IMPLEMENTATION OF INTELLIGENT CONSTRUCTION SYSTEMS IN THE HIGHWAY INDUSTRY

J. RUIZ, H. TORRES, C. MEDINA, G. CHANG & R. RASMUSSEN,
The Transtec Group, Inc., USA
mauricio@thetranstecgroup.com
J. Epps
Texas Transportation Institute, USA
j-epps@tamu.edu
T. Cackler
Iowa State University, USA
tcackler@iastate.edu

ABSTRACT

The implementation of new technologies in any field of engineering is a task that is becoming a necessity in today's projects. The technologies being used in road pavements have become a vital tool to evaluate, design, and construct high quality projects that meet the standards and specifications required by highway agencies and concessionaires around the globe.

In the United States, emerging technologies in the area of pavement construction are becoming more intelligent. The term "intelligent construction" is used to describe a technology that has the ability to sense its environment, collect, and analyze information in real time to enable paving contractors and highway agencies make smart decisions during the construction stage, leading to develop better final products and projects. Intelligent construction tools provide information to make necessary adjustments and changes "on the go" to achieve high quality pavements while being both cost and time effective.

This paper aims to present a review of the advancements achieved in three intelligent construction technologies used in the highway industry in the United States. First, intelligent compaction is a technology used for materials including soils, aggregates, and asphalt mixtures (subgrade, base, and asphalt layers). This technology allows performing real-time adjustments in the compaction process, improving current practices and achieving high quality and uniformity of pavement layers, which in turn ensure long-lasting high-performance pavements.

Another technology reviewed herein is the real-time measurement of pavement surface smoothness. This allows making adjustments to the paving operation in nearly real time, instead of having to perform expensive corrective actions after construction. Measuring real-time smoothness helps construct more comfortable and durable pavements.

Finally, the implementation of an automated curing and monitoring system is presented. This technology is used to continuously check the curing process of concrete pavements in the field and issue warnings when there is risk for premature deterioration of the concrete. By continuously monitoring the curing process, automatic adjustments can be made to curing methods, resulting in high quality pavements.

This paper identifies the benefits obtained from these three technologies and also describes how they are helping construct a better highway infrastructure.

1. INTRODUCTION

1.1. Background

Technology is the enabling force behind advancement in any industry, and pavement construction is certainly no exception. The United States Federal Highway Administration (FHWA) recognizes that there is a strong sense of urgency to deliver projects faster and implement the latest technology and innovation sooner. This is reinforced through new initiatives such as Every Day Counts [1]. As quality demands increase and funds decrease, it is as important as ever to determine what innovative technologies are available and which can and should be implemented in the realm of the intelligent construction of pavements.

Intelligent Construction Systems (ICS) can be defined as technology with the ability to sense its environment, collect information, analyze information, make an appropriate decision, and execute that decision to make smart adjustments during construction. In other words, ICS have the ability to vary behavior in response to varying situations and requirements.

1.2. Ongoing work on ICS In paving

There has been tremendous progress in production of ICS in all areas of roadway construction including the following [2,3,4]:

1. Positioning systems – are used from layout to machine guidance to quantity tracking and many points in between.
2. Project Scheduling/Construction Staging – 3D and 4D modelling are used for project visualization and scheduling.
3. Paving Equipment Improvements – offer improved quality of the final PCC pavement, and construction cost and time savings.
4. Machine Guidance and Automation – use GPS, total stations, and 3D site plans for machine control to improve laydown, compaction, and finishing.
5. Quality Monitoring – to reduce variability in moisture, density, smoothness, and other material properties and performance characteristics.
6. Data Management – automatic data transfer between field and office improve process control, scheduling, pay quantity measurement, and inspection.

More specifically to pavements, several initiatives are currently in progress in the United Sates to move forward the implementation of ICS in both the asphalt and concrete paving industries. These include efforts such as the Concrete Pavement (CP) Road Map where there is a specific task to do research on non-destructive testing and ICS technologies [5], the Asphalt Road Map, that identifies the need of ICS technologies for improving construction practices and quality management systems [6]. Furthermore, the current Strategic Highway Research Program (SHRP2) is working on speeding project delivery where non-destructive testing and ICS technologies are currently being tested [7].

1.3. Scope of this paper

This paper aims to present a review of the advancements achieved in three specific intelligent paving construction technologies currently being implemented in the United States. These ICS technologies are intelligent compaction (IC), real-time measurement of pavement surface smoothness, and an automated curing and monitoring system. This paper depicts the benefits obtained from these three technologies, and also describes how they are helping construct a better highway infrastructure.

2. INTELLIGENT COMPACTION

The compaction of pavement materials in roadway construction is vital to obtain a long-term performance facility. Conventional compaction equipment works with operational procedures and density measurement protocols that do not consistently result in the desired compaction/density levels in all pavement areas [8]. To overcome this drawback, IC technology offers greater control of the entire compaction process. The results are an optimization in the use of resources (time, equipment, and personnel) to achieve the specified quality requirements. Intelligent Compaction technology provides better control of the status of roller operations and improved documentation in terms of vibration frequency, roller passes, amplitude, and HMA surface temperatures, all in real-time. Another advantage is that a contractor is able to estimate the stiffness of the underlying pavement materials, which in the end, improves quality of the construction work.

2.1. Background

Compaction is one of the most important processes in roadway construction. Pavement materials need optimum densities to ensure a strong support and good stability of the overall pavement system. Conventional quality control procedures include in-situ spot tests (using nuclear or non-nuclear gauge density devices) and a manual count of passes of the compaction equipment over a given area. These conventional methods have well known issues, which include 1) a limitation of in-situ spot tests or cores conducted at random locations or points because the tests do not necessarily represent the entire pavement area; 2) the presence of weak or unqualified compaction areas not identified by the limited spot tests; and 3) the measured density of top bound layers not indicating the structural capacity of the entire pavement structure. These issues generally lead to a premature failure and a reduction of the effective life of the pavement. Therefore, IC has been developed to address all these issues.

Intelligent Compaction technology has been used in Europe and Japan for years and has been recently introduced to the US [9]. Therefore, there is still a lack of experience, knowledge, and availability of IC equipment in the US. Meanwhile, the IC technology is still evolving, especially for hot mix asphalt (HMA) compaction [10]. These limitations have called for an implementation program by State Departments of Transportation (DOTs) and paving project teams. These efforts are being coordinated with the help of the Federal Highway Administration, through the transportation pooled fund (TPF) project "Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials". Initiated in 2007, this effort has evolved into a Road Map for Intelligent Compaction or *"FHWA's IC Road Map."* The goal of this project was to accelerate the implementation of IC technology, and since then, IC demonstration projects have been conducted in 12 states in the US: Minnesota, New York, Kansas, Mississippi, Maryland, Georgia, Indiana, Wisconsin, Texas, North Dakota, Pennsylvania, and Virginia. These projects have been coordinated with efforts by IC roller manufacturers, researchers, earthworks/paving contractors, and government agencies.

2.2. The Definition of Intelligent Compaction

Intelligent Compaction is a technology used in the construction industry for various materials such as cohesive/non-cohesive soils, granular subbase, stabilized base, and asphalt materials. This technology allows performing real-time adjustments in the compaction process, improving current practices and achieving high quality and uniform pavements, which in turn ensure long-lasting high-performance structures.

Intelligent Compaction technology uses vibratory rollers equipped with a real-time kinematic (RTK) global positioning system (GPS), roller-integrated measurement system (accelerometer-based), feedback controls, and onboard real-time display of all IC measurements. Intelligent Compaction rollers maintain a continuous record of measurements that include among other factors the number of roller passes, roller-integrated measurement value (ICMV), roller vibration amplitudes/frequencies, roller GPS location, and HMA surface temperatures. These measurements are then plotted on an onboard color-coded display, so roller operators have the option to either manually or automatically adjust the machine settings for achieving an optimum compaction.

2.3. Intelligent Compaction Systems in the US

There are three basic types of rollers being utilized on HMA compaction depending on the design and project requirements. These include static steel-wheeled, pneumatic-tire, and vibratory rollers. The most common roller used for HMA in the US is the double-drum vibratory roller. There are currently five major manufacturers who offer single-drum and double-drum IC rollers in the US. Their features are described in Table 1 and Table 2, respectively [10,11].

Table 1 - Summary Table for Single-Drum IC Rollers

Vendor	Ammann/Case	Bomag	Caterpillar	Dynapac	Sakai
Model	ACEplus	VarioControl	NA	DCA-S (GPS)	CIS
Model Number	SV	BW213-4BVC	NA	CA 152–702	SV505/SV510
Auto-Feedback	Y	Y	Y	Y	N
With Measurement System	Y	Y	Y	Y	Y
Measurement Value	Kb	Evib	CMV	CMV	CCV
Measurement Unit	MN/m	MN/m^2	Unitless	Unitless	Unitless
GPS Capability	Y	Y	Y	Y	Y
Documentation System	ACEPlus	BCM 05 Office and Mobile	AccuGrade	DCA	AithonMT-S
Development Status	In production	In production	In production	In production	In production
Availability	Current	Current	Current	Current	Current

Table 2 - Summary Table for Double-Drum IC Rollers

Vendor	Ammann/Case	Bomag	Caterpillar	Dynapac	Sakai
Model	NA	Asphalt Manager	AccuGrade Compaction	DCA-A	CIS
Model Number	NA	BW190AD-4AM	CB534D,CB534D-XW,CB564D	CC 224 etc	SW850/SW880 /SW890
Auto-Feedback	NA	Y	N	N	N
With Measurement System	NA	Y	Temperature and Pass Count	Y	Y
Measurement Value	NA	Evib	Temperature	NA	CCV
Measurement Unit	NA	MN/ m^2	°C	NA	Unitless
GPS Capability	NA	Y	Y	Y	Y
Documentation System	NA	BCM 05 Office and Mobile	AccuGrade	DCA	AithonMT-A
Development Status	Under development	In production	Available as special order	In production	In production
Availability	Future	Current	Special order	Future	Current

NOTES: ACEplus: Ammann Compaction Expert-Plus, DCA-S (GPS): Dynamic Compaction Analyzer for Soil with GPS, Kb: Stiffness or ground bearing capacity (as related to the plate loading tests), Evib: Vibration modulus, CMV: Caterpillar and Dynapac Compaction Meter Value, CIS: Sakai Compaction Information System, CCV: Sakai Compaction Control Value, Availability: It refers to the availability in the US. DCA-A: Dynamic Compaction Analyzer for Asphalt, CC 224 Etc. Availability: It refers to the availability in the US.

For the majority of the IC projects conducted in the US, RTK GPS is used to provide survey grade positioning measurements with the current focus on the horizontal precision of 40 mm. RTK GPS is normally achieved by utilizing an onsite, network, or virtual GPS base station to provide correction signals. Hand-held GPS rover units are also used for measuring locations of traditional spot testing (such as light-weight deflectometer, dynamic cone penetrometer, nuclear and non-density gauge tests) for correlations of IC roller data. The Universal Transverse Mercator (UTM) and State plane coordinate systems are used to provide geodetic data in northing and easting [12,13].

2.4. Implementation in the US

Intelligent Compaction technology has been implemented in the US in recent years. The US Federal Highway Administration (FHWA) is working with State Agencies and researchers on a pooled fund project,TPF-5(128), to accelerate the implementation of IC Technology in Soils, Aggregates and Hot Mix Asphalt pavement materials [13].

Eighteen (18) field demonstrations were conducted under study for various earthworks and HMA construction projects and information regarding all aspects of IC can be found on the www.IntelligentCompaction.com website. Readers are referred to the NCHRP soils and MnDOT IC studies among many others [14,15].

Through the above mentioned studies, IC technology has shown various benefits to the earthwork and paving industries, among those benefits are the following:

- Tracking compaction operation to facilitate decision-making: IC can be used to track roller passes, HMA surface temperatures, machine operation settings, and ICMVs for roller operators and paving to adjust the operations in real time instead of an after-the-fact. (see Figure 1)
- Identification of weak spots with mapping operations: IC allows mapping or proof-rolling existing support layers to identify weak areas that need corrective actions prior to placing and compacting upper layers. (see Figure 2)
- Improved rolling patterns: IC tracks roller passes and HMA surface temperatures to maintain a consistent rolling pattern within optimal ranges of temperatures for 100 percent coverage that results in uniform, quality pavements. (see Figure 3)
- Determining optimal roller passes and measuring uniformity: IC can be used to determine optimal roller passes based on compaction curves and provide metrics for uniformity of compaction - which can be crucial for better long-term performances. (see Figure 4)
- Overcoming difficulties associated with night paving operations: IC technology can be especially beneficial during night paving operations due to crushed construction schedules and for hot weather conditions. (see Figure 5)
- Cost saving: IC technology allows for a better use of resources (equipment and personnel) to meet specified quality requirements for compaction that lead to cost saving.

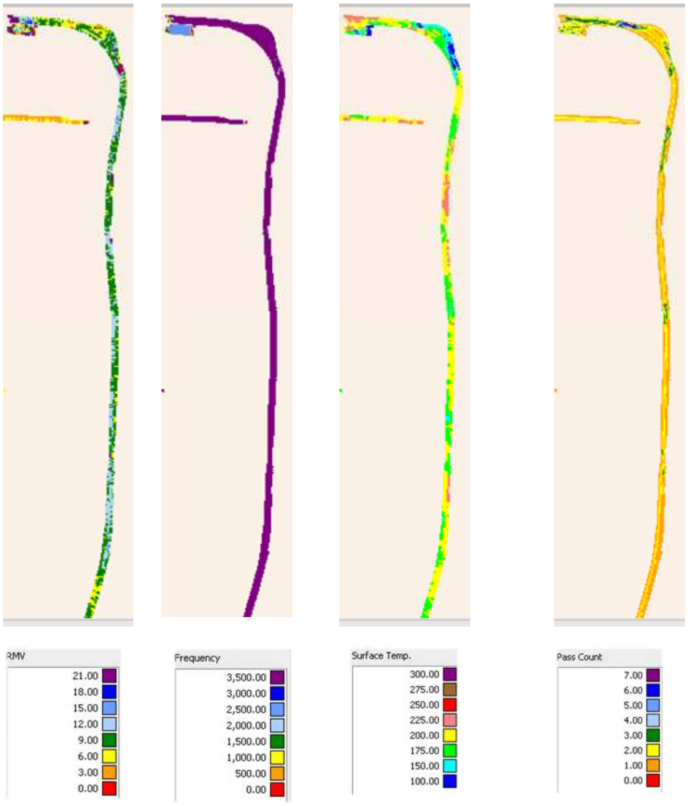


Figure 1 - An example of IC maps for Sakai CCV, frequencies, surface temperatures, pass counts (FHWA TPF California HMA IC demonstration)

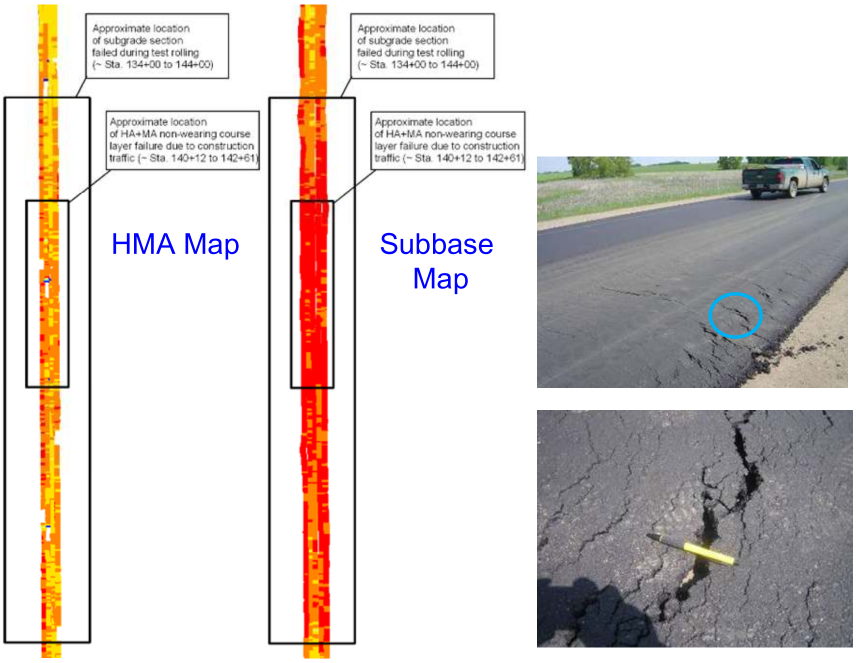


Figure 2 - An example of IC mapping that identifies a weak spot that leads to premature failure without corrective actions (FHWA TPF Minnesota HMA IC demonstration)

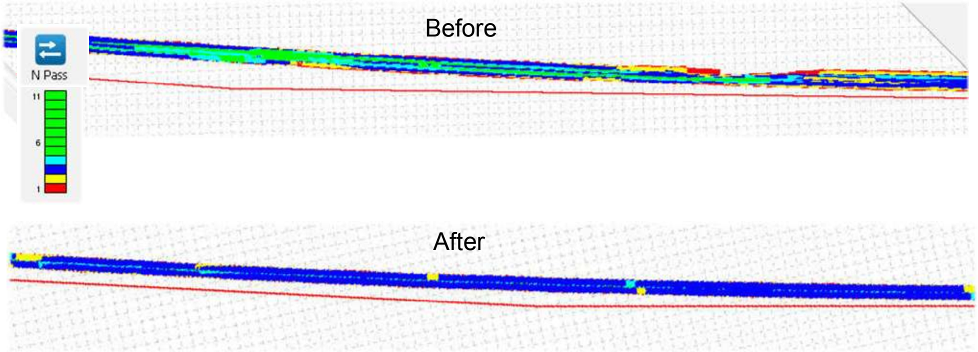


Figure 3 - Improvement of rolling patterns using IC technologies (FHWA TPF Indiana HMA IC demonstration).

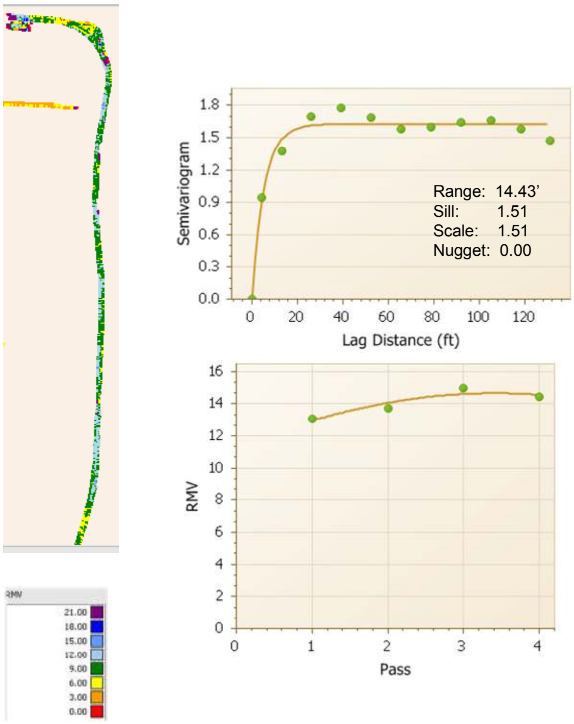


Figure 4 - Sakai CCV map, semivariogram (a metric for uniformity), and compaction curves (plot to determine optimal roller pass) (FHWA TPF California HMA IC demonstration).

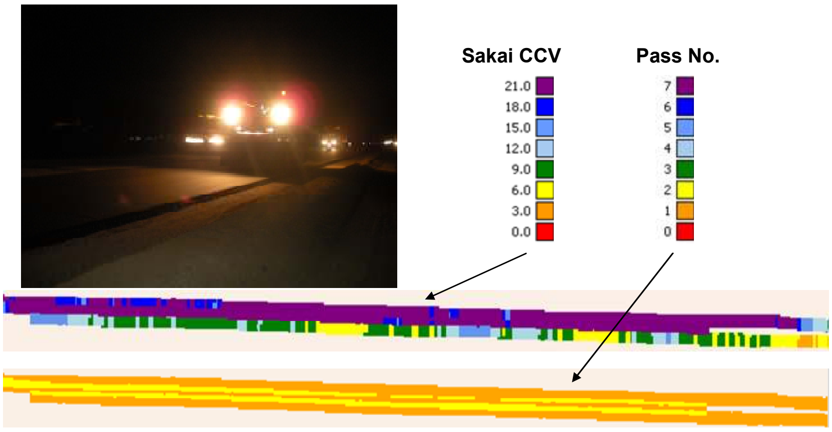


Figure 5 - Overcoming difficulties associated with night paving operation with IC (FHWA TPF Maryland HMA IC demonstration).

2.5. Future Development

It has been proven that IC can be used for Quality Control (QC) to improve roadway construction operations resulting in longer lasting pavements. Intelligent Compaction is also evolving and improving by addressing various areas identified during the wide-spread implementation efforts, including the following [16]:

- An improved IC measurement model to decouple stiffness for each material layer is needed to better evaluate compacted materials such as thin overlays.
- For soil/subbase compaction, real-time moisture mapping is needed for ICMV to account for the effect of moisture on a specific soils/aggregate types.
- For HMA compaction, internal asphalt layer temperature estimated from surface temperature measurements are needed, and an improved ICMV model should account for the effect of asphalt temperatures.
- A multivariate correlation should be used to better understand the effects of various factors (such as operational, vibration frequencies and amplitudes) on the ICMV.
- A simpler, robust, and cost-effective RTK GPS is needed for practical IC implementation.
- A further geostatistical study should be performed to provide guidance for setting target values for compaction acceptance specifications.
- An IC data management and analysis tool is needed to handle massive data.
- Monitoring of long-term pavement performance for IC projects is needed to better quantify benefits (such as uniformity).

The upcoming report from the US FHWA/TPF IC study will provide practical guidelines for implementation.

3. REAL-TIME SMOOTHNESS

The term “real-time smoothness” is used to describe road profile measurements immediately after the concrete pavement is placed while still in plastic state. Real-time profilers may be attached to the paving equipment as shown in Figure 6, where the technology is mounted to the back of the paver (profile pan). In addition, these profilers may be mounted to stand-alone devices independent from the paving operation as shown in Figure 7. The latter setup allows the profile measurements to be conducted at specific locations along the paving train, such as before or after the hand finishing operation, texture-cure cart, etc. In most cases, the stand alone setup allows to conduct profile measurements on the hardened concrete as well.

3.1. Background

Real-time profiling technologies have been commercially available for at least a decade. One example is the GOMACO Smoothness Indicator (GSI), shown in Figure 6 (paver mounted) and Figure 7 (stand-alone unit), which is currently used by highway and airport paving contractors throughout the United States and the world [17,18]. This device utilizes sonic and slope sensors to measure the road profile. Another example is the Ames Engineering Real-Time Profiler (RTP), a laser based profiler that mounts directly onto the paving equipment as shown in Figure 8 [19].

Figure 6 - Real-time smoothness measuring device attached to the concrete paver.

Figure 7 - Stand-alone real-time smoothness measuring system.

More recently, a slightly different real-time smoothness device was developed for the Texas Department of Transportation (TxDOT) by the University of Texas at Arlington (UTA) and the Texas Transportation Institute (TTI) [20]. The device consists of a sliding platform (snowboard) that carries hardware and software to measure slope and distance as it is towed behind the paving equipment on the fresh concrete. Its primary capability is described to be the detection of bumps / localized roughness in real time.

Figure 8 - Real-time smoothness measuring device attached to the concrete paver.

3.2. The Concept of Real-Time Smoothness

Real-time smoothness systems act as a QC tool employed while the paving operation is in progress, as opposed to conventional profiling on hardened concrete for acceptance. Figure 9 illustrates how real-time smoothness data collection and interpretation can be implemented. It begins with the various factors that can potentially impact the smoothness of concrete pavements, which include elements of pavement design, materials selection, climate, and construction technique. Next, the technology is used to measure the road profile in real time. Analysis software is used to assess the measured profile and determine smoothness statistics and the presence of objectionable profile characteristics.

Smoothness statistics refer to indices such as the International Roughness Index (IRI) and the Profilograph Index (PI), and provide the paving contractor a relative indication to whether smoothness specifications are being met or not. Note that the smoothness statistics in real time differ from the smoothness statistics on the final hardened concrete, since the effects related to post-placement events such as joint sawing (of jointed concrete pavements, JCP), texturing, tinning, curling / warping, etc. may not be captured in real time.

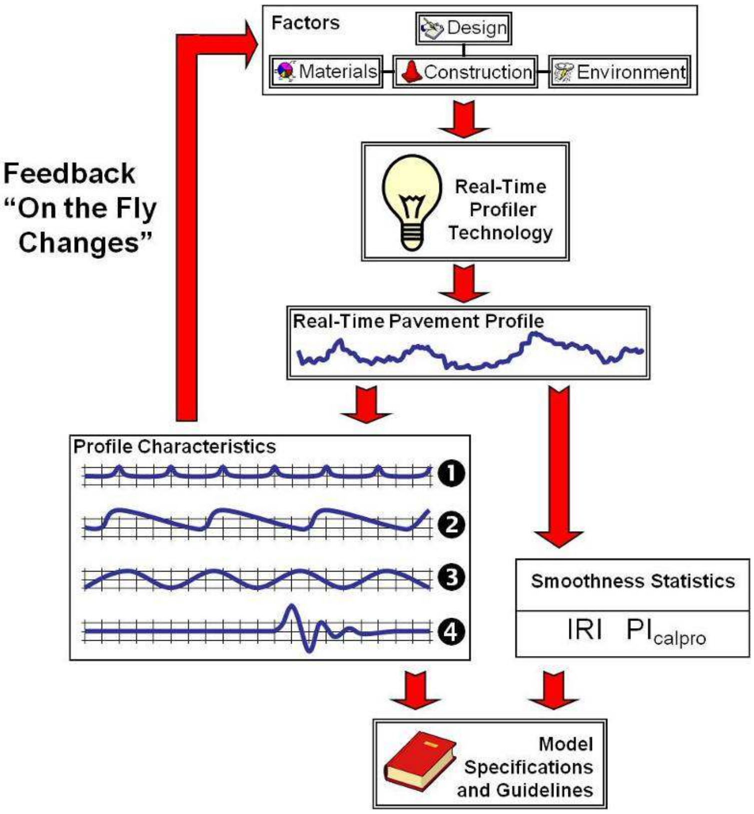


Figure 9 - Conceptual implementation of a real-time smoothness system.

The assessment of objectionable profile characteristics in real time is a promising application and is currently in the development stages for inclusion in the analysis software for these technologies. The "Profile Characteristics" box in Figure 9 depicts objectionable profile characteristics that may happen in real time, such as: 1) dowel basket rebound (in JCP) or transverse reinforcement rebound (in continuously reinforced concrete pavement, CRCP), 2) concrete loading / delivery effects, 3) sagging string lines, and 4) localized roughness (bumps). The first three are likely to be repetitive features in the road profile, while localized roughness involves isolated events. Profile analysis techniques that may be used to identify such profile characteristics include Power Spectral Density, Cross-Correlation, and Continuous IRI Reporting [21,22].

Ideally, the analysis software for these systems will alert the paving contractor in real time when there is a risk of not meeting specifications in terms of IRI/PI or if there is presence of objectionable profile characteristics. The contractor will then make the necessary adjustments in real time to the paving operation.

3.3. Benefits

As depicted in Figure 9, a model real-time smoothness system attempts to identify the influence of design and construction factors in the road profile as it is being constructed (real time). With a better understanding of these factors, concrete paving contractors are able to make adjustments as soon as possible in order achieve a smoother pavement surface. Making adjustments while paving is still in progress helps reduce the expense of grinding the final surface to meet smoothness requirements. In addition, remedial measures may be taken to address localized roughness, in some cases during the finishing operation while the concrete is still plastic.

In the United States almost all State Highway Agencies employ smoothness specifications for concrete pavement construction, and the majority of them utilize monetary incentive and / or disincentives. The ability to assess smoothness in real-time represents a win-win situation for all parties involved. With these tools, concrete paving contractors are more efficient in providing owner-agencies with smoother, longer lasting pavements, and ultimately, the travelling public enjoys a better ride quality.

3.4. Implementation in the US

In 2004, the Federal Highway Administration and the Iowa Department of Transportation sponsored a research to evaluate two real-time smoothness systems (GSI and RTP) in the field [23]. The study concluded that both devices were able to detect roughness characteristics in real time that can affect the final concrete pavement surface and ride quality. As previously mentioned, TxDOT has been working on the development and implementation of a real-time smoothness monitoring system.

Currently, there is a SHRP2 project entitled, Real-Time Smoothness Measurements on Portland Cement Concrete Pavements During Construction [24]. The project objectives are to evaluate and demonstrate real-time smoothness technologies, and to draft model specifications and guidelines to be used with these technologies. The results of this effort are anticipated to be published in 2012.

4. AUTOMATED CURING MONITORING

4.1. Background

Concrete pavement construction represents a large investment intended to last for many years. However, it is during the first few days after construction of the pavement when many of the concrete properties develop, which in turn depend in large part on the surrounding moisture and temperature conditions. As a result, adequate curing procedures are of paramount importance during the construction stage to prevent pavement damage due to inadequate or insufficient curing such as thermal cracking, plastic/drying shrinkage cracking, poor abrasion resistance, and spalling. Adequate curing is also important to ensure that the concrete will achieve its intended properties, resulting in a durable product.

Extensive guidelines on adequate curing of concrete pavements are available and have largely become state of the practice [25,26,27]. However, adequate curing requires of continuous and consistent attention to environmental conditions and paving operations in the field where the benefits of automation are obvious. To improve current practices, the FHWA recently sponsored a research project to develop user-friendly computer-based guidelines for curing of portland cement concrete (PCC) pavements [28]. The primary intent of this project is to develop a tool for monitoring the paving process in real time. Some of the requirements for this tool are to be able to validate compliance with state specifications and to recommend curing materials and procedures as a function of current conditions.

4.2. The SmartCure System

As part of this research project, the SmartCure curing system was developed as an aid for evaluating curing conditions during paving and to provide reliable and realistic guidelines on proper curing. SmartCure consists of hardware and software components that can graphically monitor the paving process in real time and warn the user whenever a risk for damage to the pavement structure is identified as a function of climatic conditions. As shown in Figure 10, the hardware components are affixed to the curing cart of the paving train and these include field-monitoring devices that measure climatic conditions, PCC temperatures, and location on a continuous basis.

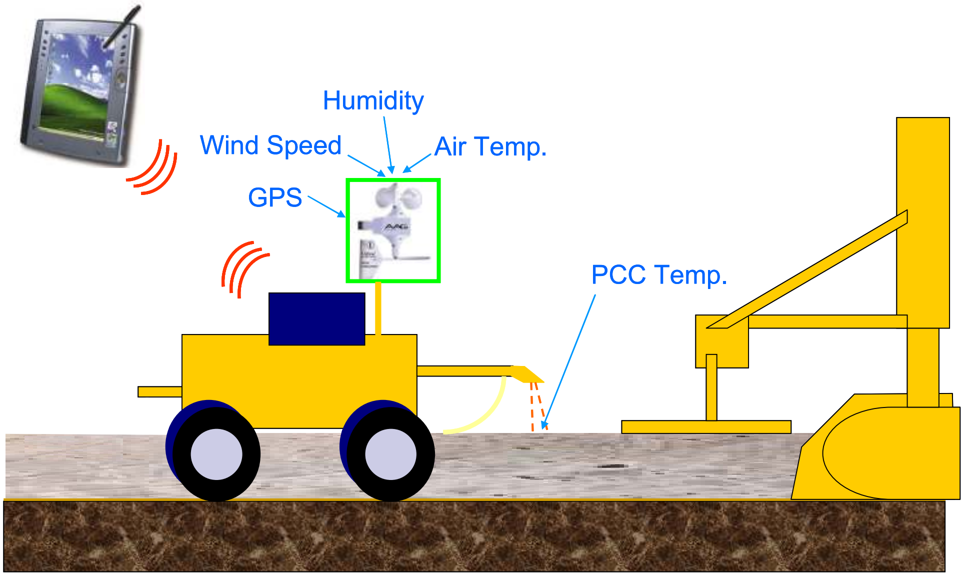


Figure 10 - Schematic Representation of the SmartCure System.

The system framework is illustrated in Figure 11. SmartCure consists of the following components:

1. A portable weather station used to monitor wind speed, air temperature, and relative humidity.
2. Continuous positioning of the paving operations as well as time and date of placement are obtained with the use of GPS.
3. A non-contact infrared pyrometer is used to monitor concrete temperatures.
4. Information from the individual components is accessed by a computer operating the Windows®-based SmartCure software program for data reporting and storage.

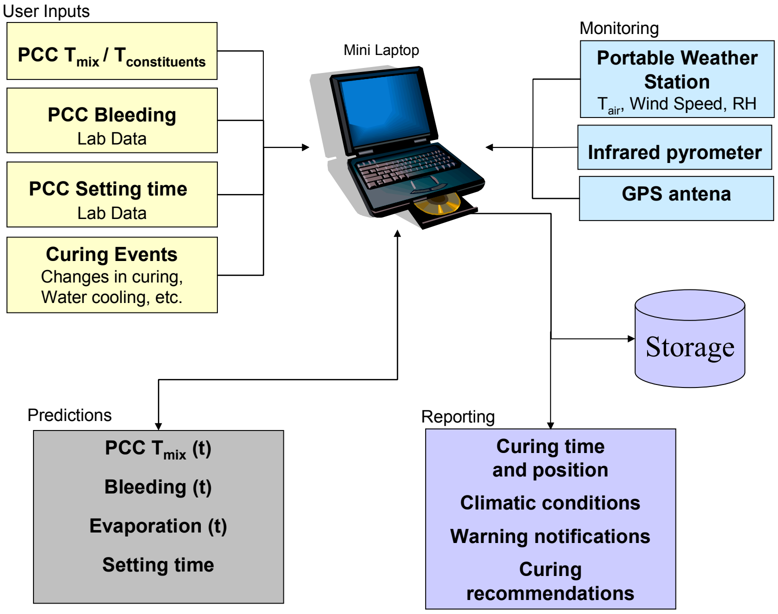
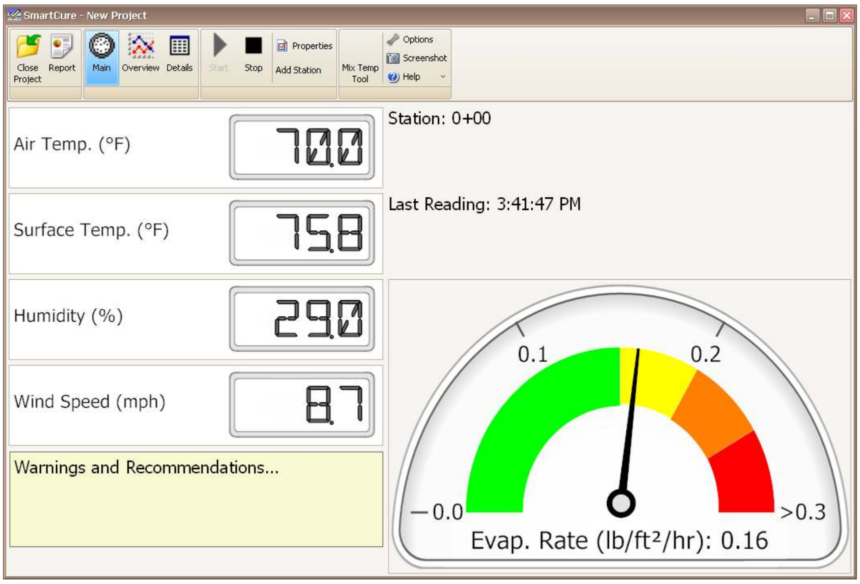


Figure 11 - SmartCure conceptual framework.

Figure 12 shows the main screen of the SmartCure system. SmartCure is intended to monitor the paving process, create a permanent record of date and time of curing, position, and climatic conditions. In addition, this tool provides real-time warnings and pertinent curing recommendations when environmental conditions result in excessive evaporation rate that may lead to moisture loss from the pavement surface or extreme temperature conditions that may suggest an increased risk of damage to the new pavement structure.



Air Temp. (°F) 70.0

Surface Temp. (°F) 75.8

Humidity (%) 29.0

Wind Speed (mph) 8.7

Warnings and Recommendations...

Station: 0+00

Last Reading: 3:41:47 PM

Evap. Rate (lb/ft²/hr): 0.16

Figure 12 - Screenshot of the main SmartCure software screen.

A default set of editable curing recommendations is available to fit specific highway agency specifications. Display of warnings and recommendations are triggered by the use of evaporation rates and field concrete temperature thresholds identified by the hardware components. In addition, the user has the option to define evaporation thresholds in agreement with predicted bleeding rates if these are available.

The equivalent age concept is used to predict time of setting under field temperatures departing from time of setting under standard laboratory conditions of temperature via

ASTM C 403 as recommended in the FHWA curing guidelines [25]. Times of setting results predicted by the SmartCure System are used to estimate the timing of curing procedures. This information may be also helpful in scheduling saw cutting operations.

4.3. Implementation in the US

Initial evaluations of the SmartCure system have been conducted on site during real pavement projects (Figure 13). Three locations were chosen as field evaluations sites based on varying regional climatic conditions:

1. Highway US-59 southwest of Houston;
2. Widening of I-435 in Overland, Kansas, and State Highway 71 in Kansas City, Missouri; and
3. SR 9 near Martinsburg, West Virginia.

The purpose for the field trials was to evaluate SmartCure's effectiveness in terms of data collected and produced by the system; and feasibility of use in a field environment.

The field evaluation phase proved the SmartCure System as functional, reliable and accurate in the field. The system successfully relates ambient weather conditions to fresh concrete properties and alerts the user of potentially critical conditions based on user defined or default thresholds. However, at that stage, it was identified that the system required of adjustments to improve practicality.

Figure 13 - Evaluation of the SmartCure system in the field.

Most immediate problems with regards to components and software were addressed during, or just after individual site visits. However, it became clear that providing wireless functionality would optimize practicality making SmartCure more portable, and more suitable for field applications. To achieve this objective, additional research was conducted to determine the availability of commercial off-the-shelf state-of-the-art software and hardware. Based on this research, the existing SmartCure measuring components were connected via serial ports to a serial server and then to a wireless (RF) modem by an Ethernet cable.

The modified SmartCure was subjected to additional testing to ensure that the data would relay successfully via a wireless connection to the laptop. This additional testing proved that this wireless version of SmartCure works in the field as long as there is continuous line-of-sight between the RF modems. Recommendations were provided for positioning antennae as high as possible to improve line of sight. High-gain antennas and mesh networks may also improve performance distance and line of sight.

4.4. Future Efforts

Limitations due to a dependency on line of sight for data collection and relay suggest that an alternative option that includes a data logger should be considered. If line of sight is lost, data collected by the measuring components is still recorded by the data logger and can be retrieved either from the data logger itself or by the laptop whenever line of sight is restored.

Additionally, although timing is recognized to be the focus of this project, it is believed that SmartCure has the potential for controlling or at a minimum monitoring the application rate with the inclusion of additional sensors to monitor the flow rate of the curing material.

Also, in addition to the laptop, alternate reporting options to a hand held receiver (e.g., pocket PC or cell phone) that could receive the warnings and recommendations SmartCure generates would increase practicality by offering mobility thereby making the system less obtrusive to the cure cart operator. A handheld, wireless receiver would allow an inspector, project manager, or paving supervisor to be more aware of curing conditions no matter where they are on the job as opposed to only the cure cart operator standing next to the laptop screen.

During the field trials, a GPS tracking device (independent of the SmartCure system software) was mounted onto the paver for manual calculations of distance after the fact. It is believed that monitoring distance between the paver and curing cart and tying this information to environmental conditions will result in useful warnings and recommendations. For example, generating warnings when harsh environmental conditions occur and the cure cart needs to be as close as possible to the paver to ensure adequate timing of curing.

With practicality issues solved, SmartCure should be instrumental in improving construction practices that can lead to improved concrete pavement performance. With this technology, it is anticipated that a process will result that will allow pavement construction engineers to make rational adjustments to the construction practices in order to improve the ultimate quality of concrete pavements.

5. SUMMARY AND CONCLUSIONS

This paper describes some of the implementation efforts of emerging ICS technology in the US, specifically for three applications, namely, intelligent compaction technology, real-time smoothness, and automated curing monitoring. The key to implementing technology in any industry is an understanding of what the specific needs are and which available resources are implementable based on usefulness, accessibility, and cost-effectiveness. It is believed that the technologies above described possess significant potential for improved quality and faster delivery of concrete pavement construction and will be gradually adopted as these technologies continue maturing and are well known by the paving industry.

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