Field Evaluation of Stringless Portland Cement Concrete Paving

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ABSTRACT

This paper describes results from a study evaluating stringless paving using a combination of global positioning and laser technologies. A concrete paver manufacturer and a machine guidance solution provider developed this technology and successfully implemented it on construction earthmoving and grading projects. Concrete paving is a new area for considering this technology. A concrete paving contractor in Iowa agreed to test the stringless paving technology on two challenging concrete paving projects located in Washington County, Iowa during the summer of 2003. The research team from Iowa State University monitored the guidance and elevation conformance to the original design. They employed a combination of physical depth checks, surface location and elevation surveys, concrete yield checks, and physical survey of the control stakes and string line elevations. A final check on profile of the pavement surface was accomplished by the use of the Iowa Department of Transportation Light Weight Surface Analyzer (LISA). Due to the speed of paving and the rapid changes in terrain, the laser technology was abandoned for this project. Total control of the guidance and elevation controls on the slip-form paver were moved from string line to a global positioning system (GPS). Results indicate that GPS control is a feasible approach to controlling a concrete paver. Further enhancements are needed in the physical features of the slip-form paver hydraulic system controls and in the computer program for controlling elevation.

INTRODUCTION

Current Portland cement concrete (PCC) pavement construction technology employs the use of physical guidance systems in the form of a string or a wire line on one or both sides of the slip-form paving train of equipment. This approach provides both the horizontal and vertical control for the machine to place the required pavement thickness in the required location (Figure 1). Though this method has been very successful in practice, there are a few disadvantages with it and can possibly be addressed by recent development in technologies such as Global Positioning System (GPS) and laser surveying and equipment control. Establishment of the traditional string line guidance system is a very costly and time consuming process. Using the traditional stringline control method, most projects require a crew of 4 to 6 people and three separate survey circuits. This normally requires several weeks for a project with 5 to 10 km in length and is very unlikely to be overlapped with other activities. It also creates a need for space on each side of the paving machine to set the survey control line near the paver. With the stringlines in place, access to the construction site becomes awkward and inconvenient. Spacing of the control line stakes can also have a positive or negative impact on the smoothness of the final pavement surface (Rasmussen et al. 2004). The actual placement and verification of the physical guidance systems on each side of the paving machine costs time, requires manpower, and limits access to the area in front of the slip-form paver.

Figure 1. Sensors Used to Read String Lines

Automated control of the construction machines such as trimmers, slip-form pavers, and texture/cure machines should provide both vertical and horizontal control to the machines and eliminate the need for the control staking lines. GPS based control system has been successfully use on grading equipment. In the research project described in this paper, the same control system used for the development of the graded cross sections will be used for the slip-form paver control. The objective of the research is to test if the automated equipment control system can be used to control the horizontal and vertical alignment of the slip-form paver and provide a smooth riding surface for the final product as the stringline control method does. To answer this question, both control methods were used on different sections of two PCC paving projects located in Washington and Keokuk Counties of Iowa. With a focus on elevation control, four types of data, plastic thickness, elevation conformance, yield quantity, and profilograph, were collected and quantitative comparisons were made between sections using different control methods.

At the beginning of the research, two companies expressed interest in demonstrating their system. The first automated control system, developed by Leica Geosystems, could only be fitted to GOMACO Paving equipment of a relatively new vintage at this time. Due to construction equipment specification and research project site limitations, this automated control system was not evaluated in this project. The research team gave consideration to the second vendor. CMI Terex Corporation and Geologic Computer Systems developed a system called GeoSite

Manager System, which has been successfully used on earthmoving and grading projects. Washington and Keokuk County staff in Iowa were aware of this limitation and agreed to proceed with the research project.

STRINGLESS PAVING APPROCHES

Automation of operations involving adverse environments or intensive labor requirements has been an active area of research and innovation. Many such automated operations are being used in agriculture, mining, and construction industries. One of the barriers to achieving a higher level of automation, and also a topic that has been actively researched in recent years, is the positioning and guidance of this equipment.

Various types of equipment are used in heavy highway construction. Peyret (2000) classified the construction machines used for road construction into three main groups based on different positioning accuracy requirements:

- Earth-moving and mining equipment, e.g., shovels, drills, scrapers, bulldozers, excavators, etc.
- "Surfacing equipment", which refers to machines that move on the surface of the ground without noticeable changes in height. These include compactors, concrete spreaders, mixers, and trimmers.
- "Profiling equipment", which refers to machines that modify the profile of the worksite by addition or removal of material. These include pavers, autograders, and milling machines.

Different levels of accuracy are required of the positioning and control systems on these construction machines. The accuracy requirements in terms of level for the various layers of pavement are typically ± 3 cm (± 1.2 in.) for sub-base, ± 2 cm (± 0.8 in.) for the base, ± 1.5 cm (± 0.6 in.) for the binder course, and ± 0.5 cm (± 0.2 in.) for the wearing course (Peyret 2000). While some of these requirements are easy to meet, the accuracy level of positioning of slip-form pavers, which certainly lies in the wearing course category, remains a challenge for stringless control systems.

Construction equipment positioning and control requires control of all six degrees of freedom of the equipment (x, y, z, roll, pitch, and yaw). Technologies that are popularly used or considered promising to solve the problem include Real Time Kinematic (RTK) GPS, laser levels, and robotic total stations.

Guidance with Robotic Total Stations

Successful applications of robotic total stations on heavy highway construction equipment, including concrete pavers, have been reported by GOMACO Corporation and Leica Geosystems in several cases around the world. The 3-D machine control system developed by Leica Geosystems has the following components (Leica Geosystems 2001):

- The Leica "Commander Box" with an industrial PC, a touch screen, an integrated floppy drive, a keyboard, and a radio modems
- The "LMGS-S for Slip-Form Pavers" software package
- Automatic total station(s) TCA 1800/2003
- Dual axis tilt sensor(s)
- Required accessories, like the 360° precision prisms, TCPS26 radio modem, data transmission cables, batteries, and masts.

GOMACO and Leica's system has been tested on a number of different projects including an airport taxiway and 335 m (1100 ft.) of a residential street in Ida Grove, IA. The system has been developed to be applicable to grading and paving equipment. The total stations are standard surveying total stations that can be used for survey work, staking, and checking. The typical accuracies that GOMACO has found using this system are 1 – 3 mm (0.04-0.12 in.) with a 100 – 200 m (300 to 650 ft.) shooting distance.

To use GOMACO and Leica's stringless control system, it requires digital plans and a few adjustments to a normal paving machine including mounting the prisms and control computer and the addition of some tilt sensors. It will require that accurate monuments be set along the project for the total stations to be set on and localized. These total stations will then be used with a third total station while paving to keep two total stations within range of the paving machine at all times. The system also requires more technical workers with surveying and computer knowledge to set up, run, and fix any problems that might occur. GOMACO's system has to have a clear line of sight to the prisms on the paving machine. Each total station has to be set up and localized before its data can be used by the paving machine control system, which introduces more possibilities of error.

Guidance with GPS and Lasers

GPS is a system developed by the Department of Defense for navigation and positioning use by both the military and civilians. While the accuracy of positioning available to civil engineers was approximately 100 meters (328 ft.) when it first appeared, this number has been significantly reduced in recent years. Commercially available GPS receivers using Real Time Kinematic GPS (RTK GPS) technology provide positioning (horizontal) accuracy at the level of 10 mm (0.4 in.). This accuracy is satisfactory for the positioning of construction equipment that requires lower levels of accuracy. Whether it is accurate enough to be used in a paving operation remains to be determined.

The main shortcoming for using GPS for construction equipment positioning is its accuracy in measuring elevations, which is normally twice as large as the horizontal accuracy of the same GPS. According to a study conducted by Peyret (2000), the overall accuracy of RTK GPS can be represented by

- a bias between +20 mm (+ 0.8 in.) to -20 mm (– 0.8 in.)
- a standard deviation under 10 mm (0.4 in.)

Thus, for the slip-form paving application, raw measurements from RTK GPS cannot be used directly because of lack of accuracy. The study further proved that the bias, or drift, which is related with the constellation plot, and some local phenomena such as multi-path effects, is repeatable within given limits of time and space. Based on this repeatability, the accuracy of the RTK GPS results can be improved using modifications external to the GPS signal processing.

Another method to compensate the inadequate elevation accuracy of the GPS results is using laser levels in combination with GPS for construction machine positioning. Typically, rotating-beam lasers are used in this kind of system with rotation speeds in the range of 300 to 600 rpm. The laser levels typically have a working radius of up to 300 m (1000 ft.) and an accuracy of better than 10mm (0.4 in.) per 100 m (330 ft.).

While laser levels can improve the elevation accuracy of the control system, a few obvious disadvantages exist with this method (Geologic Computer Systems 2003):

- Optical equipment is vulnerable to environmental inference (e.g., rain, dust, snow, and temperature) and requires line of sight.
- Lasers only work within the height of the receiver mast.
- Lasers and laser masts are mechanical devices and suffer from wear and tear.
- Rotating lasers consume a lot of power – operation requires a deep cell battery charged daily to run.
- Lasers are potentially unstable – windy conditions easily make a laser tripod sway in the wind, affecting accuracy.

STUDY METHODOLOGY

The research methodology included the following activities:

1. Identification of two Portland concrete paving projects in Washington and Keokuk Counties scheduled for paving in 2003 to test the stringless control system.
2. Placement of the GPS and laser control system on the contractor's slip-form paver to sense and control the elevation and location of the pavement edges.
3. Use of Quality Management Concrete (QMC) specifications for monitoring and appraising the project.
   a. Use of the Iowa DOT profile device to establish the final road surface profile in the outer wheel path of the roadway in each direction.
   b. Depth checks by the research team and county personnel to verify the pavement section being built.
   c. Selected coring of the final pavement surface to determine the depth of concrete relative to the final surface elevations.
   d. Measurement of the concrete payment by the cubic yard and square yard to reduce the risk to the contractor for placement depths.

    e. Survey of the final paved surface to verify the vertical and horizontal alignment of the final pavement surface at the edges and centerline.
4. Analysis of results and recommendations.

FIELD TESTS

Two paving projects in Washington County were selected for evaluating the stringless paving technology. The first project, called “Coppock Quarry Road project”, was completed on 320th Street in Washington County. The street is approximately 4.6 km (3 miles) in length, contains minor horizontal curves, and has considerable vertical slopes. The pavement was built on an existing granular surface road that had been reconstructed in two segments over the last six years.

The second project, referred as the Ashby project, was completed on 170th Street in Washington County. The street is 9.6 km (6 miles) in length, contains minor horizontal curves, and has considerable vertical grades as well. The contractor for both projects was Fred Carlson Company Inc., a large paving contractor headquartered in Decorah, Iowa.

Washington County surveyed the existing graded surface and created a 3-D design model. This was done to establish the horizontal and vertical alignment for finish grading and paving purposes. The survey information was placed in a design model for input into the stringless machine control system.

Stringless Paving Equipment Used

CMI Terex Corporation and GeoLogic Computer Systems, a Michigan-based company, are the leading firms behind this new method of GPS stringless paving. Their method uses a global positioning survey system accompanied by lasers to control and guide a paving machine. There are a number of other smaller contributors helping with this system including Marsh Electronics of California. This was the first time that this system had ever been used on a slip-form paving machine and is still in its experimental and developmental phases.

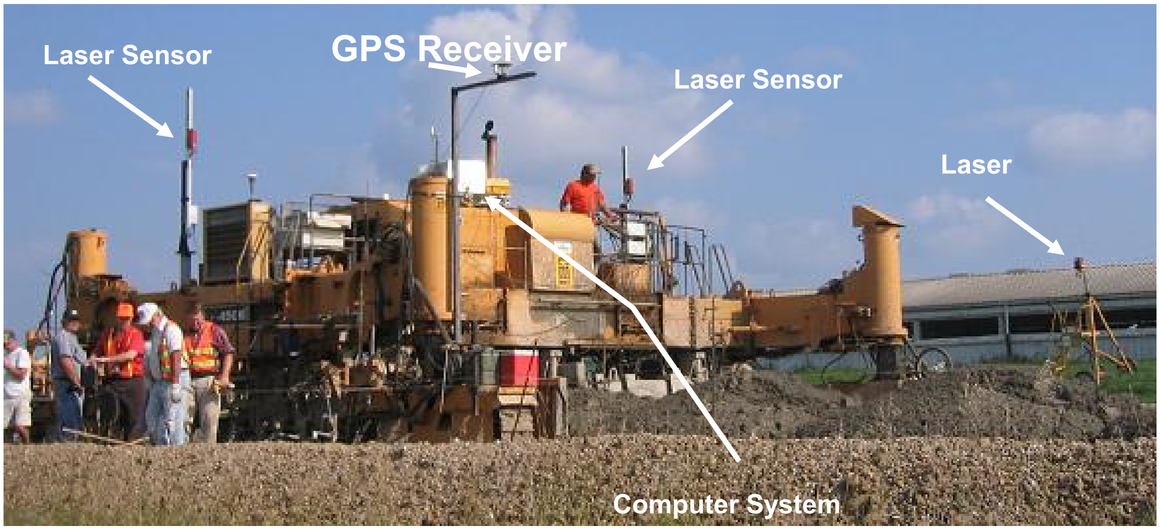
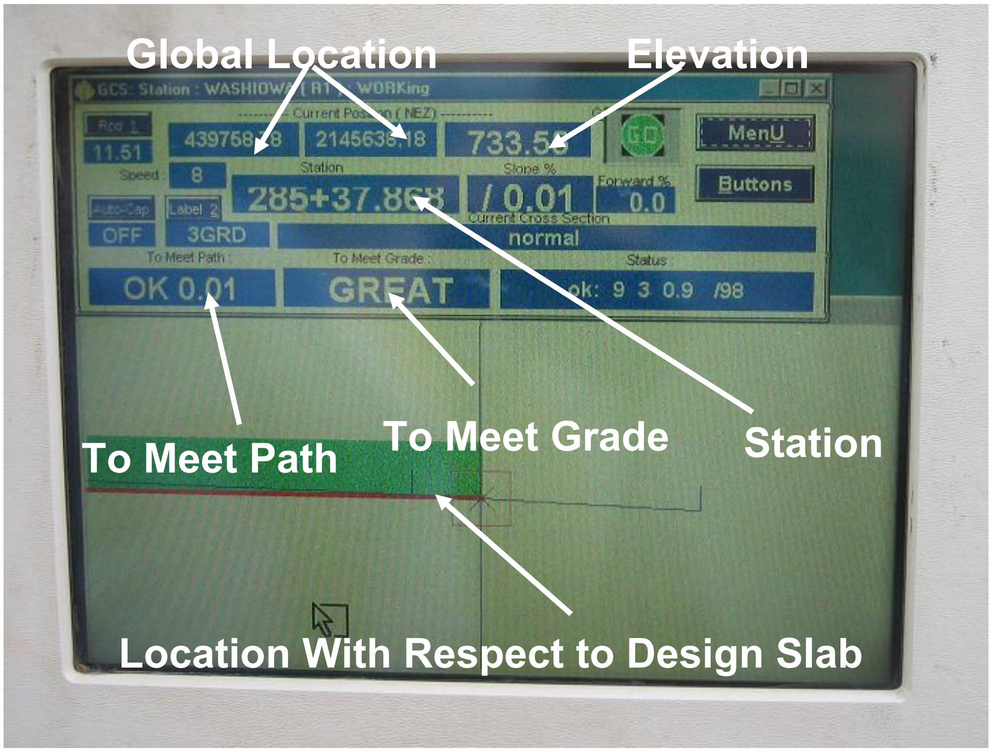


Figure 2. CMI Slip-form Paving Machine with GPS Guidance Equipment Attached (Courtesy to Chris Bauer)

Carlson and GeoLogic fitted a CMI 1992 slip-form paving machine with the new system. It included a GPS receiver mounted over the front right track and two laser sensors mounted on separate 1.68 m (5.5 ft.) laser masts located on opposite sides of the paving machine (Figure 2).

Figure 3. GPS Controller, Screen, and Keyboard with Laser Height Gages



Current Position (NEZ): 439758.[illegible]8 2145638.18 733.5[illegible]

11.51

Speed: 8

Station: 285+37.868

Slope %: / 0.01

Forward %: 0.0

OFF 3GRD

Current Cross Section: normal

To Meet Path: OK 0.01

To Meet Grade: GREAT

Status: ok: 9 3 0.9 /98

Figure 4. Sample Screen of Data from Stringless Paving Control Computer (Courtesy to Chris Bauer)

Final trimming of the subgrade was accomplished by a modified CMI autograder (Iowa Special). This machine both trims the subgrade and conveys the Portland cement concrete from the haul units to the trimmed subgrade. The Iowa Special (30 years old) and texture/cure machine were not equipped with the GPS stringless system, so two string lines were still constructed and used by these machines. The slip-form paver can also be controlled by the string lines so that when the new system fails, the project is not significantly delayed. In addition to the installation of the new control system, new hydraulic valves are also required in the slip-form paver. The new control system can be observed in Figure 3.

The stringless paving computer system, which combines the GPS data with the laser data and controls the paving machine, runs on a standard Windows operating system. In Figure 4, one can see a sample screen for the

Washington County project while the paving machine was running. It has the current GPS coordinates and elevation, the station that is nearest to these coordinates, and the distance that the paving machine needs to go to meet the design at this station. In this figure, the paving machine is off the path by one hundredth of a foot, and the elevation is near perfect. Below these data in Figure 4, is a cross sectional view of the pavement slab and where the paving machine is located with respect to this slab.

Coppock Quarry Road project (320th Street)

Paving of the Coppock Project started on August 12, 2003 and ended on August 14th. Paving started from station 299+90 (equals to 29900+90 ft, same hereafter) and ended at station 154+40.

The paving process started with traditional string line control. The GPS steering (horizontal x, y coordinates) control was initiated near station 292+00 and ended at station 259+75. During this process, laser elevation control was turned on and off several times. The GPS horizontal control proved very successful during the 1000 m (3300 ft.) section. A few problems were identified with the laser elevation control. Some of these problems were related to the disadvantages of using laser control listed previously. Some were related to the computer program developed by Geologic. After a meeting with all the parties involved in the research, it was decided that GPS elevation control will be used in place of the laser control. With the current technology, the elevations obtained by GPS devices should be accurate enough for the purpose of this paving project. For the remainder of the project, the Geologic engineers continued to adjust their system to use GPS for the elevation control.

Ashby Road (170th Street)

Paving of the Ashby Project started on August 25, 2003 and ended on September 3rd. Paving started from station 315+13 and ended at station 0+08. The first a few days of the project turned out to be a testing and correction process for the Geologic computer system. After a few days of switching on and off the stringless control system, a relatively long section was finally paved continuously under GPS elevation control. This section is about 400 m (1300 ft.) in length, and extends from station 17+10 to station 3+80. Data collected from this section were used to compare with data from sections where string line control was used.

Issues Encountered During Construction

The two paving projects provided excellent opportunities for testing the stringless control system, during which a few problems were identified. The greatest challenge encountered came from the programming of the computer system that controlled the paving machine. Watching the computer screen, which showed the deviation from the design location and elevation, it appeared that the GPS and lasers were accurate enough to steer the paving machine. However, the GPS elevation data experienced high variability between readings. Field observations during paving attribute the variability to a combination of soft subgrade in the paver track line and computer overcorrection. The computer program tried to adjust the paving machine to these changes when in reality it was unnecessary. The research team sees this project as developmental research to allow the computer programmers to find out what their programs need to do. This research allowed them to make changes to their programs to see how these changes would affect and control the paving machine on a real project.

It was also observed that the stringless control system required frequent adjustment to the location of the paving machine, causing some of the hydraulics and valves to be constantly moving up and down. This type of movement is also observed under string line control, but it is not as violent as experienced with the GPS controlled equipment. This constant adjustment created excessive wear on these pieces of machinery, and Carlson people did not let this continue as they observed what the stringless system was doing to these hydraulic valves.

Moreover, the actual location of the GPS receiver on the paving machine proved to be an important detail. The GPS receiver needed to be mounted above the front track of the paving machine. This track controls the turning of the slip-form paving machine, and if the receiver is not mounted over this location, the system will not recognize a turn instantaneously. If a turn is not immediately detected, the control system will try to further correct for the deviation from the design when the correction has already been made.

DATA COLLECTION AND ANALYSIS

Four aspects of pavement quality are considered relevant to the choice of paving machine positioning control method: pavement smoothness, pavement thickness, yield quantities, and conformance to the design elevation. Data related to these aspects were collected from sections of the Ashby project and analyzed to test if the proposed stringless paving method can provide the same pavement quality as the string line control method.

Pavement Smoothness

Pavement smoothness is the primary concern for public road owners such as counties and state DOTs. Many states, including Iowa, use an incentive mechanism in their standard specifications to encourage contractors to achieve better pavement smoothness (Iowa DOT 2001). Typically, the unit price of the construction contract is adjusted according to the achieved pavement smoothness. Therefore, the pavement smoothness is also of particular interest to the pavement contractors. A Light Weight Profiler was used to detect the profile of the finished surface in the outside wheel-path in both directions of a section (from station 54+00 to station 3+00) of the Ashby project. The level of smoothness obtained was established using the profiles. This work was done by the research team in cooperation with the Iowa DOT Office of Special Investigations.

The profiles were divided into five intervals. The section between station 17+00 and 4+00 was selected to represent stringless paving because only stringless control was used in this section. Pavement smoothness indices of this section were compared with other sections of the profile.

The California Profilograph Index (CPI) is the most popularly used index in the US. Iowa DOT also specifies their smoothness incentives in terms of CPI. CPIs for the five intervals were calculated using Profile Viewer and Analyser (ProVAL, Federal Highway Administration 2003). The California Profile Index for each interval in the two profiles shows that the interval using stringless control in the profiles for both directions has higher CPI's (20.55 in/mile east bound and 26.80 for westbound) than all other intervals (between 1.58 and 7.86 inch/mile for east bound, and between 1.44 to 6.47 inch/mile for west bound). This means that the pavement smoothness using stringless control is not as good as the result of using string line control.

As a confirmation, other ride statistics, such as International Roughness Index (IRI), Profile Index (PI), Ride Number (RN), were also calculated for these intervals using ProVAL. The statistics reflect the same conclusion as the CPI does. Details of determining the IRI, PI, and RN can be found in I.M. 341 (Iowa DOT 2004) and in The Little Book of Profiling by Sayers and Karamihas (1998).

Pavement Thickness

Pavement thickness is considered an important aspect because it influences the strength and durability of the pavement, as well as the construction cost. To check the pavement thickness, two methods were used: pavement thickness check when the concrete is still plastic (plastic thickness) and measurement of core lengths. Most states use the core lengths in their standard specifications and few use the plastic thickness, probably because the cores are more accurate and reliable than plastic thickness. The New York state DOT requires the measured plastic thickness must equal or exceed the thickness required in the contract documents (New York State DOT 2002). Areas having a substandard thickness will be treated as "Damaged or Defective Concrete." If two consecutive substandard thicknesses are obtained, the paving should be stopped and the paving operation should be reestablished to achieve acceptable thickness. Iowa DOT uses core lengths to calculate a thickness index (TI), which is used for acceptance and payment adjustment. According to design, the depths should be 9 in. at the edges and 7 in. at the centerline.

Plastic thickness was checked for the Ashby project from Station 137+50 to Station 5+00 at an interval of 76.2m (250 feet). The thickness was measured at the centerline, and at points about one foot within both edges. The design thicknesses at these points are 178 mm (7 in.) at the centerline and 225 mm (8 5/6 in.) at the edge points. Result of the pavement thickness check (including stringless paving section) shows that 11 of 108 (10.2 %) edge points are less than 8 5/6 inches, and 4 of 54 (7.4%) center line points are below 7 inches. For the stringless paving section, 3 of 10 (30%) edge points and 1 of 5 (20%) centerline points are below the required thickness.

Ten cores were taken at about 90 cm (3 ft.) inside the edges of the pavement, three of which were taken from the stringless paving section. All of the 10 cores met the required depths.

Because the probe used in the plastic thickness checks may be stopped by the gravel inside the concrete paste instead of the metal plate laid at the surface of the subgrade, the plastic thickness is not a very reliable way of determining the pavement thickness. Thus, even though deficient points in the stringless paving section have a higher frequency of appearance, it is not sufficient to assert that the pavement thickness control by the stringless paving system is not as adequate as the string line control method.

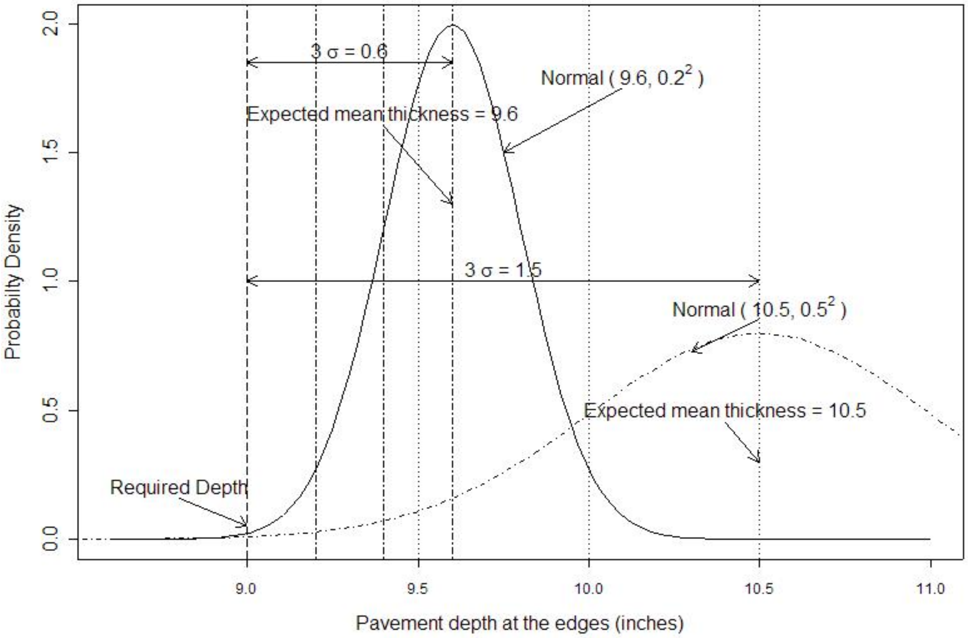


Figure 5. Target Pavement Thickness at Different Standard Deviation Levels

The quality performance of the machine control system on pavement depths can also be measured by the standard deviation of the achieved pavement depths. Assuming the achieved pavement depths are of normal distribution, contractors generally need to set the target mean pavement depths two or three times of standard deviations higher than the design depths to make sure that higher percentage of the checked depths exceed the requirement. For example, if the contractor wants to keep the amount of substandard checked depths below 0.1%, the target achieved pavement depth should be set three standard deviations higher than the required depth. As shown in Figure 5, if the standard deviation (σ) is 12.7 mm (0.5 in.), then the target depth should be set at 266.7 mm (10.5 in.) to make sure 99.9% depth checks meet a 9-inch (228.6 mm) thickness requirement. If the standard deviation is 5mm (0.2 in.), the target depth can be set at only 243.8 mm (9.6 in.). Thus, a control system that produces lower standard deviations is more desirable because it allows the contractor to lower the expected mean depths and, henceforth, reduce the construction cost. From the collected data, the standard deviations of pavement depth for sections using string line control are 15 mm (0.5860 in.) at the south edge, 7 mm (0.2676 in.) at the north edge, and 17 mm (0.6982 in.) at the centerline point. The standard deviations for the stringless paving sections are 6 mm (0.2404 in.) at south edge, 9mm (0.3469 in.) at north edge, and 12 mm (0.4710 in.) at the center line. On average, the standard deviations for stringless paving system are smaller than the string line control system. Thus, with the data available, the stringless paving system has a better accuracy and is more desirable for use on Portland concrete paving systems.

Yield Quantities

Measuring yield quantities is also important because it is directly related to the construction cost. Contract price for the two test projects are determined by the yield quantities. Daily yield quantities for the main line pavement were collected for both Ashby and Coppock roads. Actual cumulative yield quantities and the quantities calculated from the design drawings were compared.

According to design, the area for the cross-section is 1.49 m2 (1.78 yd2) for both the Ashby and Coppock projects. The total length for Ashby Road is 9,602.7 m (31,505.07 ft.), which equals 10,501.69 yards. The total length for Coppock Quarry Road is 4,434.9 m (14,550.23 ft.), which equals 4,850.08 yards. Thus, the total quantity of concrete by design is 14,274.0 m3 (18,669.67 yd3) for the Ashby project and 6592.3 m3 (8,622.36 yd3) for the Coppock project.

The total yield quantity is 14,667.9 m3 (19,198 yd3) for Ashby project and 6685.3 m3 (8,744 yd3) for the Coppock project. The Ashby project yield quantity exceeds the design quantity by 2.8%. The Coppock project exceeds design quantity by 1.4%.

Conformance to Design Elevations

While no express specifications were found about how close the finished pavement elevation should be to the design elevation, this quality has a close relationship with the thickness and yield amounts. It is difficult to imagine that significant deviation from the design elevation occurred, and the above two quantities are still well under control. The research team conducted surveys to verify if the elevation deviation of the finished surface using stringless control is significantly larger than that using the string line control method. Two sections were selected for comparison from the Ashby project, each representing the product of a different control system. For string line control, pavement surface elevations between Station 135+00 and Station 115+00 were used. For stringless control, data from the section between station 17+00 and 4+00 were used. Elevations were taken every 7.62 m (25 ft.) at both pavement edges and the centerline using survey levels. Difference between the actual top of concrete elevation and the design elevation (referred as elevation deviation) was calculated for both sections using the different control method. Then a t-test was conducted to test if the difference between the elevation deviation means using the two control methods was statistically significant.

The results show that the differences in mean elevation deviations (actual minus to design) for both edges are significant. The stringless control results actually had better elevation conformance than the string line control method. The mean elevation deviations at the north edge are -15.2 mm (-0.05 ft.) for string line control and -12.2 mm (-0.04 ft.) for stringless control. This t-test has a significance level of 0.016. The mean elevation deviations at the south edge are -9.1 mm (-0.03 ft.) for string line control and -3.0 mm (-0.01 ft.) for stringless control with a significance level less than 0.0001.

CONCLUSIONS AND RECOMMENDATIONS

The GPS based stringless paving approach is still in the development stage. This research was successful in demonstrating the use of GPS to guide the slip-form paver and determining the top of pavement elevation. GPS receiver locations on the slip-form paver (front, middle, or rear) are critical to coordination with the 3-D design program and proper machine control. Concrete yield, depth, and profile elevations (pavement centerline and edges) can adequately be controlled with GPS to meet pavement design requirements. GPS computer control was not able to produce pavement surface profiles smooth enough to allow for ride incentive to be paid. Paving equipment hydraulic controls (valves) and computer software must be modified to allow for uniform changes in elevation as the equipment moves forward to meet profile specification requirements.

Based on the findings of this research, several recommendations are suggested in order to enhance the functionality of this system:

- Urge continuation of GPS slip-form paver control system development. The GPS system, in its current state, is capable of guiding the paver and controlling elevation to achieve acceptable concrete yield and reasonable profile for low volume roads. Additional software development is required to control elevation that will result in surface profiles that provide for DOT specification incentive payments.

- Identify additional demonstration projects to allow for fine-tuning of the software for profile control. These sites would be used to evaluate continued development in the elevation profile control with GPS or GPS/laser systems. They can also be used to evaluate other potential limitations in the operation of GPS control such as loss of line-of-sight with satellites.

- Consider DOT specification changes that use 3-D models to control the paving and profile operations for quality, quantity, and depth evaluation.

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REFERENCES

1. Federal Highway Administration, Transtec Group, the, 2003, ProVAL, Pavement Profile Viewer and Analyzer, the Transtec Group, http://www.transtecinc.com/proval/.

2. Geologic Computer Systems. 2003. Positional equipment comparisons. http://www.geologic3d.com/support/positional_equip.htm.

3. Iowa Department of Transportation. 2004. Instructional Memorandums. I.M.341.

4. Iowa Department of Transportation. 2001. Standard Specifications, Section 2316.

5. Leica Geosystems. 2001. Product information LMGS-S.

6. New York State Department of Transportation, 2002, Standard Specifications, Section 502.

7. Peyret, F. 2000. High-precision application of GPS in the field of real-time equipment positioning. Automation in Construction 9: 299 – 314.

8. Rasmussen, R. O., S. M. Karamihas, W. R. Cape, and G. K. Chang. 2004. String line impacts on concrete pavement construction. Record of the Transportation Research Board.

9. Sayers, M., and S. Karamihas. 1998. The Little Book of Profiling. Ann Arbor: Transportation Research Institute, University of Michigan. http://www.umtri.umich.edu/erd/roughness/lit_book.pdf.

10. Thales Navigation, Inc., 2004. Z-Xtreme Specifications. http://products.thalesnavigation.com/en/products/product_specs.asp?PRODID=38.