AUTOMATED QUALITY CONTROL OF HOT-MIX ASPHALT CONSTRUCTION OPERATION

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Abstract: The quality of finished Hot-Mix Asphalt (HMA) pavement is important to owners, contractors, and highway users. Primary factors affecting quality of HMA pavement are material properties, mix volumetrics, compaction energy, temperature, moisture content, thickness of mat, and subgrade support. A systems approach is necessary to control these multiple and often-changing factors during HMA construction operations in an effort to achieve a quality pavement. The framework is developed through a systems approach using currently available state-of-art technologies. These technologies are comprehensively reviewed, and selected technologies are recommended for the future research and development of the proposed quality control system.

Keywords: quality control, hot-mix asphalt, systems approach, construction operation.

1. INTRODUCTION

Highway construction is known to be the most conservative segment of the construction industry. In particular, the current practices of Hot-Mix Asphalt (HMA) construction are largely based upon experience and standard acceptable practice. HMA construction demands improved process control, monitoring, and feedback documentation to meet the new requirements set by the Superpave™ and Quality Control/Quality Assurance (QC/QA) specifications.

The quality of finished HMA pavement has significant financial implications upon HMA contractors because quality measures are the mechanism to determine contractor payment by the owner. These quality requirements are of vital importance to owners and users because they are directly related to serviceability throughout the intended design life, by providing the end-user with riding comfort and safety. Generally, three properties are measured to describe the quality of finished HMA pavement: (1) material properties, (2) density, and (3) smoothness.

Factors affecting the quality of HMA pavement are material properties, mix volumetrics, compactive effort, temperature, thickness of mat, and subgrade support. Historically, monitoring of mix properties has been used to measure and control the quality of a mix. However, mixes produced with the required asphalt content (AC) and aggregate gradation have not always performed as intended. A change in the fundamental composition of the mix occurs from design to construction.

Incorporating volumetric mix design properties into the field QC system can help identify mix-related problems before HMA is placed on the roadway. When these properties are monitored in the field, engineers have the necessary information to identify potential problems and make corrective actions. Figure 1 presents the relationship between the field lab and HMA construction operations.

The framework for the quality control of the HMA operations is proposed using a systems approach. The framework is developed through a systems approach using currently available state-of-art monitoring technologies. These technologies are

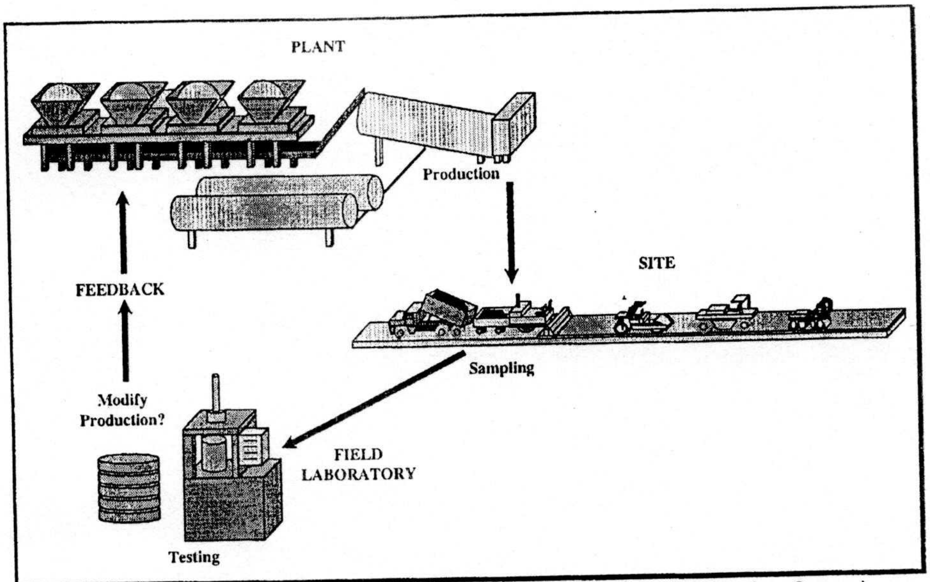

Figure 1. Relationship of Field Laboratory Testing to HMA Construction Operations

comprehensively reviewed, and selected technologies are recommended for the future development of the field management system.

1.1. Problem Statement

Current HMA construction operations require innovative process control techniques to meet the new requirements set forth by the Superpave^{TM} and QC/QA specifications. It is an opportune time to integrate state-of-art technologies into HMA construction operations thereby linking inputs, processes, and outputs of the system. Accurate and efficient measurement of these system variables is critical to understand densification characteristics of HMA during the rolling process. Integrating these technologies to balance quality and productivity from the systems perspective is not an easy task.

The development of computerized tools is desirable to perform the above tasks efficiently. The construction industry has traditionally lacked an organized assemblence of data; data that can be used to understand the process and provide important feedback. Recent rapid deveopment in electronic and computer industries has produced innovative technologies and products that can be readily adapted to HMA construction operations.

1.2. Research Objectives

There are three principal objectives of this paper: (1) to investigate the influential factors that affect the quality of HMA pavement, (2) to investigate the currently available technologies for real-time monitoring of the factors, and (3) to develop a framework for quality control system of HMA construction operations by integrating material and construction concerns.

1.3. Research Methodologies

Organization of HMA operations into a single system is complicated and has a great number of variables that are dynamic and constantly changing. An appropriate method to explore this scenario is to use a systems approach. The central tools of system analysis are models. System analysis requires models to predict the consequences that would result from certain inputs. The most frequently used modeling techniques for systems analysis are quantitative [1].

In this paper, quantitative models such as statistical models are the vital tools for systems analysis.

2. FACTORS AFFECTING QUALITY

2.1. Factors Affecting Density

There are numerous factors that affect the densification of HMA by the rolling process. Factors can be largely divided into (1) mix-related properties, (2) compactive effort, (3) temperature, (4) thickness of mat, and (5) subgrade support.

Several properties of both the coarse and fine aggregates are important in achieving the desired density. Particle shape, angularity, absorption, and surface texture are important properties of the individual aggregates. Aggregate shape and surface texture contribute to the toughness of a mix.

Aggregating gradation is perhaps the most important property of the mix. It affects all the important properties of HMA, including stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance, and resistance to moisture damage. The gradation of the combinated aggregates as influenced by the maximum aggregate size, the concentration of coarse aggregate, the amount of fine material, and the amount and type of filler, all play important roles in influencing density [2].

If AC, which is the most important parameter determined during the mix design, is low, the mix acquires a certain stiffness making it difficult to compact. On a number of projects, the amount of density obtained in the field increases significantly by an increase of 0.2 to 0.3 percent in AC [3].

Filler and the ratio of filler to AC, often called the filler-asphalt ratio, both have an influence on the density of a mix. Another mix property that affects compaction is fluid content, which is the sum of the AC and the moisture content of the mix [4].

Compactive efforts are applied by both paver and rollers. The paver applies the compactive effort with the screed and results in the initial density of mat. Other density requirements are met by a series of rollers, that apply the compactive effort by combinations of several controllable variables, such as static force, dynamic force (frequency, amplitude, eccentric weight), speed, tire pressure, and number of passes.

It is generally agreed that with a normally-behaving mix, the compaction is difficult at temperatures below 175 °F. Also, it will be logical to assume that the stiffness of the supporting material is important.

Thickness of mat is important from three standpoints: (1) absolute thickness of mat being compacted, (2) thickness in relation to the largest size of aggregate in the mix, (3) uniformity of the thickness, and (4) the ability to retain heat as the thickness increase. [4].

2.2. Factors Affecting Smoothness

Pavement smoothness can be a function of many construction variables, such as mix-related properties, operation-related variables, and condition of existing pavement base. The size of aggregate could affect the smoothness if the maximum aggregate size of the HMA equals the depth of the lift and comes in contact with both the underlying course and roller drum.

Mix stiffness is controlled at the asphalt plant by keeping the mix temperature, aggregate gradation, and fluids content (AC plus moisture content) within normal specification limits. Any factors that cause either the volume or the stiffness of the mix at the screed to rise and fall can cause roughness in the HMA pavement [5].

Long waves in the smoothness can be caused by truckload-to-truckload segregation of the mix and by changes in mix temperature. Delivery of the mix to the paver can be a factor in long-wave roughness, particularly if the haul truck abruptly impacts the paver or if the truck driver holds the brakes while the truck is being pushed by the paver.

In a longitudinal direction, the rollers should not stop at the same transverse endpoint with each pass of the roller, nor stop abruptly. The reversal points should be staggered to prevent shoving of the mix. Also, the proper coordination of frequency, amplitude, and speed for vibratory rollers is essential to achieve acceptable smoothness [4].

One final factor can be the condition of the underlying surface. The long waves may be a reflection of the waves present in the base material.

3. MONITORING DEVICES

A system can not be achieved without effective monitoring of inputs, processes, and outputs. The measurement and feedback from an appropriate monitoring system will enable the efficient communication between the systems, as well as within a system. There are technologies currently available to meet this requirement. Some technologies are not intended to be used by the construction industry, however, necessary modifications will satisfy the specific needs.

The objective of the system is to collect the information of continuously changing variables of interest. The system for HMA construction will require the information related to properties of HMA, compactive effort, temperature, thickness of mat, speed, position, density, smoothness, and so on.

The following sections discuss the available technologies to monitor factors. Most of these technologies are real-time, but some are not. However, such non-instantaneous technologies are also important because they can transmit feedback to the system quickly enough to make corrective actions. Table 1 summarizes the recommended monitoring devices for the system.

The Superpave™ Gyratory Compactor (SGC) is a key component of the Superpave™ mix design procedure. This device has been designed to compact HMA samples to a density similar to that obtained in the field. There are three parameters that control the compactive effort on the SGC; vertical pressure, angle of gyration, and number of gyrations. The Superpave™ procedure is well explained in the Superpave™ Asphalt Mixture Design Illustrated: Level 1 Lab Method [6].

A demand for a faster and safer method to determine AC led to the development of nuclear gauges capable of estimatting the AC in HMA samples. Measuring the AC of compacted specimens by Nuclear Asphalt Content Gauges (NACG) produces satisfactory results once proper calibration is made.

The use of nuclear density gauges on asphalt concrete grew rapidly during the 1970's, as many agencies responded to the speed advantages of

Table 1. Monitoring Devices

Factor (1)	Implementable Device (2)	Note (3)
Lab Density	Superpave Gyratory Compactor	Non- Instantaneous
AC	Nuclear Asphalt Content Gauge	Non-Instantaneous
Field Density	Nuclear Density Gauge or Ground Penetrating Radar	Non-Instantaneous Real-Time
Smoothness	Inclinometer-Based Profilometer or Ground Penetrating Radar	Real-Time Real-Time
Position & Speed	Global Positioning System	Real-Time
Vibration	Transducer	Real-Time
Temperature	Infrared Thermometer	Real-Time
Thickness	Ground Penetrating Radar	Real-Time
Moisture Content	Guided Microwave Spectrometry	Real-Time

nuclear gauges over cores [7]. The short test time for nuclear gauges allows sampling frequencies to be increased. More importantly, it provides contractors with feedback while the pavement is still hot, thereby allowing further compaction.

The need for more accurate and cost-effective data-gathering techniques, as well as the increasing demand for spatial data, require the latest and best technology available. One technology that makes these tasks easier, and more accurate is the Global Positioning System (GPS). Among various types of GPS, real-time kinematic GPS is desirable for monitoring position and calculating speed of equipment used in HMA project.

A thermometer successfully employed by past research projects to measure the temperature of HMA mat during compaction was the non-contact infrared thermometer. This provides temperature data via both current and thermocouple output for closed-loop control.

For measuring internal moisture trapped in HMA, a unique technology known as Guided Microwave Spectrometry (GMS) may be an ideal solution to a problem. GMS can be installed on a paver to automatically measure trapped moisture. This would improve accuracy and save time [8].

Transducers may be used to measure vibration when attached to the rotation shaft inside the roller's drum. This type of device is generally used in mechanical industry, and this converts mechanical stimuli into electrical output.

Various types of equipment have been developed to evaluate the smoothness of pavements over the past century. The devices that deserve a closer attention are the inclinometer-based profiling system, that are usually portable, easy to operate, and accurate. They are commonly pushed by the operator at walking speed. It continuously records the relative height of successive points at intervals, storing the vertical and horizontal deviation from the starting position in an on-board notebook computer.

Ground Penetrating Radar (GPR) and capacitance-based dielectric surface probe devices are used to measure fluctuations in air voids, bitumen content, or both, in newly-placed pavements without causing structural damage. GPR enables pavement thickness as well as variation in pavement voids content to be measured rapidly from a moving vehicle.

The past research project by the authors has tried nuclear density gauge, real-time kinematic GPS, and infrared thermometer on several paving jobs. The testing results showed that the GPS, and infrared thermometer produce fairly precise measurements. However, the precision and the accuracy of the nuclear density gauge were relatively lower than expected and this problem could be overcome by proper calibration, more number of measurements, and appropriate statistical technique such as moving average method. The tests have proved that the recommended devices can be integrated into one system to achieve the field management of HMA construction operations.

4. ENVISIONED SYSTEM

The characteristic of monitoring and feedback of the system in real-time provides a dynamic means for implementing effective quality control during construction. This characteristic improves construction operations by optimizing resource handling and also improves product quality and productivity. The field management requires design standards, field data collection, field management, site constraints, and project designs to be processed together.

Project personnel in the process require information on what is occurring within the system to decide if corrective action should be taken. Feedback requires project personnel to communicate project concerns with one another. If changes to the preceding process are required, based on the output of the succeeding processes, field personnel aware of required changes must provide the feedback to the preceding process for correction.

For feedback to be used effectively, all parties involved in the quality control system should have up-to-date information on defects, causes, and corrective actions. This will lead to improvements in the process, resulting in a better quality product. Likewise, improved feedback can lead to efficient HMA construction, resulting in a higher quality pavement.

A systems approach is applied to HMA construction operations by integrating (1) field laboratory results, (2) real-time monitoring of environmental conditions and resources, and (3) construction equipment characteristics, using a compaction model. This model will benefit users and contractors by enhancing control and decision-making to achieve improved productivity as well as enhanced quality. These integrated components will systematically use mix properties measured in the field lab, with Superpave™ equipment, and estimate how construction methods should be planned and controlled in real-time to efficiently complete paving operations with the optimum quality of the finished product.

5. PROTOTYPE MODEL

Based on (1) factors that have been known to affect the quality of HMA mat, (2) empirical modeling techniques, (3) simulation modeling techniques, and (4) currently available technologies, the prototype model of field management system of HMA construction operations can be developed by integrating all the components into a system. Figure 2 presents the model. The figure basically illustrates two parts: (1) the system for the field management of HMA construction operations and (2) technologies available to monitor or to control the inputs and processes within the system.

There are two types of inputs: (1) variable and (2) stable. Variable inputs are ones that continuously change and/or can be adjusted by the system. On the contrary, stable inputs are fairly constant throughout the day or the project duration. For example, once the asphalt binder grade has been selected for a project, it is likely that the same binder will be used throughout the project duration. Likewise, the static force of the roller will not vary significantly during the operation. Other variable inputs such as position, speed, frequency, and amplitude will vary continuously.

An interesting fact is that these position, speed, and vibration are also generated by the system as the control outputs. This happens because they are controllable variables as well as inputs. The narrow arrow on the right side illustrates this feedback loop. Slightly different types of control output are aggregate gradation and AC. They are sent to the outer system, production system in this case, and serve as the inputs of that outer system. The other narrow arrows illustrate this feedback loop.

The system consists of three modules: (1) database, (2) analysis/modeling, and (3) control. Whenever input enters the system, it passes through the database to be stored and redirected to analysis/modeling and control modules. The analysis/modeling module analyzes and develop empirical models with the input. The developed model is sent to the database module for storage and to the control module for decision-making. The control system decides whether to generate new control output based on the models and inputs received from the database and the analysis/modeling modules. A more detailed description of the system can be found in Lee [10].

6. CONCLUSION AND RECOMMENDATION

The current practices in HMA construction operation are largely based upon experience. The new mix design protocols from Superpave™ and QC/QA necessitate efficiency in both crews and equipment. HMA construction requires better process control, monitoring, and feedback documentation to meet the new requirements.

Factors that affect density and smoothness of HMA pavement are material properties, mix volumetrics, compactive effort, temperature, thickness of mat, and subgrade support. Compaction is considered to be the single most important factor affecting the performance of HMA pavements.

The field management system of HMA construction operation should be supported by state-of-art technologies to monitor the operation in real-time and to send the feedback promptly and continuously. Currently available technologies can readily support the system by monitoring processes and factors mostly in real-time.

The continuous effort to advance data collection techniques and the willingness to employ them to the HMA operations are vital for the successful development and implementation of the proposed system.

The following issues are recommended for the future research:

- Adaptation of the technologies to actual HMA construction projects to collect data and to assess the limitations in implementation; and
- Develop a compaction model in the form of every measurable independent variable [e.g., density = f(aggregate gradation, AC, moisture content, compactive effort, speed, thickness of mat, temperature, etc.)].

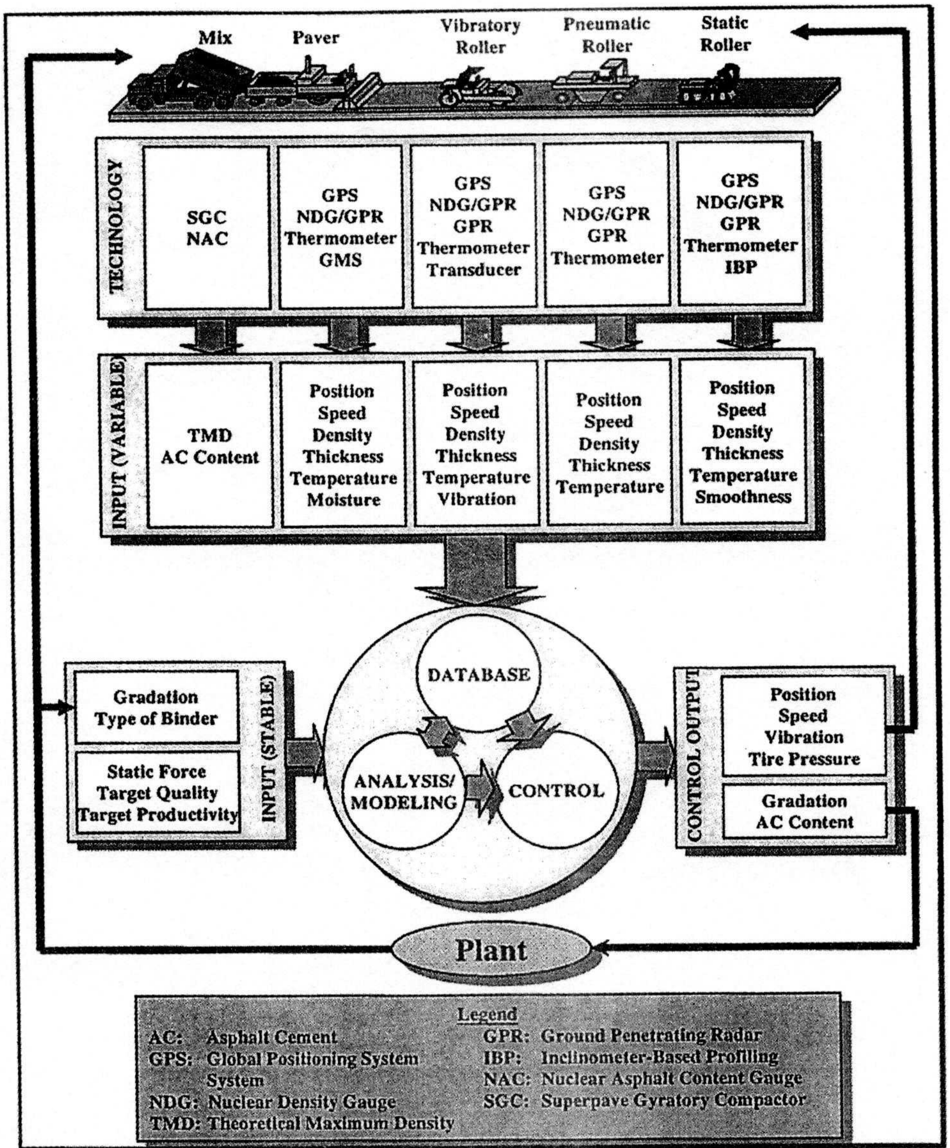

Figure 2. Framework for Field Management of HMA Construction Operation

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