Automated Hot Mix Asphalt Construction System by Integrating Productivity and Material Quality

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Abstract

This paper describes the current progress on the development of an automated Hot Mix Asphalt (HMA) construction system that integrates productivity and material quality to achieve the cost-effective construction operation within material specification criteria. It is a challenging task to analyze HMA operation, as its elements are complex and dynamic. This difficulty can be overcome by adapting systems approach. The analyses of HMA operation using systems approach are provided. Quantitative models are widely used tools for systems analysis. Simulation and empirical modeling techniques, which are appropriate for quantitative models, are adopted for this research. Resource usage options and productivity performance can be evaluated with simulation models. Brief comment on simulation tools for the system is provided. Material property data, such as pavement density and temperature, are measured during compaction process to monitor whether specification criteria are achieved. The regression analysis of material property data collected in the summer of 1997 is provided to show the progress on the empirical modeling. The analysis shows the variables that have significant effect on densification of HMA mat. This automated system is expected to improve the current HMA construction practices that are based on empiricism and insensitive to the changing environmental conditions.

1 Introduction

Hot Mix Asphalt (HMA) pavements account for approximately 96 percent of all paved highways in the United States with annual expenditures for HMA pavements of over $10 billion [1]. HMA contractors, public agencies, and researchers share the common objective of properly constructing functional and high-performing HMA pavements. Meeting this objective requires cost-effective construction, increased productivity, and assurances for quality.

Typically, HMA operation can be divided into two processes: production and construction. HMA production and construction processes combined with delivery process forms the construction phase in the HMA project delivery system. Production processes are performed at either fixed or mobile HMA mix plants. Construction processes can be further divided into placement and compaction processes. Placement process is performed by a paver, and compaction process by series of rollers. Figure 1 shows the sequence of HMA operation.

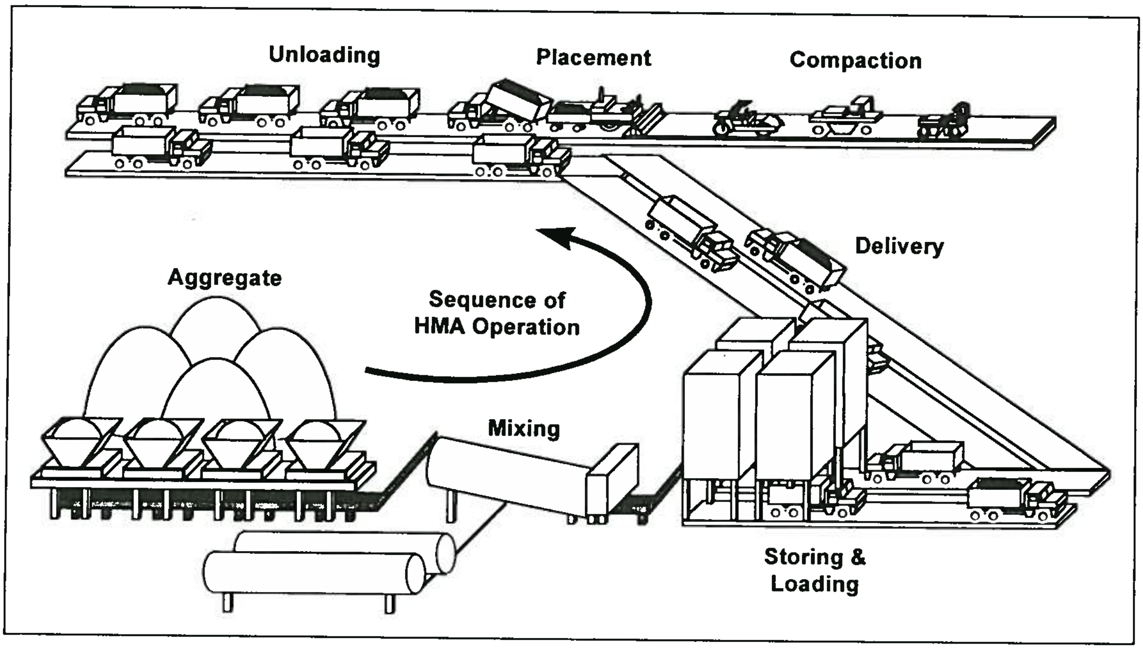

Figure 1. Overall View of Hot-Mix Asphalt Operation

Understanding HMA operation from the process and material points of view is a challenging task, as the operation has complicated organization and a great number of dynamic processes. An appropriate method to explore this kind of subject is systems approach. This paper presents the use of systems approach to explore HMA operation. Quantitative models such as simulation and empirical models combined with this systems approach are used to analyze the operation. Brief discussion of simulation models is provided, as well as the analysis of densification data collected during the summer of 1997 that forms the empirical models.

2 Background

Improving productivity is important for a project success. Financial savings for HMA contractors by improved productivity can be a great amount, because HMA projects are usually large scaled. Schmitt et al. reported that a 10% increase in HMA construction productivity translates to a 50% increase in profit [2]. For example, reducing HMA construction costs from $5.00/ton to $4.50/ton can result in a increase of profits from $1.00/ton to $1.50/ton.

Generally, two properties are measured which describe the quality of finished HMA pavement; density and smoothness. These measures have significant financial implications to HMA contractors, as these are the means to determine the payment to the contractor by the owner. They are also important to owners and users because they are directly related to economic management of infrastructure, riding comfort, and safety.

Quality and productivity should not be handled separately for HMA projects. Instead, these two issues should be balanced to achieve maximum success of HMA projects. Varieties of technologies are available to make improvements on both issues, but integrating these technologies to balance quality and productivity is not an easy task.

HMA operation is dynamic and includes elements such as production and construction processes. Elements of HMA construction process are continuously moving and they interact each other. These facts of HMA operation make it difficult to understand.

Productivity, or production rate, generally refers to the number of units of work produced by a unit of equipment or a person in a specified unit of time [3]. The overall productivity of HMA operation is determined by several processes that form the operation, and balancing production rates of each process is critical to achieve the maximum overall productivity as shown in Figure 2. HMA contractors must continually balance plant production, delivery, placement, and compaction production rates to ensure maximum productivity and a high quality mat [4].

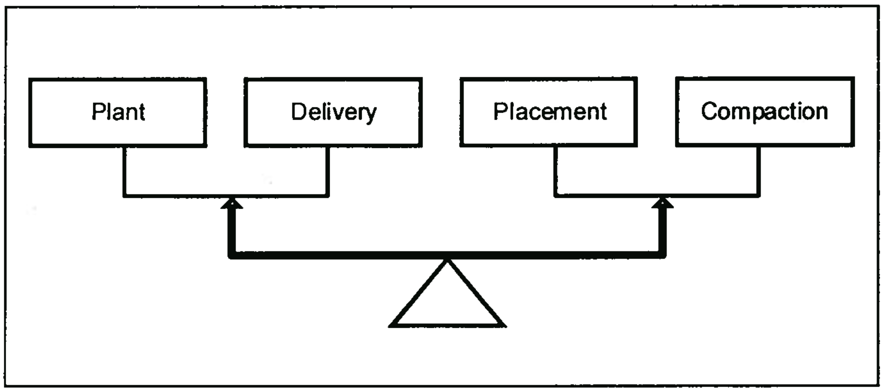

Figure 2. Balancing Act (AASHTO & NAPA 1993)

The unit of productivity employed in this research is HMA tonnage produced, delivered, placed, or compacted per unit of time, depending on the sequence of processes. The time unit can be hour, day, or project duration. This research considers density of HMA mat to determine the quality, because the measuring method of smoothness has not been set. These HMA tonnage and density along with cost expended by each process should be well balanced throughout the process to successfully complete the project.

3 Systems Approach

The adoption of a systems approach can generate new ideas and new ways of evaluating HMA operation. A system is any collection of elements that interact in a sufficiently regular manner to be of interest. Elements of the system at different times take distinguishable different states, which are the system variables. A control system is one in which the elements continue to interact and change but at least one variable remains within a specified range [5]. For example, HMA contractors are given time, cost, target amount of work, and quality requirements, and the contractors are expected to complete the various stages of HMA projects within these targets.

Also, the interaction between a system and its environment is important. A system can be defined by identifying all of its elements. Anything not listed but which has a significant effect on the system forms part of its environment. The interactions between the system and its environments fall into two categories: inputs and outputs. Feedback, which is essential for control system, is defined as a system having an effect on its environment and being aware of that effect. Control system also requires that the system has an objective or goal and needs the ability to take corrective actions. Figure 3 shows this relationship.

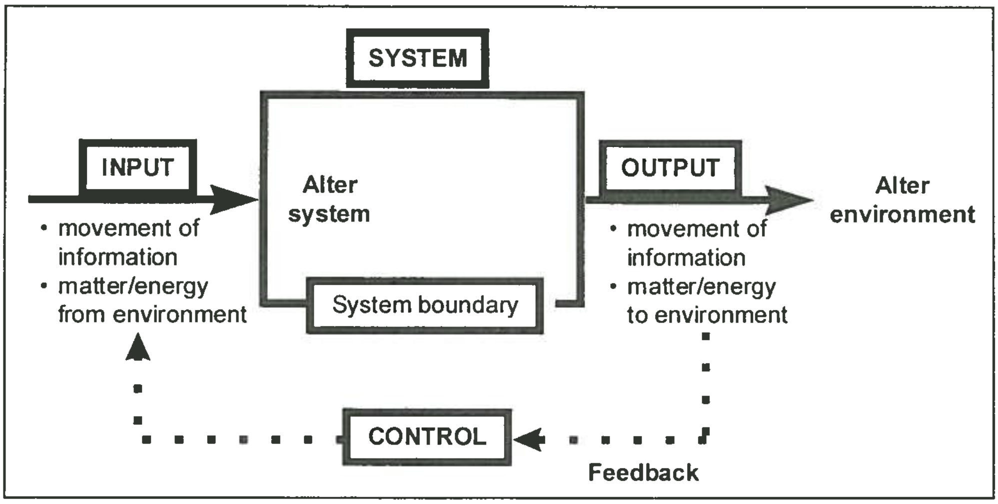

Figure 3. Control System [5]

Hierarchies of systems exist within construction project organizations. They consist of subsystems, which form part of a larger main system, sub-subsystems, which form part of a lager subsystem, and so on through as many levels as are useful. Logically there should also be supersystems and indeed many construction projects do form part of megaprojects or supersystems.

The hierarchies of system need to be translated for construction operations, furthermore for HMA operation. The good starting point is to compare the hierarchies of system to the hierarchical levels of construction management defined by Halpin and Woodhead [6].

The main focus of this research is HMA construction process that belongs to HMA operation. HMA operation will be a main system, and HMA production and HMA construction processes will be subsystems respectively. HMA construction process, which is a subsystem, can be further divided into delivery, placement, and compaction processes. These processes consist of work tasks that are performed by individual equipment and operator, and these work tasks can be defined as sub-subsystems. Figure

4 relates hierarchies of both construction management, systems, and HMA organization (specifically for HMA compaction process by roller).

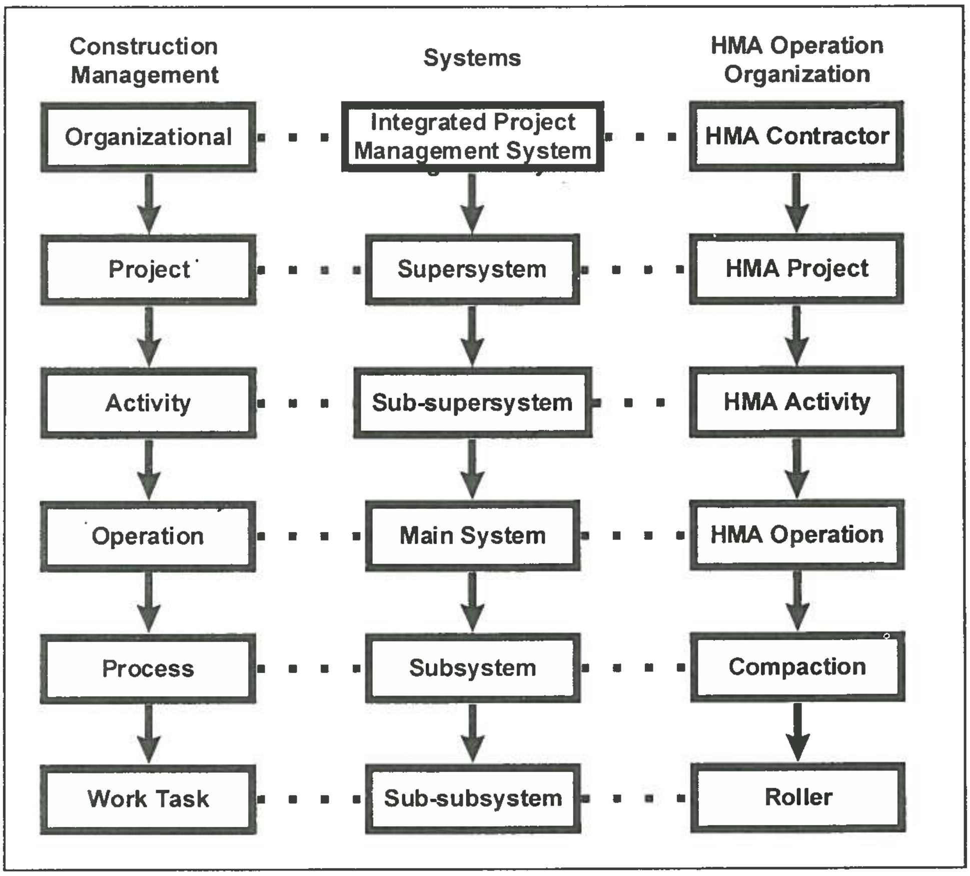

Figure 4. Hierarchies from Different Viewpoints

Figures 5 through 7 show the conceptualization of systems approach for each HMA process. Figure 5 is the control system for HMA construction process.

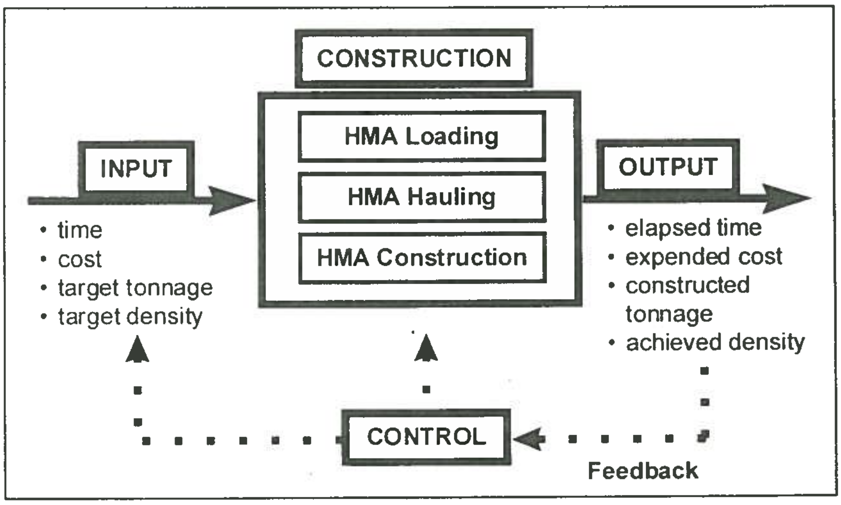

Figure 5. Control System of HMA Construction Process

The inputs are expected to be time, cost, target HMA tonnage, and target density of HMA, and outputs to be elapsed time, expended cost, constructed tonnage, and achieved density by this process or system. The process itself includes several other subsystems such as HMA delivery, placement, and compaction processes, which should be performed in series. The information generated by this system is sent to the control module, where the effort to change the system components or modify incoming inputs takes place to balance inputs and outputs. If the system can not achieve desired output level by itself, the information is directed to the upper level of the system, such as project control division at the head office, to change the process or target from the root level.

Figure 6 is the control system for delivery process. The system is expected to deliver target tonnage of HMA from a plant to a field within given time and cost. The system elements consist of number, capacity, and speed of trucks, which are changeable depending on the input and output. Simulation modeling is the appropriate tool to analyze this system.

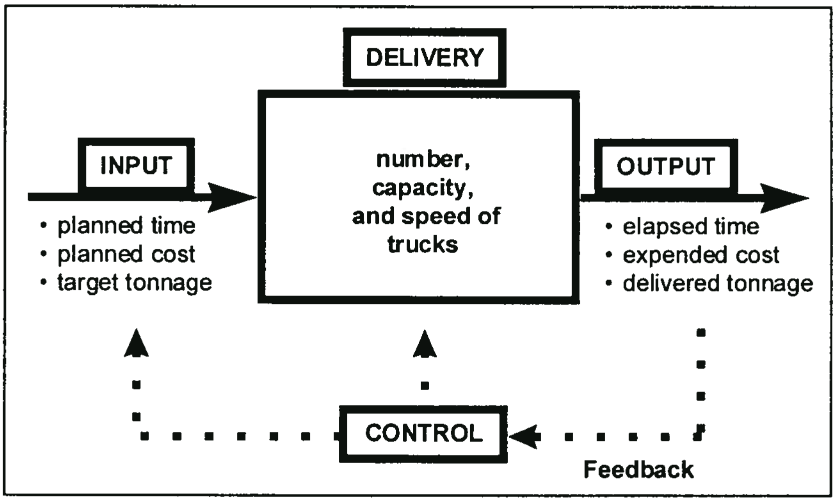

Figure 6. Control System of HMA Delivery Process

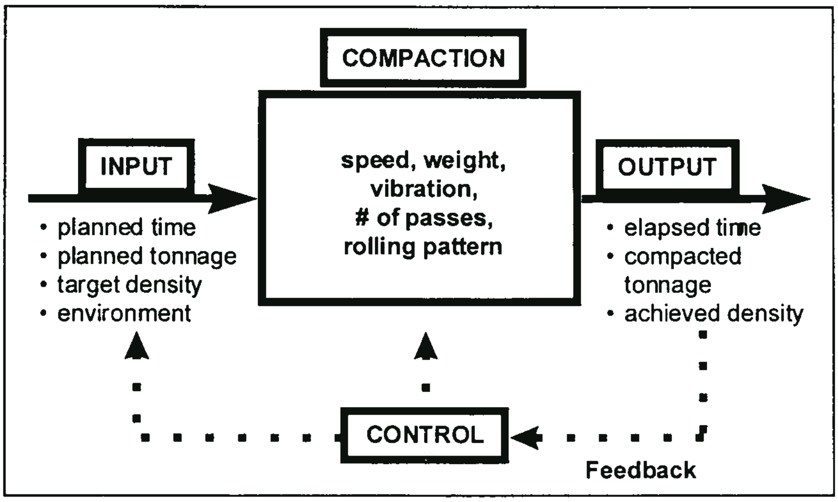

Figure 7. Control System of HMA Compaction Process

Figure 7 is the control system for compaction process by a roller. Since this system handles only one roller, it falls into sub-subsystem. The system is expected to compact a certain tonnage of HMA mat to a target density within given time and environment (i.e., temperature of HMA mat, prior density before compaction, property of HMA). The system elements are speed, acceleration, deceleration, weight, amount of vibration, number of passes over one point, and rolling pattern, all of which are changeable depending on the input and output. Empirical modeling technique is used to analyze this system. The control element of this system serves as a real-time field control system of HMA construction process. Input of this system can be obtained from real-time data collection system. A detailed discussion of these two systems is provided in the previous research by Lee et al. [9].

4 Tools for System Analysis

The central tools of system analysis are models. The most used modeling techniques for systems analysis are using quantitative models. Common analytic models and simulation models are types of quantitative model [7]. In this research, quantitative models are underpinning techniques for systems analysis. Systems for HMA operation themselves are complex, dynamic, and characteristics of HMA during construction process are not fully understood. Quantitative models such as simulation models and empirical models from statistical analysis are appropriate for this kind of situation, and are used throughout this research.

4.1 Simulation Modeling

With the complexity of interaction among units on the job site and in the construction environment, simulation techniques offer the only general methodology that affords a means of modeling such a situation [6]. The more detailed discussion is given by Lee et al. [9].

Simulation modeling can be programmed with common computer languages such as C, FORTRAN, and BASIC. Special simulation software packages have been developed to offset the difficulty often encountered when writing detailed computer code. Simulation software packages include languages such as GPSS/H^{TM}, MicroCYCLONE^{TM}, and Arena^{TM}. The simulation packages allow rapid programming of complex system simulations, freeing more time to research and possibly improve the model. Initial studies will use one of simulation packages like GPSS/H^{TM} or Arena^{TM}. One of the advantages of Arena^{TM} is that this is Windows^{TM} based software and enables integration with other applications such VisualBasic^{TM} [8]. Since the real-time field control and data collection systems in this research plan to use VisualBasic^{TM} as their language, this feature is very desirable.

4.2 Empirical Modeling

Empirical modeling techniques are used for the analysis of HMA compaction process in this research. The main issues in this research are (1) to find significant variables affect the densification characteristics during HMA compaction by rollers, (2) to build empirical models of these characteristics using multiple regression analysis, and (3) to estimate future amount of densification using these empirical models. The main task of the regression analysis is to explore the relationship between the amount of densification (response, percent density) and a number of predictor variables that are thought to affect pavement density during compaction.

Several variables were measured on five paving projects during the summer 1997 to determine significant variables affecting pavement density. The projects were constructed around Madison, Wisconsin, U.S.A. The first three projects were resurfacing jobs for secondary roads and were used as exploratory projects where data collection issues were encountered, understood, and modified. The last two projects had more detailed data collection based on lessons learned from the earlier projects. These two projects were binder and surfacing jobs for heavy traffic roads. The regression analysis was based on the data of last two projects

Typical project sections were one or two lifts of asphalt overlays placed on milled or crushed mill-and-relay asphalt base, having a 4 to 6-meter lane width and 50 to 75-mm lift thickness. Paving equipment consisted of a Blaw-Knox PF180H™ paver, Bros VM225™ vibratory roller for breakdown rolling, and Bomag BW 120 AD-2™ vibratory roller for finish rolling. The same crew and equipment were used throughout data collection to understand variables for obtaining density with a given set of resources.

Testing equipment used to collect the data were: (1) three nuclear density gauges, (2) Global Positioning System (GPS), (3) infrared temperature probes (both continuous and hand-held), (4) manual thickness probes, and (5) hand rulers. Three different nuclear gauge models were used including CPN model MC-1DR, Seaman Nuclear Corp. C75, and Seaman Nuclear Corp. C200. Test duration of 15 seconds was used so that density measurement would not interfere with rolling operations. GPS and continuous temperature probes were directly connected to the main notebook computer via radio modems or direct cables to collect the data instantly. Hand-held temperature probes, and hand rulers were used to manually collect temperature and thickness data.

Regression modeling was used in the analysis to determine those variables affecting pavement density during construction. Regression was chosen due to the continuous nature of the data, as opposed to a factorial analysis where discrete values are preferable for analysis. Density was designated the dependent variable and those potential variables affecting pavement density were designated the independent variables. In the analysis, the response was the percent density achieved after hot roller, or cold roller. Predictor variables used were number of rolling passes over one point, speed, thickness, temperature of mat, prior density before rolling by a roller, and project day. Table 1 shows a summary of regression modeling. Significant and non-significant variables from the analysis, and the regression equation are provided in the table.

Multiple regression analysis for hot rolling on both 4th and 5th projects reveals strong evidence that temperature and number of passes have effect in pavement density. Prior density has significant effect on changes in pavement density. Rolling at higher temperatures, more number of passes, and on less compacted mat has a greater percent change on density. The results are found to be reasonable. Differences due to project days are found not to exist.

Table 1. Summary of Regression Analysis

Project & Roller Type (1)	Significant Variable (2)	Non-significant Variable* (3)	Regression Equation (R-Squared Value, Method) (4)
4th & 5th Project Hot Roller	Temp Passes Density$_1$	Thick Speed Interactions	%Density = 66.4 + 0.0378 Temp + 1.55 Passes + 0.153 Density$_1$ (26.6%, Common)
4th Project Cold Roller	Temp Passes Density$_2$ Temp∗Passes Passes∗Density$_2$	Other Interactions	%Density = -13.3 - 0.0785 Temp + 27.8 Passes + 1.29 Density$_2$ + 0.0721 Te∗Pa – 0.431 Pa∗D$_2$ (67.5%)
5th Project Cold Roller	Temp Passes Density$_3$, Temp∗Passes Passes∗Density$_3$	Other Interactions	%Density = -13.3 - 0.0785 Temp + 28.3 Passes + 1.29 Density$_3$ + 0.0721 Te∗Pa – 0.431 Pa∗D$_3$ (67.5%)

*Note: Temp = Temperature, Thick = Thickness, Passes = Number of times that the roller compacts one point, Density$_1$ = Density after Paver, Density$_2$ = Density after Hot Roller, Density$_3$ = Density after Pneumatic Tire Roller

Analyses for cold rolling of 4th and 5th projects show that there is significant evidence of temperature, number of passes, prior density, interaction of temperature and number of passes, and interaction of temperature and prior density having effect on achieving density. One interesting point in these analyses is the different coefficients pertaining to the number of passes for each project.

5 Conclusion

Improving productivity and achieving specified quality are important because they are directly related to a project success. Balancing two attributes for HMA operation is difficult because of the complexity and dynamic characteristics of HMA processes. Adapting systems approach for HMA operation is shown and reveals that this approach is appropriate for analyzing the operation.

Quantitative models such as simulation and empirical models are discussed to analyze the operation. Brief discussion of simulation models is provided, as well as the analysis of material property data collected during the summer of 1997. Regression analysis of material property data shows that variables such as mat temperature, number of passes, and prior density have effect on achieving density.

6 References

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