Design of Real-Time Site Operations Control for In-Place Asphalt Pavement Recycling

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Recent improvements in computer technology have advanced industrial processes toward more autonomous control, with opportunities that offer superior handling, reliability, and enhanced overall quality. Although the highway construction process has advanced over the years as a result of rapid improvements in material technology, the on-site construction process still remains, for the most part manual. This is attributed primarily to the variability that exists on the road sites, creating situations that, under normal circumstances, are difficult to project and replicate from site to site. The use of automated equipment for hot in-place asphalt resurfacing is discussed as a modern technique that has advanced and provides the potential for further automation and improvements to current in-place technology. Breakthroughs that have been achieved by the authors toward improving this particular site process through real-time data handling are also discussed. The specific approaches are addressed that have been taken to automate and improve the process by incorporating the development of a nondestructive field-sensing process for identifying pavement and material characteristics, a blackboard procedure for field decision making based on real-time decision response to field conditions and information, and computerized process control that allows the integration of these new technologies with present equipment technology.

For some time the recycling process, with the use of glass and rubber materials, has been an ecologically attractive alternative in highway construction. These products have been used so successfully that now they are often mandated for use. With such technologies, recycling of the asphalt pavement itself has rapidly developed in the last decade in response to continued scarcity of materials and as a result of environmental, economical, and societal issues. Recycling of pavement materials offers several advantages over the use of conventional new materials. Observable benefits include the conservation of aggregates, binders, and energy; reduced hauling of materials; and the preservation of the environment and existing highway geometries (*1*).

Despite its attractive advantages, pavement recycling is associated with material-handling problems. Two fundamentally different approaches are applicable to the recycling process: one that considers the use of a central plant for preparation of the asphalt and one in which the asphalt is prepared in-place, i.e., at the site.

When central plant recycling is used, many steps are involved. They are milling of the old pavement surface; collecting and loading of the milled materials; hauling the reclaimed asphalt pavement material (RAP) to a central asphalt mixing plant; recycling RAP by hot mixing with virgin aggregates, fresh asphalt cement, and rejuvenating agents; hauling material back to the site; laying the recycled mix (after cleaning and tack-coating the new pavement surface); and rolling and compaction. Side issues are also involved, including the physical evaluation of the RAP properties, fresh asphalt, and virgin aggregates; design of the recycled mix; and quality control for evaluating the properties of the final mix. These steps usually enforce a substantial time gap between hauling the RAP to the mixing plant and the production of the recycled mix.

IN-PLACE HOT PAVEMENT RECYCLING PROCESS

Generally, modern hot in-place surface recycling methods use a piece of equipment known as a remixer, which adopts a train-like moving operation (see Figure 1). A large portion of the in-place hot pavement recycling technique is conducted on site, with the need to haul only the additive components to the field location. The existing damaged wearing course is softened by preheaters and the remixer. Rotating scarifiers on the remixer loosen the bituminous material mixture, which is augured to the center of the machine where it enters a pugmill mixer and is mixed thoroughly with virgin materials. The new mix is then placed evenly to grade and slope by a compacting screed (*2,3*). One of the most useful remixer technologies is the WIRTGEN system, available in the marketplace for more than a decade.

Heating Pavement

Heating the pavement surface to between 140°C and 170°C softens the bituminous layer. Softening is done by clusters of infrared heaters fed with propane gas, which radiate thermal energy onto the wearing course. The heater units are quickly adjusted to the actual working width of the remixer. Because the gas pressure of the heater unit is individually adjustable, heat output is easily adapted to the ambient temperature, working depth, and material stiffness to avoid overheating of the bitumen.

Scarifying Wearing Course

Rotating scarifier shafts, fitted with spiral shaped carbide-tipped teeth, scarify the surface to the required depth. The scarifier can be adjusted to suit varying road lane widths. A leveling blade to the rear of the scarifier precisely skims the loosened material so that it can be augured to the mixer.

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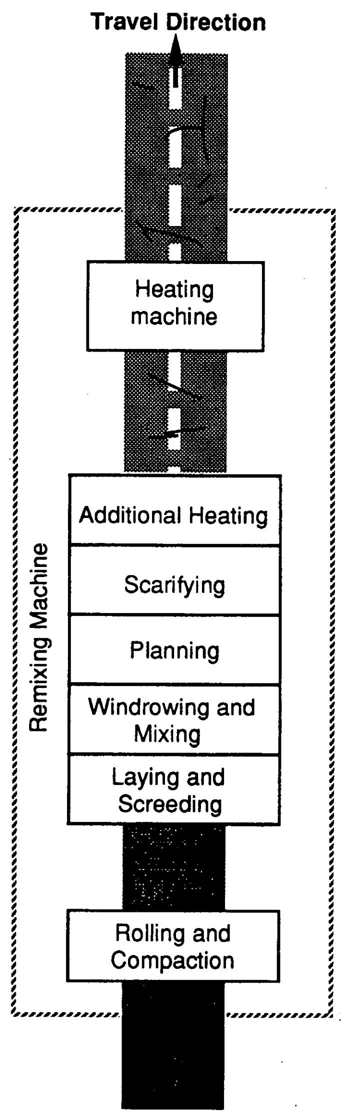

FIGURE 1 Train-like process for hot in-place asphalt pavement recycling.

Mixing Reclaimed Material

With the current technology, the design formula for the admixture is based on a prior core analysis of the existing pavement. The new material is either a hot bituminous mixture, a graded aggregate, a binder, or a rejuvenator. The virgin bituminous mixture for the new wearing course is mixed together with the reclaimed material in the compulsory pugmill mixer on the road. Trucks transfer the virgin material to the remixer and tip it into the receiving hopper. From there, it is conveyed by a drag-slat conveyer to the mixer. Exact mixing ratios are achieved by calibrating the speed of the electronically adjustable drag-slot conveyer to the foreword advance speed of the remixer. If the bitumen or rejuvenator is to be mixed with the reclaimed material, this can be supplied from a heated tank installed on the remixer. The virgin binder or rejuvenator is sprayed onto the reclaimed material by an adjustable pump. After thorough mixing, the material is discharged from the mixer through a window in front of the auger and screed.

Placing Mix

After the recycled material is discharged from the mixer onto the heated base, the mix is accurately placed to profile by an infinitely variable screed. The base material is heated separately to ensure a firm bond with the recycled mix by "hot in hot" placing. Final compaction is done by rollers.

SITE OPERATIONS CONTROL TO IMPROVE IN-PLACE ASPHALT RECYCLING

The central site recycling process has remained the favorite of the two processes because it allows greater control of the final product through centralized processing. It nonetheless dictates a more manual approach to be used at the site. The in-place recycling technique is much more efficient and innovative with respect to site material handling, yet several important problems that need to be addressed predominate. Because of the continuous nature of the process, there is no time to evaluate the old pavement material along the road for a proper design of the recycled mix. This requires tedious coring and sampling before construction operations. Furthermore, the inhomogeneous nature of old pavement surface and the inability to sense this variability along the road for a proper design and to provide continuous correction of the recycling formula usually cause follow-up variability of the recycled layer (an intrinsic difficulty in accounting for 100 percent recycling of old asphaltic materials characteristic of in-place operations). These difficulties and the sensitivity of in-place recycling to the variability in the old pavement cause a reluctance among pavement engineers to use the in-place technology.

Several novel techniques have been designed to improve the in-place recycling process. They are (a) discrete in-place field sensing, (b) intelligent monitoring and interpreting sensed properties in real time, and (c) continuous corrective control of the material component, handling, and quality control of the in-place recycling process.

By incorporating these technologies, a continuous travel condition is achieved with minimal delays through providing in-place discrete sensing, decision analysis, and feedback control. The sensing devices and units are based on new spectrometer technology applied to asphalt paving materials. The conceptually integrated procedure includes the following:

- Sensor unit for monitoring the old asphaltic layer and component properties;
- Heating unit for heating the top layer to be recycled and integrated with a sensing device that will monitor pavement temperature;
- Remixing machine that contains additional heating units, a scarifying unit, a planning unit, a windrow and mixing unit with sensing and control devices monitoring quality and quantity, integrated with storage and feeders for soft asphalt, fresh bituminous mix, and rejuvenating agent; and
- Laying and screeding units.

Furthermore, the procedure is designed to use a sensor unit for monitoring the new recycled asphaltic layer and its component properties, other conventional sensors integrated in the traveling recycling unit as installed by the manufacturer, an intelligent blackboard-based computer environment for decision analysis and feedback (which provides highway data on solutions to deterministic and nondeterministic asphalt conditions and knowledge sources on highway specifications and performance characteristics), and appropriate control characteristics, which implement corrective control to the overall process. The characteristic of monitoring and feedback of the system in real time provides a dynamic means for implementing quality control of the final product. This characteristic improves construction operations by optimizing material handling and also improves product quality and saves unnecessary costs.

Practical and economical reasons are obvious for maintaining a system with minimal manual intervention. This issue is further encouraged by the need for maximum efficiency. The use of advanced technologies for implementation in ill-structured construction environments encompasses the selective use of information systems, sensors, locomotion, and manipulation techniques, as well as control systems based on task needs (*4*). As these technologies are improved, their implementation through technology transfer ensures the growth of the benefiting fields. To achieve an integrated cycle as described, the site process must be controlled in real time. This requires design standards, field data collection, field management, site constraints, and project designs to be handled together. Intelligent data handling at the site level is difficult. An artificial intelligence procedure driven by a Site Operations Control System (SOCS) has been developed to overcome the data handling complications, which preclude the process from being achieved in real time (*5*). The SOCS is designed to interface with the remixing machine to provide intelligence, control, and advice. To achieve these characteristics, the SOCS includes

- A dynamic data base,
- Modular knowledge sources,
- A control module,
- An interface with the remixer's on-board controller,
- An interface with the site supervision group, and
- An interface with external files that characterize design information.

Blackboard System for Intelligent Data Handling in Real Time

The central component of the system is a blackboard control environment. The blackboard is a problem solving model that provides a conceptual framework for organizing knowledge and a strategy for applying that knowledge (*6*). It consists of three basic components: (a) blackboard data structure, (b) knowledge sources, and (c) a control structure. The blackboard data structure is a global data base that holds the current solution space, which is gradually built through the opportunistic contribution of the knowledge programmed into the machine's memory (knowledge sources). The control mechanism monitors the changes on the blackboard and allows the knowledge sources to respond to those changes. The system is integrated into the working structure of the remixer's onboard computer. The blackboard is used to monitor and control the flow of materials and provide feedback to the site supervisor. It is essentially an intelligent analyst and site inspector.

In general terms, the blackboard has been chosen because of its specific functionality. It has unique characteristics that are useful for site management and the remixer. They include its

- Support for the independence of expertise,
- Opportunistic problem-solving methodology,
- Ability to consider external information that arrives sporadically, and
- Event-based activation mechanism.

The blackboard views each knowledge source as a black box. In other words, it supports modularization of expertise. This is useful to the system primarily because of the different types of knowledge—operational, procedural, and organizational—that exist. Modularity of knowledge permits modification, addition, or deletion of knowledge source without affecting the other knowledge sources, thus for example, making changes to asphalt mix without interfering with road geometry and design specifications (see Figure 2).

The opportunistic reasoning mechanism provides the ability to consider external information that arrives sporadically. Field problems are not always a result of a single condition that arises. In the field, conditions change sporadically. It is important for the system to keep track of the information as it arrives and assign importance to the use of this information. This ability of the blackboard to consider information that arrives sporadically and to update impacts on the basis of this information is the only way that has been identified to allow the remixer to continue in its travel direction without interruption.

The blackboard provides an event-based activation mechanism. Instead of letting each knowledge source scan the blackboard system searching for an event in which it is interested, the blackboard keeps records of the information as the remixer moves down the travel direction and tracks what knowledge sources are to be considered for activation whenever the scheduled event occurs. Each source of knowledge (knowledge source) contains information about the situation it is interested in. The blackboard is assigned a strategy (function) to make local decisions about when each knowledge source should contribute to the problem-solving space.

The characteristics of the blackboard and its contributions to real-time process control are realized more fully by investigating specific contributions to the improved recycling system functions, namely, the real-time field sensing, process control, and real-time data monitoring that takes place.

Spectrometry

A method for characterization and prediction of different asphalt parameters using Near Infra-Red (NIR) spectrometry has been developed by the Transportation Research Institute of the Technion in Haifa, Israel (Ishai, unpublished report). The method is generally based on scanning the reflection of NIR radiation from the surface of the material. It is known that the NIR spectrum is sensitive to the movement of large molecules, thus providing the possibility of predicting different chemical and physical properties of the material.

The Transportation Research Institute of the Technion in Haifa, Israel, in cooperation with Pazkar Asphalt Company, has conducted a number of experiments that indicate the technology's success in predicting pure asphalt parameters, such as penetration (accuracy of ± 1.5 dmm), softening point (± 1.1°C), and polymer (SBS) content in modified asphalts (± 0.02 percent). After calibration and verification, a test measurement may take only a few minutes, including sample preparation, as compared with conventional methods, which take hours or days. Although development is in its infancy, it is believed that this technology will represent a breakthrough in

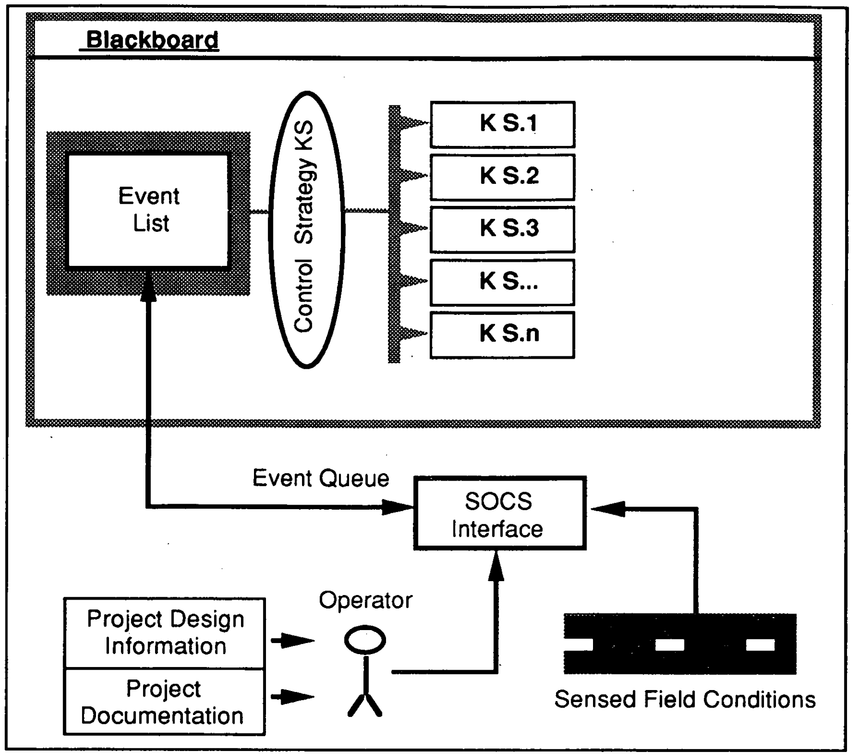

FIGURE 2 Blackboard structure for real-time control.

asphalt testing and prediction. Developmental issues investigated for using this technology on the remixer are multifaceted. They are

- Characterization of pure empirical and aged asphalt cements. Detailed experiments have evaluated such parameter characteristics as ductility, chemical composition, absolute and kinetic viscosity, flash point, and so forth. All these parameters are measured before and after thin film oven testing.
- Characterization of the loose bituminous mixture with respect to asphalt content and asphalt characteristics.
- Characterization of compacted or cored bituminous concrete samples in the laboratory with respect to density, asphalt content, and asphalt characteristics.
- Sensing and characterization of the asphaltic surfaces with respect to the same properties as noted previously.

The sensing system is composed of a fiber-optic sensor with a computer interface for scanning the road surface, a spectrometer responding to the reflected infrared light from the road surface, and a computer unit with the required interfaces for data acquisition. This technology is essential to the improved design of the remixer. Information is fed into the on-board computer of the remixer (which is controlled by the blackboard) through the sensors at various instances (see Figure 3). The blackboard priority ranks the incoming information and activates the appropriate knowledge source needed to feed information further down the train-like process. The knowledge sources represent information that has been provided through historical characterization in the laboratory to be available to the system in real time.

Controls for Material Handling

Automatic control and handling of materials are key features in the integration of computer-based information systems with automated equipment. The control issues for the materials handling of the asphaltic materials in the system reflect a proper response to the following impending requirements:

- Integration of handling and temporary storage activities in a feasible manner that includes reception, inspection, and temporary storage of asphalt materials;
- Effective use of available in-vehicle storage cubic space for handling the immediate and end-point materials;
- Mechanization of the handling process to increase efficiency and economy; and
- Application of quality control principles to the end product.

The blackboard controller is designed to coordinate the entire process. Proper sensing through weight, proximity, and motion sensors (tachometers, position encoders) provides the necessary feedback information for maintaining a stable system. There are three essential areas that require integrated controls functioning between the blackboard computer environment and the automated equipment.

1. The blackboard will evoke an event to read the pavement temperature, which is transmitted through the spectrometer and a discrete event sensor. With the spectrometer, a processing element is used to adjust the signal of the infrared heaters according to the desired temperatures and the actual temperatures as measured by the

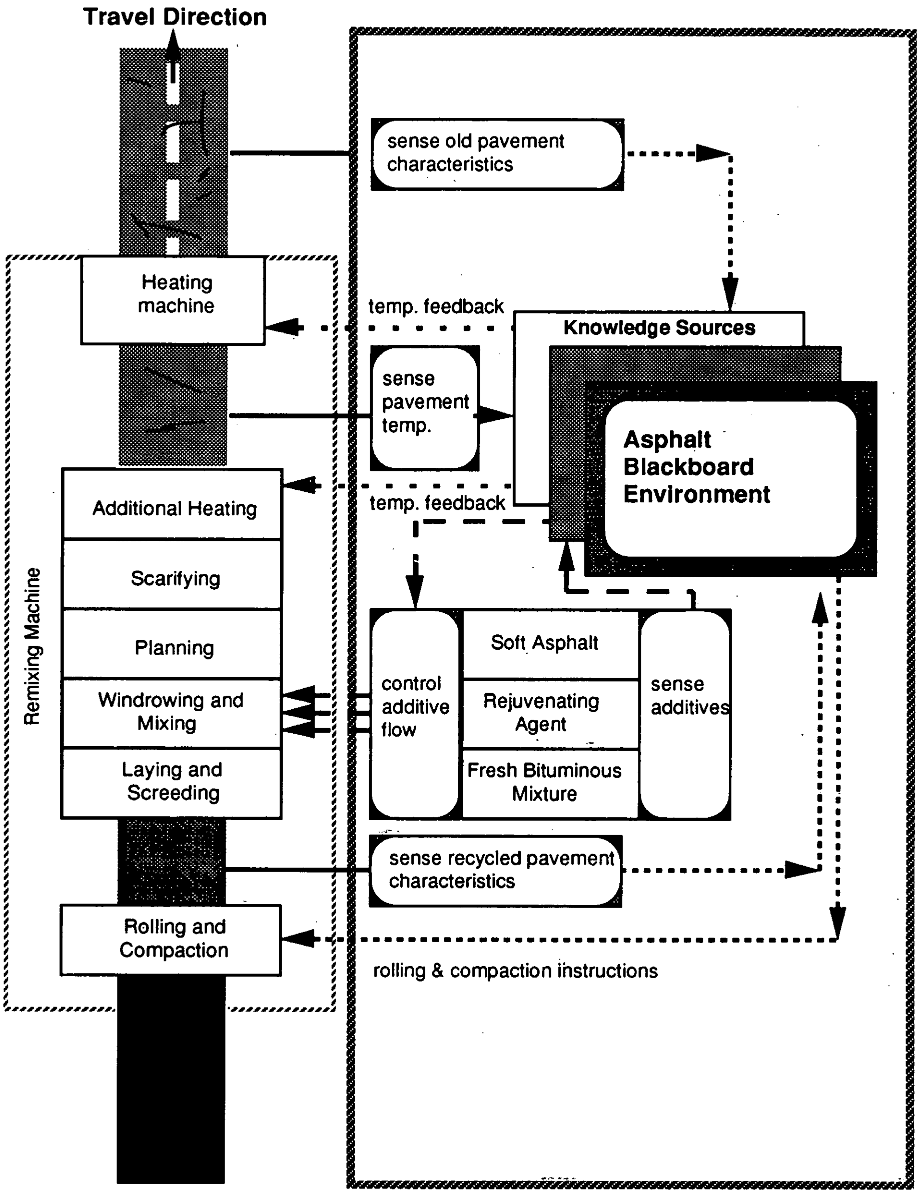

FIGURE 3 Overview of feedback system design for asphalt remixer.

thermocouple. A second signal establishes a decentralized control loop, for feedback of additional heating to the road surface (see Figure 4). An analog-to-digital converter translates the signal, which is read by the computer data bus, and the information is fed to the blackboard. This event on the blackboard immediately recalls the reference knowledge source that provides feedback about temperature sensitivity to the design parametry.

2. Specific NIR sensors are used to measure asphalt viscosity and asphalt content in the mixture relating to the external needs of the closed-loop recycling system. These sensors have their signal converted through A/D to the computer data bus where the information is retrieved by the blackboard and processed for instructions. The knowledge sources each provide reference data about asphalt content and viscosity that will be required externally by the system to meet design standards. The blackboard interprets the recommendations of the knowledge sources, which are then transmitted as instruction signals through the controller reference input (see Figure 5) as a means of controlling the additive flow (see Figure 6). The information is relayed as requests for additional material, which is received by the storage bins on the remixer. The controller reference input constantly monitors flow to ensure design parameter requirements.

3. The last monitoring function of the system is to provide reference quality of placed material during rolling and compaction and computer feedback, which is stored as memory further down the travel direction. This feature is important to the system because it provides a means for updating the blackboard data base and storing physical actions taken in correcting the mixture (see Figure 7). This closed-loop feedback suggests that the system has a capacity of learning from its own prior experiences. Essentially the rolling and compaction requirements decided on the field are based on field evaluation and inspection. The decision to proceed with rolling and

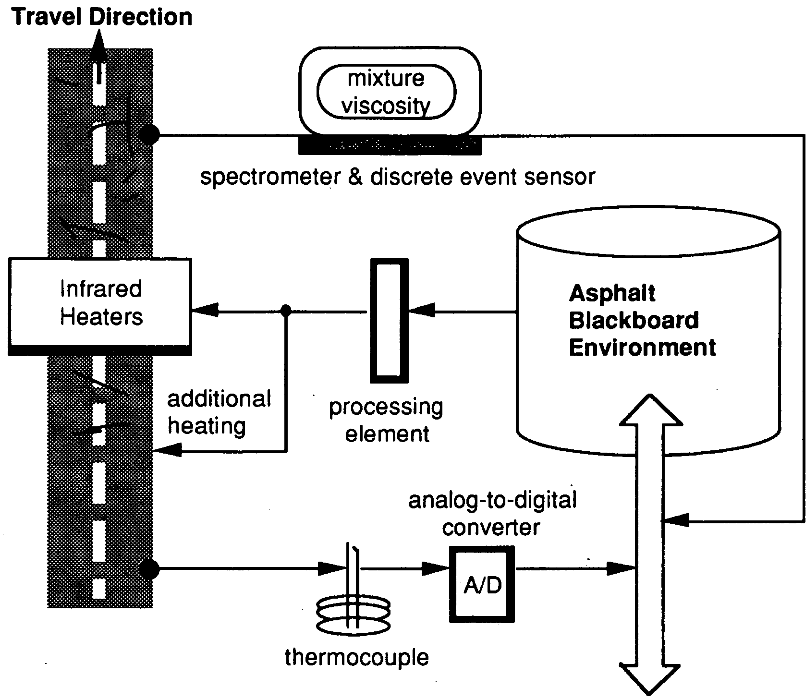

FIGURE 4 Temperature feedback and control for remixer.

compaction is provided to the field supervision group by the blackboard control system, which has interpreted the scenarios that required such actions previously and has chosen the most appropriate recommendations. The system then has the capacity to review the compacted asphalt and decide whether the present conditions of the pavement meet the intended specifications.

Asphalt Knowledge Sources

The knowledge sources are structured to learn from design characteristics integrated into the pavement data base, and the design problems are integrated to complement field uncertainties, operational procedures, and other bottlenecks. For example, design characteris-

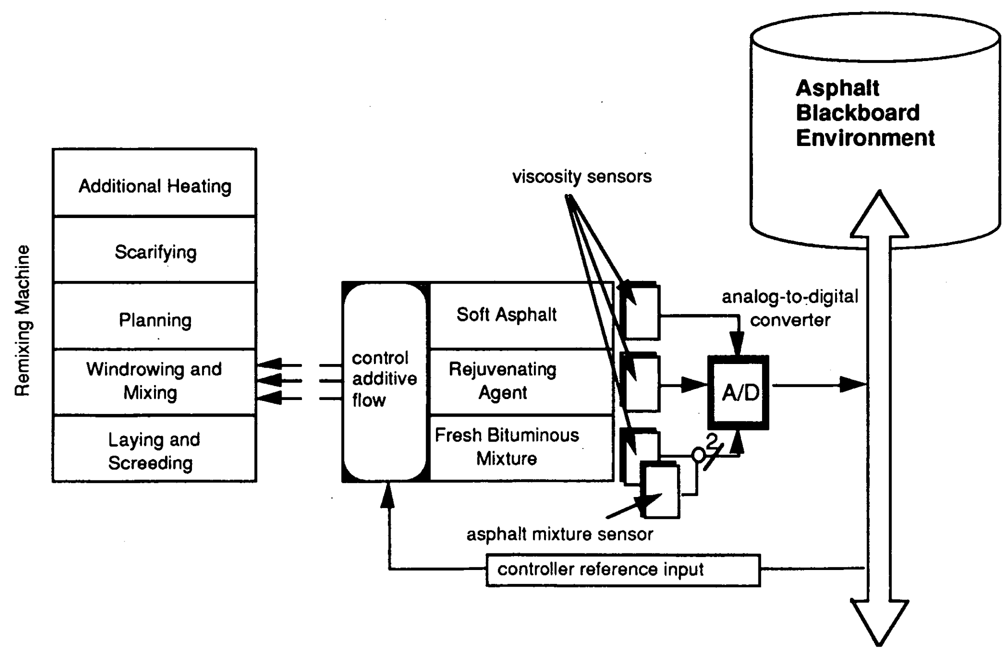

FIGURE 5 Control of reference inputs for asphaltic parameters.

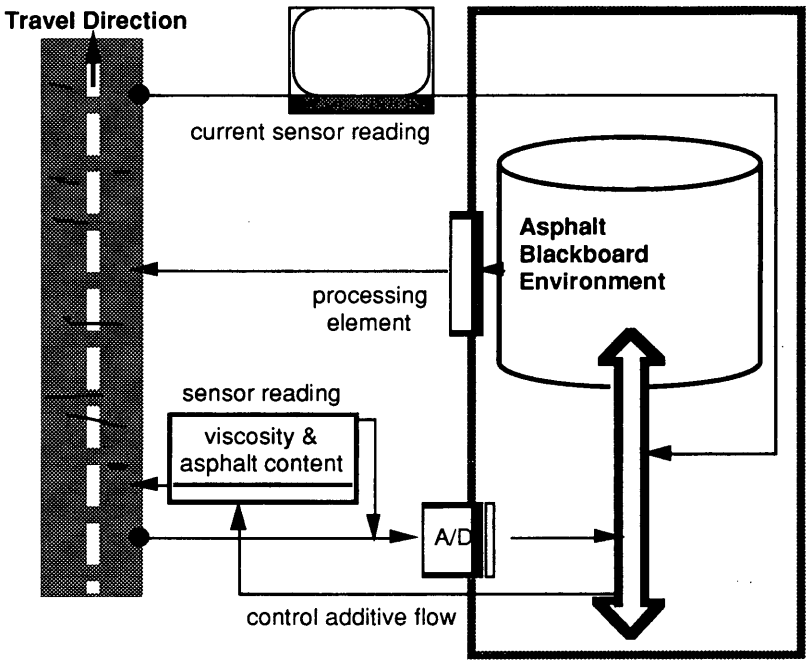

FIGURE 6 Monitoring and control of additive flow.

tics relating to the properties of the material at varying temperatures are integrated to provide essential feedback to system equipment responding to mix, placement, and rolling. The following specific operations are addressed in the asphalt knowledge source:

- A reference, about asphalt hardness: the knowledge source diagnoses heating temperature feedback on the basis of asphalt characteristics such as penetration, viscosity, softening point, and ductility.
- A reference regarding material content: while the mix is prepared, the system maintains an ability to monitor the asphalt being removed from the paved surface, diagnoses its worthiness, projects the requirements of additional materials to achieve optimal design conditions, and controls the mixing process.
- A reference about the finished product being placed on the road surface: the system monitors the placement of the final product with respect to density, composition (asphalt content), and asphalt characteristics.

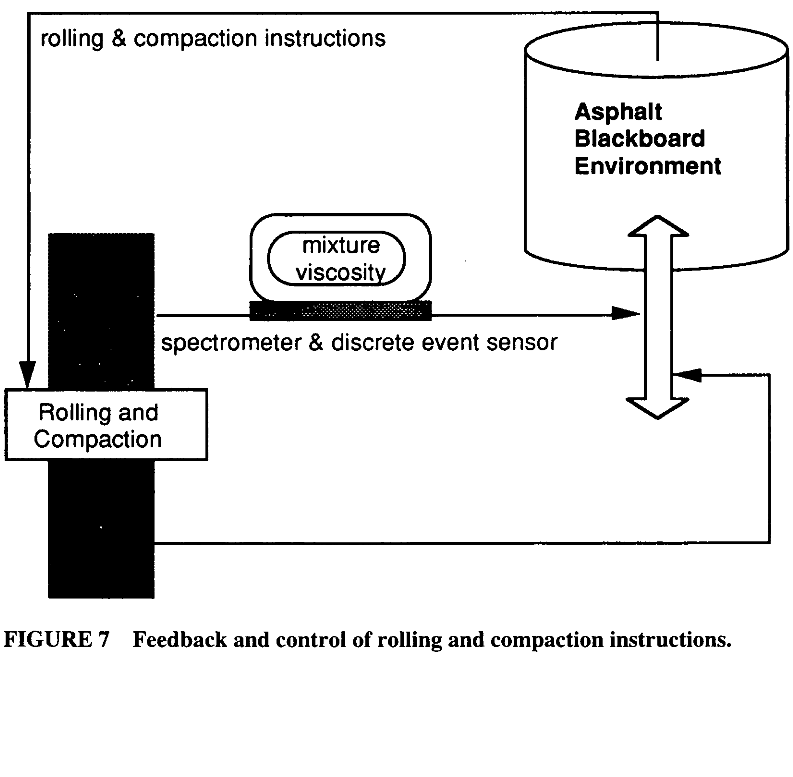

FIGURE 7 Feedback and control of rolling and compaction instructions.

Many organizations have focused on the need to evaluate condition data relevant to the pavement management system (*7*). Several ongoing efforts of the Strategic Highway Research Project have responded to the data acquisition needs of the system, such as the need to focus on material properties, environmental conditions, maintenance and rehabilitation, surface condition, and pavement response (*8*). This information provides a richness of data available to the blackboard. The knowledge made available to the blackboard will only create a system with experience if that information has been based upon field experience.

CONCLUSIONS

This report has presented an alternative approach to conducting asphalt resurfacing. Despite modern hardware and software technologies and significant economic, engineering, and material handling advantages, in-place pavement recycling is not extensively used. Primary concern among pavement engineers is the sensitivity of in-place recycling to the variability in the old pavement. Even with sophisticated equipment technologies, such as the WIRTGEN equipment, the process still relies heavily on laboratory testing of the old pavement and ad hoc evaluation of material mixture during placement, with little feedback on quality control. The novel approach of implementing smart tools through field sensing, field analysis, and feedback control provides a breakthrough in allowing the technology to be used in real time. The potential for its use is immense, especially for applications in which shut downs of the road are practically difficult, such as highway ramps and bridge crossings. The technologies brought together in this paper are still young and expected to evolve. The concept design considerations nonetheless are complete. The breakthroughs in the technology provide a unique opportunity for the highway community to review the process of construction. Through such a review it is expected that this technology will not only improve construction operations by optimizing material handling but also improve product quality and overall economy.

REFERENCES

1. Dunning, R. L., R. L. Mendenhall, and K. K. Tischer. Recycling of Asphalt Concrete: Description of Process and Test Section. *Proc. AAPT,* Vol. 44, 1975.
2. Kuennen, T. Hot In-Place Recycling Revitalizes Texas Roads. *Road and Bridges Magazine,* Oct. 1990.
3. Robb, C. It's All in the Mix. *Construction News,* June 1990.
4. Pagdadis, S. *An Advanced Technologies Assessment Strategy for Construction Automation.* Ph.D. dissertation, The University of Texas at Austin, Austin, Tex., Aug. 1990.
5. Pagdadis, S. Conceptual Model for a Site Operations Control System. *Preparing for Construction in the 21st Century,* (L. M. Chang, ed.), ASCE publication, April 1990, pp. 419–424.
6. Nii, P. Blackboard Systems: The Blackboard Model of Problem Solving and the Evolution of Blackboard Architectures. *The AI Magazine,* Summer 1986, pp. 38–53.
7. Zaniewski, J. P., S. W. Hudson, and W. R. Hudson. Pavement Condition Data Analysis. *Journal of Transportation Engineering,* ASCE, 1986, pp. 413–421.
8. Clarke, B. D., et al. SHRP Long-Term Pavement Performance Information Management System. *Transportation Research Record 1260,* TRB, National Research Council, Washington, D.C., 1990, pp. 33–41.

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