete. Specific heat testing procedures were not considered for this research.

Mixture Design

Mixtures for this study were selected in order to represent two types likely to exhibit different thermal properties. The mixes selected were a standard dense-graded mix, and a 15.9 mm maximum aggregate size stone matrix asphalt (SMA) mix. The dense-graded mix conformed to Minnesota Department of Transportation (Mn/DOT) Type A gradation limits for bituminous mixtures. The SMA mix design followed a typical gradation used in Germany [7]. The aggregate used consisted of crushed granite for particle sizes of 9.5 mm and greater, and a river gravel for particle sizes of 4.75 mm and less. A 120/150 penetration asphalt was used for both mixes. The asphalt and aggregate were mixed by Mn/DOT in a large laboratory mixer. Enough of each mix was prepared to compact three slabs, two cylinders, and conduct a theoretical maximum specific gravity analysis.

The compaction procedure was modeled after a process used by Scholz, et al. [8]. The main advantage of rolling wheel compaction related to this study was the ability to compact a slab specimen that approximates an infinite wall, one-dimensional heat transfer condition. Typical slab dimensions used by Scholz were 710 x 710 x 102 mm. The slabs were compacted with a motorized steel wheel roller.

Slabs of dimensions 380 x 380 x 64 mm were used for this research. The thickness was determined as that of a typical asphalt lift, and the horizontal dimensions were calculated to produce a thickness-to-length ratio less than 0.2. This is the limiting value for square slabs to ensure that temperature variations at mid-slab can be modeled using one-dimensional plane-wall theory [9]. A smaller version of the ramp and mold system used by Scholz was constructed out of wood. Instead of a motorized, steel-wheel roller, a water-filled 457 mm diameter by 560 mm length lawn roller was used to compact the specimen. The total weight of the roller and water at 25°C was 115 kg.

The thermal probe procedure (ASTM D 5334) required the specimen height to exceed the probe length by 100 mm. Tall cylindrical asphalt specimens, 100 by 200 mm, were compacted by a modified Marshall hammer compaction procedure developed at the University of Minnesota. These specimens satisfied the ASTM requirement for probe lengths up to 100 mm.

The mold consisted of a steel tube with an inside diameter of 100 mm and a height of 254 mm The cylinder rested on top of a base plate. A steel rod 2.4 mm in diameter was fixed to the center of the base plate so that it extended 46 mm into the compacted specimen. This created a hole in one end of the specimen so that a 46 mm thermal probe could be inserted.

The compactor used was a single rotating base Marshall hammer apparatus. It was originally designed to prepare large stone specimens with a diameter of 150 mm, and was adapted to accommodate a 100 mm diameter by 250 mm mold. The specimens were compacted in three 1300 g lifts. The number of blows for each successive lift was increased in order to equalize the compactive effort received by the three lifts to achieve consistent voids of 4 to 5 percent in a dense-graded mix. A study of air voids based on compactive effort on tall SMA specimens has not been completed. The number of blows used for the bottom, middle, and top lifts were 20, 35, and 55, respectively.

Slab Cooling Method for Thermal Diffusivity of Asphalt Concrete

Given a specimen of dimensions that approximate homogeneity and conditions that approximate one-dimensional conductive heat flow, it was possible to determine the thermal diffusivity from a first-order time-temperature relationship and a second-order space-temperature relationship. Constant heat flow and constant boundary temperatures were not required. This made thermal diffusivity measurements possible from a very simple test configuration of an asphalt slab, insulated on the sides and bottom, with the top surface exposed to air at a different temperature (Fig. 2). Spatial and temporal temperature gradients were measured with thermocouples at known depths in the specimen.

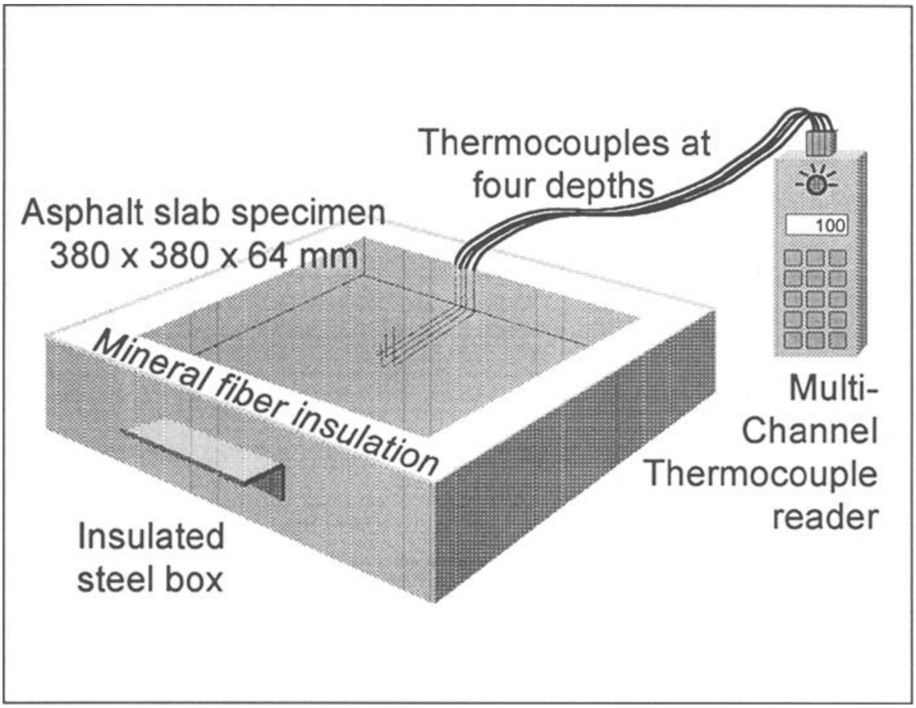

FIG. 2--Thermal diffusivity of asphalt concrete, slab cooling method.

To determine the variation of thermal diffusivity with temperature, small time intervals were selected to approximate linear relationships. At each time step, the average lift temperature was calculated. For each time interval, a linear relationship was fit to a plot of the average temperatures versus time:

$$T = b_1 t + b_2 \tag{4}$$

where

b_1, b_2 = first-order curve-fitting constants.

To approximate the spatial relationship, the temperature reading at the center of each time interval was plotted against the depth and a second-order relationship was fit:

$$T = a_1 z^2 + a_2 z + a_3 \tag{5}$$

where

a_1, a_2, a_3 = second-order curve-fitting constants.

Equation 2 was rearranged to produce the following relationship:

$$\alpha = \frac{dT}{dt} \Big/ \frac{d^2T}{dz^2} \tag{6}$$

The first derivative of Equation 4 with respect to t was determined:

$$\frac{dT}{dt} = b_1 \tag{7}$$

The second derivative of Equation 5 with respect to z was determined:

$$\frac{d^2T}{dz^2} = 2a_1 \tag{8}$$

Equations 7 and 8 were substituted into Equation 6 to determine the thermal diffusivity:

$$\alpha = \frac{b_1}{2a_1} \tag{9}$$

The measured thermal diffusivity versus temperature for three dense-graded and two stone matrix asphalt concrete specimens indicate that all except the SMA loose mix specimen exhibited a similar decrease in thermal diffusivity as the temperature increased (Fig. 3). A decreasing trend was expected, as the thermal conductivity of asphalt concrete decreases with temperature [11], and the specific heat of dry aggregates increases with temperature [11], as does the specific heat of asphalt binders [13]. A minimal density change within this temperature range is expected, so the thermal diffusivity of asphalt concrete as calculated by Equation 2 would decrease with temperature. The difference in the SMA loose mix specimen may be due to the effect of large air pockets in the mix. The thermal diffusivity of air increases with increasing temperature [5], which may cancel the temperature effects of the solid components.

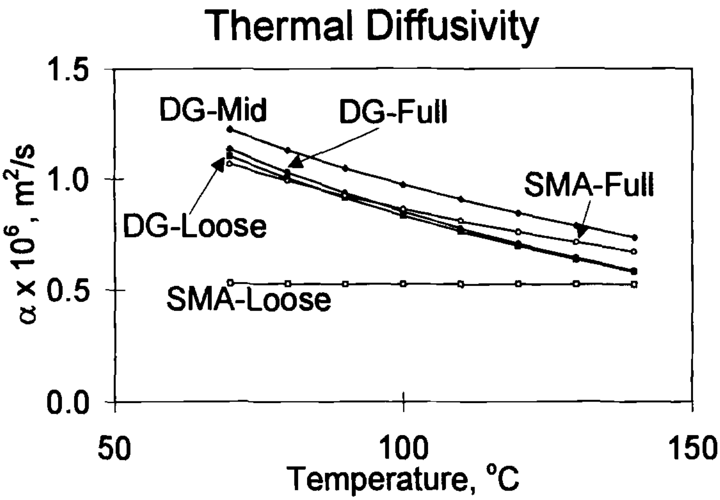

FIG. 3--Variation of thermal diffusivity with temperature.

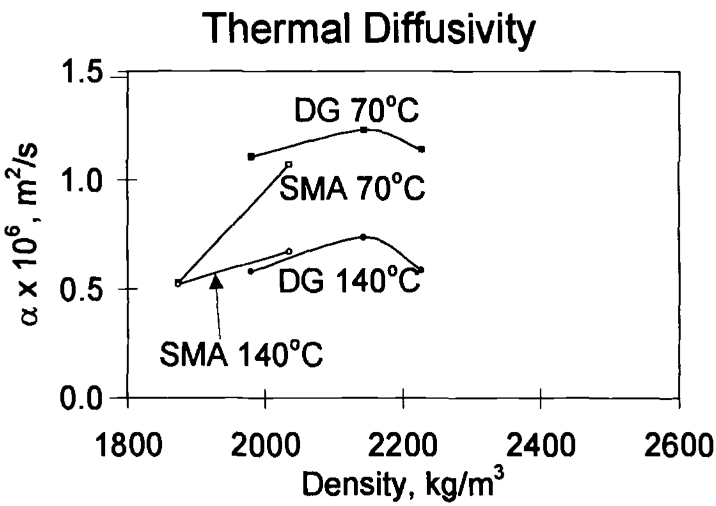

FIG. 4--Variation of thermal diffusivity with density.

The thermal diffusivity of the dense-graded specimens peaked at a point between the two density extremes (Fig. 4). The peak was more pronounced at higher temperatures. These trends were more difficult to interpret. The thermal conductivity is expected to increase with increasing density due to greater particle-to-particle contact. This results in increasing values in both the numerator and denominator of Equation 2. Also, very little is known about how asphalt specific heat varies with density. As a consequence, more detailed information is required to make predictions about thermal diffusivity-density relationships. If a similar trend occurred for SMA specimens, it was not evident as there were only two data points for each temperature.

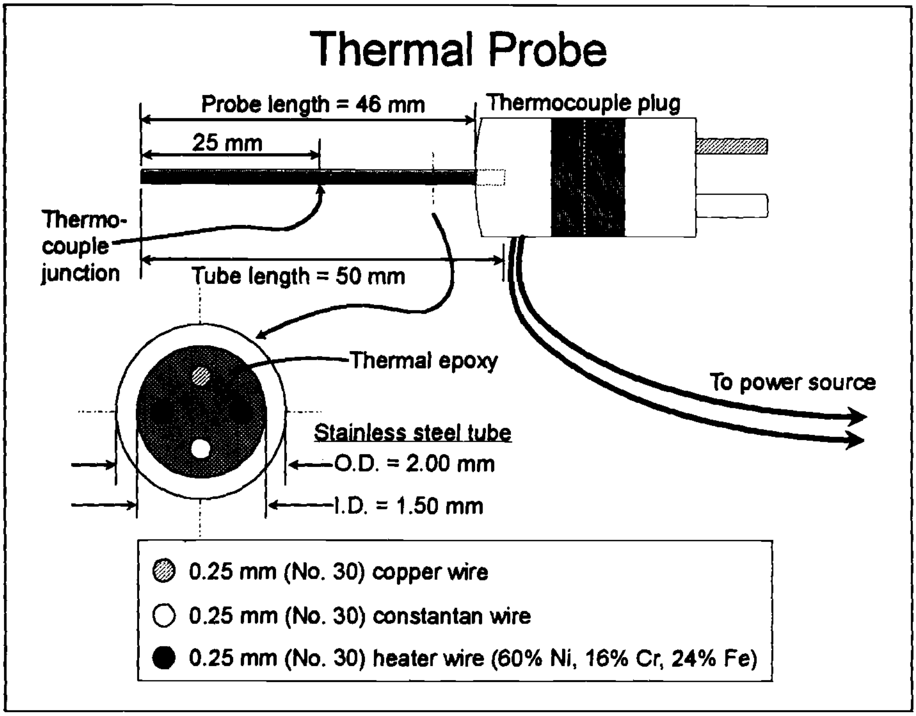

FIG. 5--Thermal probe schematic.

Experimental errors were probably responsible for some of the ambiguity in the thermal diffusivity results. There may have been errors due to interference from large aggregate particles or air pockets. Another source of error resulted from asphalt drain-down in the SMA specimens. Stabilizing materials such as cellulose fibers were not used in these specimens.

Thermal Probe Method for Thermal Conductivity of Asphalt Concrete

ASTM D 5334 required the construction of a thermal probe, which consists of a loop of heating wire and a thermocouple enclosed in a small stainless steel cylinder (Fig. 5). A probe was constructed per the instructions in the test method. The main difficulty involved finding a high-conductivity cement that was workable enough to draw through a 50 mm length of 1.59 mm stainless steel tubing. After several unsuccessful attempts, a working probe was constructed using a 2.00 mm tube. The probe was inserted into a cylindrical asphalt specimen and a constant current was applied to the heating wire (Fig. 6).

Temperature was plotted on the standard axis and time on the log axis of a semi-log graph. The linear portion of the curve was identified, and the values representing the temperatures and times at the ends of the linear portion (T_1, T_2, t_1, and t_2) were determined (Fig. 7). The following equation was used to calculate thermal conductivity:

$$k = \frac{EI}{4\pi(T_2 - T_1)} \ln \frac{t_2}{t_1} \qquad (10)$$

where

E = voltage, volts
I = current, amperes
L = heated length of probe = 0.051 m

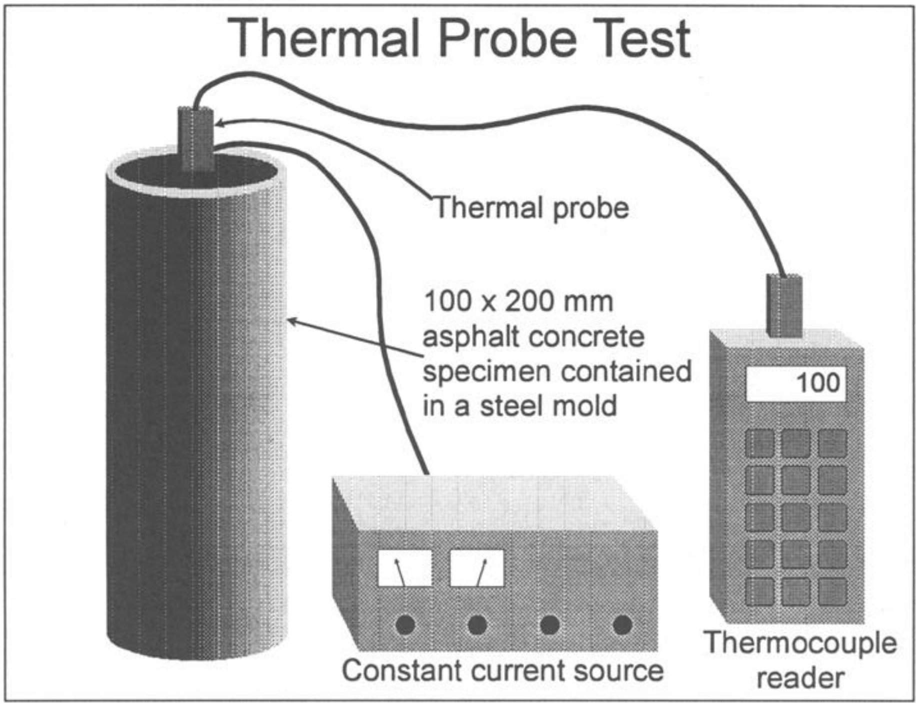

FIG 6--Thermal conductivity of asphalt concrete, thermal probe method.

Tests conducted on the dense-graded specimens resulted in curves with easily recognizable linear segments on the semi-log plots. The SMA specimens presented difficulties as large temperature gradients developed between the probe and the specimens. Large gaps between particles most likely prevented effective heat dissipation away from the probe resulting in the initial rapid temperature increase. This resulted in plots with short or non-existent linear portions. Larger probe sizes may improve the SMA test results.

Thermal conductivity differed significantly with respect to mix type, although the responses to temperature changes were similar (Fig. 8). The variation of thermal conductivity with density was also different for the dense-graded and SMA mixes (Fig. 9). Both mixes exhibited a positive correlation between thermal conductivity and density, but the SMA mix had a much steeper slope. This may be due to the greater degree of inter-particle contact in compacted SMA specimens.

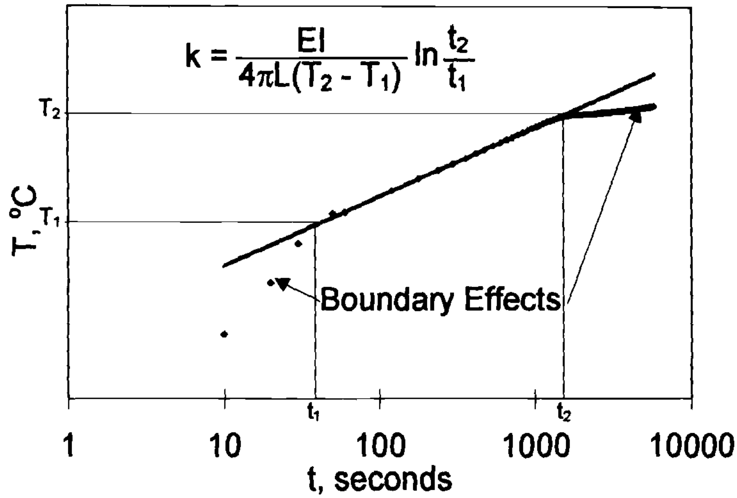

FIG. 7--Thermal probe time-temperature curve.

Although this probe had not yet been calibrated using a thermal test standard, the thermal conductivity values fell within the range of values reported in the literature (Table 1).

Effect on Asphalt Pavement Cooling Rates

Pavement cooling computer simulations were conducted for the thermal diffusivity and thermal conductivity values determined in this project. For the purposes of comparison, the specific heat was held constant at 920 J/kgK (0.22 Btu/lb°F), the value recommended by Corlew and Dickson (p. 114), and the thermal diffusivity values were calculated from the thermal conductivity values modeled in the sensitivity analysis and the specimen densities (Equation 2). The ranges of both the thermal diffusivity and thermal conductivity values measured for this study represented a tripling of the cooling rate of a 40 mm (1.6 in.) lift and a quadrupling of the cooling rate of a 100 mm (3.9 in.) lift. The model used in the sensitivity analysis indicated that decreasing the temperature from 140 to 70°C (284 to 158°F) resulted in a 20 percent increase in the cooling rate for the dense-graded mix, and between a 50 and 80 percent increase in the cooling rate for the SMA mix.

Although this analysis was based on a fairly simple pavement cooling model, the method was verified as an adequate predictor of pavement cooling rates by Corlew and Dickson. Many of the pavement properties that were assumed to be constant probably were not, but the purpose of this analysis was to gain a preliminary understanding of the impact that various thermal properties have on pavement cooling rates. The range of cooling rates predicted by this analysis indicate a need for further study of these properties and how they relate to late season hot-mix asphalt paving.

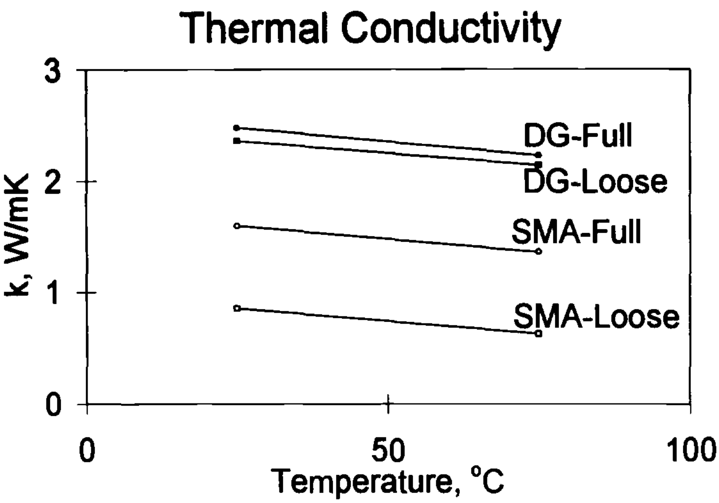

FIG. 8--Variation of thermal conductivity with temperature.

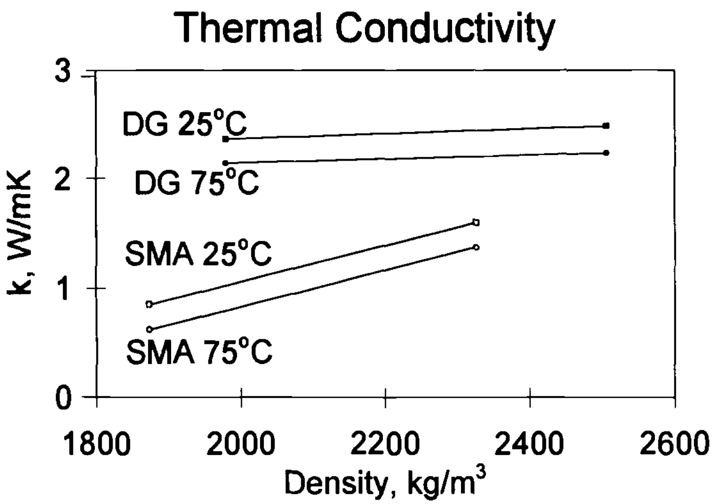

FIG. 9--Variation of thermal conductivity with density.

TABLE 1--Reported thermal properties for asphalt concrete.

k, W/mK	Cp, J/kgK	a x 10^6, m^2/s	Source
0.76	------	-----	Turner and Malloy [10]
0.80 - 1.06	850 - 870	0.37 - 0.53	Jordan and Thomas [6]
1.21	920	0.59	Corlew and Dickson [1]
1.21 - 1.38	840 - 1090	------	Tegeler and Dempsey [3]
1.49	------	------	Kersten [11]
0.85 - 2.32	------	------	O'Blenis [15]
2.28 - 2.88	------	1.15 - 1.44	Kavianipour [15]

CONCLUSIONS

1. The ranges of thermal diffusivity and conductivity values determined by the slab cooling method agree with the range of values reported in the literature.
2. The ranges of thermal diffusivity and thermal conductivity values correspond to a significant variation in pavement cooling rates.
3. Thermal conductivity values calculated from the measured thermal diffusivity values and assumed values of density (2000 kg/m^3) and specific heat (900 J/kgK) agree with the measured thermal conductivity values.
4. Thermal diffusivity values determined by the slab cooling method should be suitable for use in the adverse weather paving tool.

RECOMMENDATIONS

The following steps should be taken to verify the effects of asphalt thermal properties on hot-mix asphalt pavement cooling rates and to further the development of an adverse weather paving tool:

1. Develop a test method and apparatus for measuring the temperature at several depths in behind-the-paver hot-mix asphalt lifts.
2. Calibrate the slab cooling and thermal probe methods using thermal reference standards which have thermal conductivity and thermal diffusivity values comparable to those reported for asphalt concrete.
3. Conduct a complete test program to determine the variation in hot-mix asphalt thermal conductivity, thermal diffusivity, and specific heat values resulting from the temperature and density changes that occur throughout the compaction process.
4. Incorporate measured thermal diffusivity values into the adverse weather paving tool.
5. Locate the appropriate sources of expert information for development of the expert system.
6. Test pre-release versions of the adverse weather paving tool for field verification and software improvements.
7. Develop a training program for implementation of the final version of the adverse weather paving tool.

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