Virginia Transportation Research Council

research report

Preliminary Field Investigation of Intelligent Compaction of Hot-Mix Asphalt

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Supplementary Notes

Abstract

Attention is being directed toward intelligent compaction (IC) of pavement layers, which uses rollers especially manufactured to determine the degree of compaction and regulate the compactive effort required to produce a pavement layer with the optimum density. An IC roller should also have the capability to record a mix characteristic that can be correlated with the density of the final product. In this study, a small field investigation was conducted to determine if the stiffness measured by a particular IC roller correlated with the density of the thin surface layer of asphalt being compacted, thereby leading to a possible future end-result acceptance tool. The roller patterns were also used to determine whether the IC roller was more efficient than a conventional vibratory roller, i.e., whether fewer roller passes were required than with a conventional roller.

The following were concluded from the results of the study:

- *The IC roller was not more efficient than the conventional vibratory roller.* The IC roller may not have been able to capitalize on its "intelligent" features to provide more compactive effort when needed because of the thinness and fineness of the mat being placed in this study. A thicker, coarser mat such as that obtained with stone matrix asphalt might have produced different results.
- *The correlation between IC stiffness measurements and pavement density was poor.* Three possible reasons for the lack of correlation were the effect of the decreasing temperature of the mat on stiffness, the variation in stiffness of the underlying layers, and the use of an incorrect roller "hammer" setting.
- *As noted in the previous conclusions, proper project selection and conduct of IC experiments are important.* A new construction project would eliminate the possibility of the underlying structure influencing compaction or stiffness readings, and the presence of knowledgeable equipment personnel on the project would ensure proper operation of the equipment.
- *The IC method of compaction is not ready for use in asphalt construction at this time.*
- *Although the results of this project were not encouraging with regard to the potential use of IC rollers in asphalt construction, they should not discourage additional studies and should aid in the planning of an imminent national pooled fund study.*

FINAL REPORT

**PRELIMINARY FIELD INVESTIGATION OF INTELLIGENT COMPACTION
OF HOT-MIX ASPHALT**

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Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

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ABSTRACT

Attention is being directed toward intelligent compaction (IC) of pavement layers, which uses rollers especially manufactured to determine the degree of compaction and regulate the compactive effort required to produce a pavement layer with the optimum density. An IC roller should also have the capability to record a mix characteristic that can be correlated with the density of the final product. In this study, a small field investigation was conducted to determine if the stiffness measured by a particular IC roller correlated with the density of the thin surface layer of asphalt being compacted, thereby leading to a possible future end-result acceptance tool. The roller patterns were also used to determine whether the IC roller was more efficient than a conventional vibratory roller, i.e., whether fewer roller passes were required than with a conventional roller.

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- *The correlation between IC stiffness measurements and pavement density was poor.* Three possible reasons for the lack of correlation were the effect of the decreasing temperature of the mat on stiffness, the variation in stiffness of the underlying layers, and the use of an incorrect roller "hammer" setting.

- *As noted in the previous conclusions, proper project selection and conduct of IC experiments are important.* A new construction project would eliminate the possibility of the underlying structure influencing compaction or stiffness readings, and the presence of knowledgeable equipment personnel on the project would ensure proper operation of the equipment.

- *The IC method of compaction is not ready for use in asphalt construction at this time.*

- *Although the results of this project were not encouraging with regard to the potential use of IC rollers in asphalt construction, they should not discourage additional studies and should aid in the planning of an imminent national pooled fund study.*

FINAL REPORT

PRELIMINARY FIELD INVESTIGATION OF INTELLIGENT COMPACTION OF HOT-MIX ASPHALT

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INTRODUCTION

A special report entitled *National Asphalt Roadmap*[1] was recently developed by several organizations to identify future needs and challenges in the asphalt industry. One of the projects identified in the report was "Project 5.05 – Real-Time Process Control for Laydown and Compaction," which identifies intelligent compaction (IC) systems currently being developed as a potential technology to help achieve and verify pavement density in real time.

Ultimate IC is a process whereby a vibratory roller continuously measures and reports the stiffness of the compacted material while simultaneously and automatically adjusting its compactive effort with a stiffness feedback loop control. The roller is designed to impart more energy to areas low in density and less energy to areas high in density.[2] Other versions of rollers might also be classified as IC. For example, some rollers contain different combinations of means to measure temperature, roller pass tracking with a global positioning system, and a dimensionless stiffness type of measurement with or without feedback to a closed loop control system. IC rollers often use the global positioning system to register the compaction results on a map of the roadway in a permanent digital or hard-copy record.

IC has been used in a number of European countries, especially on soils and aggregate bases.[3] One of the cited primary advantages was that the method tends to provide a more uniform density than with the conventional method. IC attempts to adjust the compaction effort to match the need at each specific area of the roadway, whereas the conventional method attempts to provide a uniform compactive effort over the entire roadway.

The highest level of IC equipment uses automatic adjustment of either roller drum amplitude or frequency. It measures the stiffness of the layer being compacted with accelerometers and adjusts the amplitude accordingly. Most rollers use drum vibration applied vertically, but one company uses a horizontal oscillatory vibration motion. Another company is said to be working on measurement of rolling resistance to determine when optimum density has been obtained. As the layer is compacted, the roller sinks less into the layer and rolling resistance decreases.

Several companies are developing or selling IC rollers. Although development of equipment for IC of soils started in the late 1970s, it was the 1990s before equipment started to emerge for compaction of asphalt.[3] Although the use of IC appears feasible for soils, opinions differ concerning the possibility that IC can be successful with asphalt. If asphalt stiffness is

used as a regulating function for automatic control of compaction effort, one must realize that factors other than density may affect stiffness. Is the stiffness being measured that of the asphalt layer or is it partially influenced by underlying layers? In addition, since asphalt is temperature susceptible, how can stiffness be related to the density during the compaction process as the temperature drops?

Nevertheless, at least some users seem to think that the IC equipment is beneficial in achieving good results in compacting asphalt. On a construction job in North Carolina, the contractor cited an IC roller as being influential to "reduce production time and labor costs associated with it, yet experience no under- or over-compaction results."[4] Job Construction, an Oklahoma asphalt company, used an IC roller not only to proof roll aggregate base before paving but to prevent over-rolling and under-rolling of Superpave mixes.[5]

The primary interest of the Virginia Department of Transportation (VDOT) in IC equipment is its possible use as a quality control/quality assurance (QC/QA) tool. Real-time recording of stiffness, which, it is hoped, translates to density, could possibly eliminate or decrease QA end-result density measurements. Potentially, 100 percent of the mat area could be tested compared to a small percentage of the area with today's technology. Pavement density is currently measured with nuclear gauges, which require considerable regulation because of the small nuclear source. Elimination of this bother would be a huge benefit to both the purchasing agency and contractors. In addition, the IC technology is nondestructive, thus not requiring unsightly core holes.

PURPOSE AND SCOPE

The purpose of this research was to conduct a preliminary small field experiment with an IC asphalt roller. Over a 2-day period, the performance of the roller was compared to the performance of the conventional breakdown roller normally used by the contractor. Because the work involving the experimentation was not written into the original paving contract, voluntary cooperation was sought from the contractor to achieve the desired goals of the experiment.

This study served as a small preliminary investigation in preparation for the planning of a national pooled fund study involving a more thorough investigation.[6]

METHODS

An IC breakdown tandem vibratory roller, BOMAG BW190-4 AM, was used for 1 day's production, and the conventional Sakai 800 series tandem vibratory roller was used for another day's production. Pavement densities were compared between the sections produced during those days. In addition, an attempt was made to correlate the roller stiffness values with the measured density. Permeability, which is somewhat related to density and is a pavement performance indicator, was also measured.

IC Roller

The IC roller, which was manufactured in Europe, contained a system to adjust the force applied to the asphalt from the front drum by changing the direction of vibratory movement from vertical to horizontal. When the drum vibrated in a vertical direction, it applied maximum force. The maximum force could be adjusted by changing "hammer" settings. The equipment representative recommended the highest of three possible hammer settings, which was used on the project. The roller had accelerometers mounted on the roller drum to determine the degree of pavement resistance to the drum movement, i.e., analogous to pavement stiffness. The output of the accelerometers in terms of pavement stiffness could be read on a meter in view of the roller operator. The roller also contained an asphalt manager that measured the force applied by the drum and drum movement, which it used to adjust the force being applied as the asphalt layer stiffened. As the pavement layer was compacted, the stiffness values were supposed to increase, resulting in a decrease in roller compaction effort. This mechanism was supposed to result in more uniform density throughout the pavement surface. The roller also contained an infrared thermometer that produced real-time measurement of temperature on the asphalt surface directly beneath the roller. This feature allowed the operator to monitor the temperature and make sure the asphalt was compacted at the proper temperature.

A meeting was held the day before paving started so that the roller manufacturer could explain to the paving contractor's personnel, VDOT operations personnel, and Virginia Transportation Research Council (VTRC) personnel how the roller worked. A roller representative from the United States was also present on the construction site when the paving took place.

Materials

A VDOT SM-9.5AS surface mix was placed at a thickness of approximately 1.5 in. The mix contained approximately 60 percent granite, 20 percent natural sand, 20 percent recycled asphalt pavement, 5.6 percent PG 64-22 binder (0.5 percent antistripping agent), and 0.15 percent synthetic fibers. It was designed at 65 gyrations on a Superpave gyratory compactor.

Test Sections

The IC roller was used by Virginia Paving Company on an outside lane-section of Smoketown Road near Dale City, Virginia, on July 6, 2006, and the conventional roller was used on an adjacent inside lane-section on July 7, 2006 (Figure 1). Additional testing was conducted with the IC roller over 2 days in which other variables were investigated; however, the additional testing was not conducted in an experimental manner that merited being reported. Spot milling near the curb was performed in both experimental lanes prior to paving. Approximately 1,700 lane-ft was used for the roller evaluations in both cases. Prior to the beginning of each section, a roller pattern was established by determining the number of passes required to reach target density. This process indicated whether either roller was more efficient at achieving the required density.
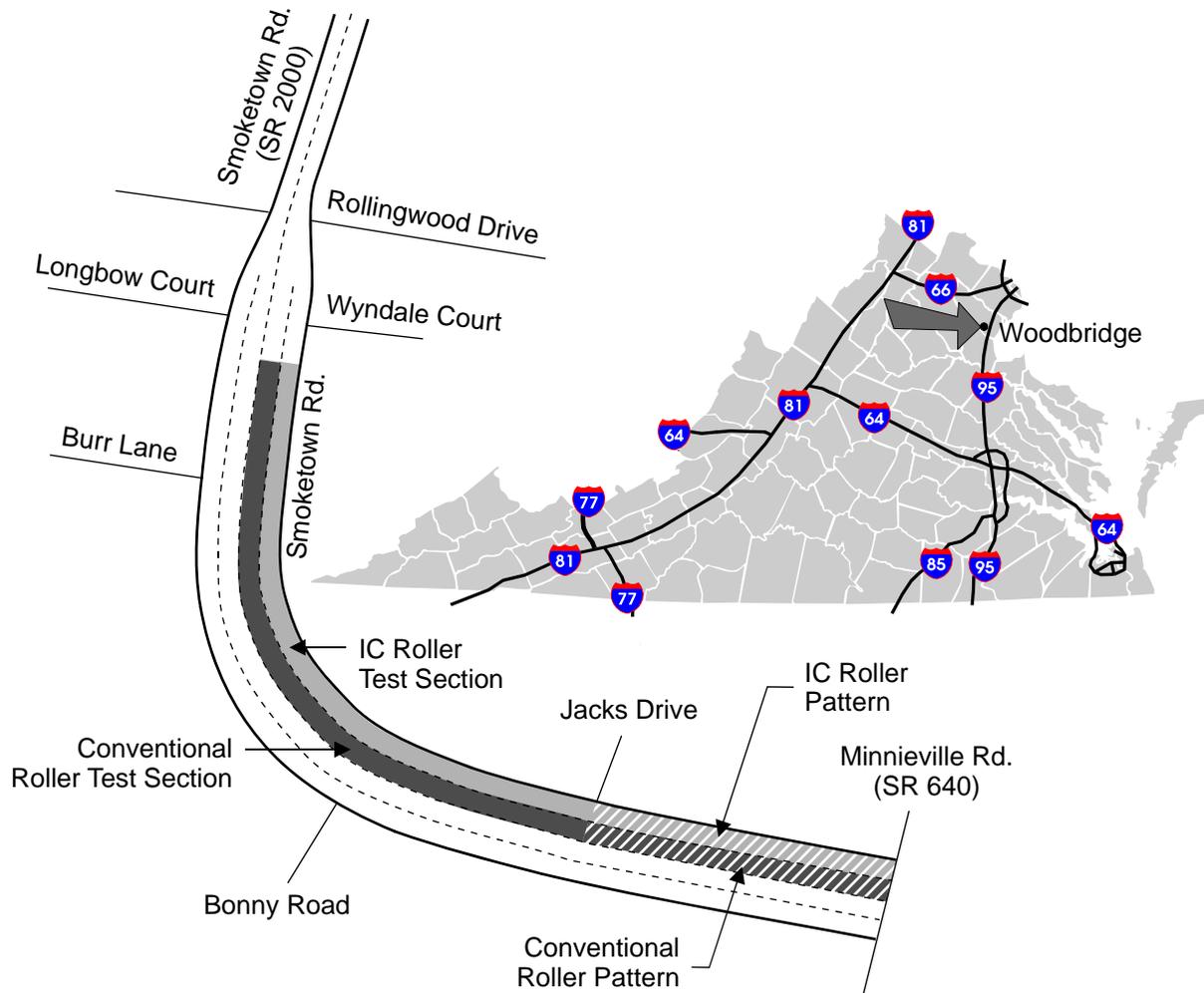
Figure 1. Location of Field Experiment

Tests

Stations were marked every 100 ft on the curb to locate subsequent nuclear density tests, extraction of cores, and stiffness/temperature recordings during construction.

Nuclear Density

Single 1-min nuclear density tests were performed with a Troxler Model 4640 density gauge every 100 ft in the left wheel path of the right lane compacted with the IC roller. The transverse location of the left wheel path was selected to eliminate variability that might be caused by milling near the curb. Similarly, the adjacent lane that was compacted with the conventional roller was tested in the right wheel path away from the curb.

Density and Permeability

Cores 6 in in diameter were wet-drilled at every third nuclear density test site. The cores were taken back to the laboratory, where density and permeability tests were performed. The

permeability tests were falling head tests performed in accordance with Virginia Test Method 120.[7] Permeability tests were also performed on specimens compacted from the hot-mix samples at various air void contents to obtain a regression plot of permeability versus air voids content.

Roller Stiffness

The IC roller had a digital display for both pavement stiffness and asphalt surface temperature. A research technician located on the IC roller recorded stiffness and temperature as the front drum of the roller passed pre-marked stations on the side of the road (see Figure 2).

Figure 2. Technician on IC Roller Recording Stiffness and Temperature Readings

Volumetric and Gradation Properties

Gradation and asphalt content were determined on mix sampled and tested at the plant during construction by the contractor. The ignition furnace was used to remove the binder in order to calculate binder content and perform the gradation. Volumetric properties such as air voids (VTM), voids in the mineral aggregate (VMA), and voids filled with asphalt (VFA) were measured on specimens made in the Superpave gyratory compactor at 65 gyrations.

RESULTS AND DISCUSSION

Mix Properties

The results of various mix tests performed on QA samples during the 2 days of construction are shown in Table 1. Although the mix was designated as a nominal 9.5 mm mix, it could have met the gradation requirements for a 12.5 mm mix.

Table 1. Volumetric Properties, Gradation, and Asphalt Content of Mix

Property	Design	Intelligent Compaction 7/6/06 (single samples)	Conventional Compaction 7/7/06 (average of 2 samples)
Rice (G_{mm})			
% Air voids (VTM)		2.2	Not available
% VMA		14.7	Not available
% VFA		85.7	Not available
Gradation (% passing)			
12.5 mm	100 $\pm$ 1	98.9	98.8
9.5 mm	91 $\pm$ 4	89.9	87.0
4.75 mm	58 $\pm$ 4	57.5	53.8
2.36 mm	37 $\pm$ 4	40.0	36.2
75 μm	5 $\pm$ 1	5.6	5.2
Asphalt content (% asphalt binder)	5.6 $\pm$ 0.3	5.6	5.3

Production tolerances are based on the average of 4 samples. VMA = voids in the mineral aggregate; VFA = voids filled with asphalt.

Permeability

Permeability tests were performed on nine cores from the IC section and six cores from the conventional section. The permeability plots for the mix sampled during compaction by the IC roller and conventional roller are shown in Figures 3 and 4, respectively. The regressions indicate that air voids had to be maintained at less than 9.7 percent and 9.0 percent, respectively, for the mix from the IC and conventional sections in order for the permeability to be less than the
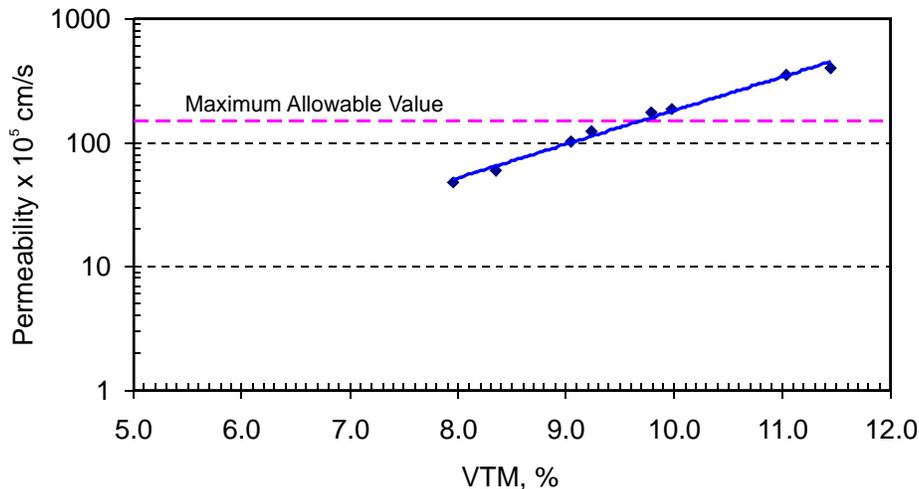

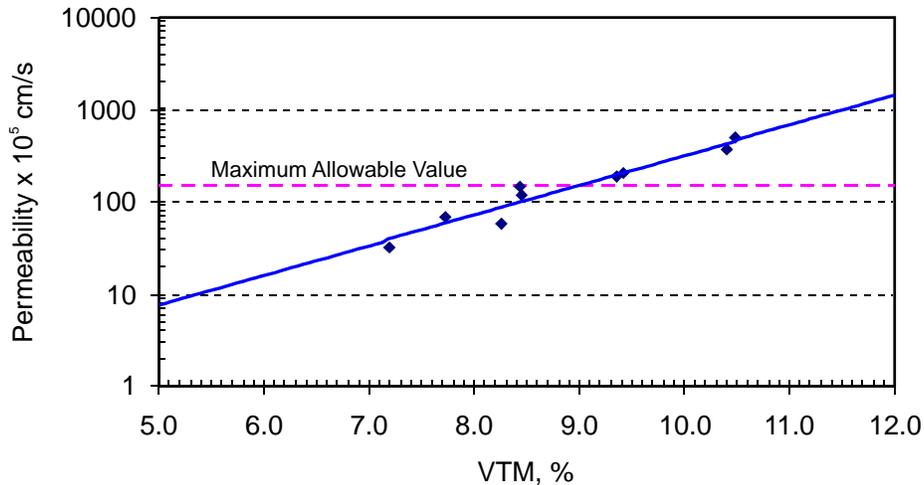**Figure 3. Permeability Tests on Mix From IC Section. VTM = air voids.**

Figure 4. Permeability Tests on Mix From Conventional Section. VTM = air voids.

allowable design value of 150×10^{-5} cm/s. These results are reasonable considering the gradation and asphalt content differences noted in Table 1 between the samples from the two sections. It made sense that the mix from the conventional section that was slightly coarser and had less asphalt binder would be somewhat more permeable.

Permeability tests on cores are typically quite variable so it was not surprising that there was not a statistical difference between the averages when using the *t* test at a 95 percent confidence level. In addition, there was not a statistical difference between variability (variances) of the two sections when using the *F* test. Two of the nine test results were above the design value of 150×10^{-5} cm/s for the IC section and one of six test results was above the design value for the conventional section.

Density Test Results

Immediately prior to construction of each section, a roller pattern was developed to determine the number of roller passes necessary to achieve acceptable density. The sections compacted with both the IC roller and conventional roller required three vibratory passes with the breakdown roller in addition to two passes with the finish roller. Therefore, there was no apparent increase in efficiency with the IC roller.

As indicated previously, nuclear tests were performed every 100 ft and cores were taken at every third nuclear test site. Cores are usually considered to give more consistent results than nuclear tests. It was desirable to have as many tests as possible to allow a good statistical comparison between sections. There were additional tests performed on the same paving project subsequent to testing reported in this document that provided additional matches of nuclear density and core density. Since there were more nuclear tests than cores, a correlation was developed between the available matches on the project and a correction was applied to the nuclear density values, which were used as the primary comparison for density. The correlation was: Corrected nuclear density = Core density, pcf = 1.464 × (Nuclear density, pcf) – 69.8, with a correlation coefficient of 0.97. The *t* test at 95 percent confidence indicated no significant difference between the average corrected nuclear density test results from the IC and

conventional sections. Similarly, the *F* test showed no significant difference in variances (variability) between the two sections. Table 2 shows the pavement density and voids results.

<p align="center">Table 2. Pavement Density and Voids Results</p>

Test	IC Roller Section	Conventional Roller Section
Nuclear Density Tests		
Number of density tests	16	16
Average density, pcf	151.9	152.0
Density variance, pcf-squared	16.3	14.9
Core Tests		
Number of cores	9	6
Average air voids, percent	8.3	6.8
Air voids variance, percent-squared	7.8	3.1

pcf = pounds per cubic foot.

Roller Stiffness Measurements

The roller stiffness measurements at each density site were observed and recorded by a VTRC technician positioned on the roller. The stiffness and temperature readings taken on the roller and corresponding density results are shown in Table 3. The technician noted that the stiffness readings were so variable that it was difficult to obtain a good reading. Typical printouts of the stiffness and temperature measured from the roller are shown in Figure 5. The three charts show differences in trends of stiffness as the roller progressed along the different sections of the roadway during the compaction process. Chart (a) shows a steady increase in stiffness as the roller progresses approximately 50 ft along the roadway. Chart (b) shows a large variation in stiffness, as much as 35,000 psi, as the roller progressed approximately 60 ft along the roadway. A saw-tooth pattern of stiffness was observed on some printouts, as shown in Chart (c) evidently occurring because the roller was jumping as it attempted to change the force applied to the asphalt mix. Perhaps the highest hammer setting producing the large vibratory amplitudes was too severe for the thin fine surface mix and a lower setting would have produced better results.

<p align="center">Table 3. Roller Stiffness and Nuclear Density Results</p>

Station	Stiffness × 100, E_{Vib}	Corrected Nuclear Density, pcf	Surface Temperature, °F
1	491	153.3	212
2	423	155.4	221
3	468	145.7	177
4	507	153.8	217
5	507	155.2	192
6	417	155.5	201
7	474	151.4	217
8	463	154.9	183
9	211	142.3	163
10	379	156.4	201
11	381	152.6	192
12	449	149.1	186
13		147.3	
14	394	150.4	226
15	439	155.2	213
16	452	152.6	208

BOMAG ASPHALTMANAGER

PASS NO.   1 For.
BOMAG AM Rev 3.4 ENG
BW190 AD-4 AM 101 920 26 1010

Settings: Manual 0,0157 in
Evib max.   =   37024 psi
Evib min.   =   11120 psi
Evib average   =   17976 psi
Frequency   =   3047 vpm
Average speed value =   2,1 mph
Track length   =   45,9 ft

Scale 16,4ft ---> Evib (psi*100) _____
            ---> Temperature('F) .....
0   100   200   300   400   500

(a)

BOMAG ASPHALTMANAGER

PASS NO.   3 Rev.
BOMAG AM Rev 3.4 ENG
BW190 AD-4 AM 101 920 26 1010

Settings: Manual 0,0157 in
Evib max.   =   50160 psi
Evib min.   =   9080 psi
Evib average   =   27144 psi
Frequency   =   3012 vpm
Average speed value =   2,0 mph
Track length   =   59,0 ft

Scale 16,4ft ---> Evib (psi*100) _____
            ---> Temperature('F) .....
0   100   200   300   400   500

(b)

BOMAG ASPHALTMANAGER

PASS NO.   1 For.
BOMAG AM Rev 3.4 ENG
BW190 AD-4 AM 101 920 26 1010

Settings: Auto   3.
Evib max.   =   50744 psi
Evib min.   =   0 psi
Evib average   =   40640 psi
Frequency   =   2934 vpm
Average speed value =   2,3 mph
Track length   =   492,3 ft

Scale 16,4ft ---> Evib (psi*100) _____
            ---> Temperature('F) .....
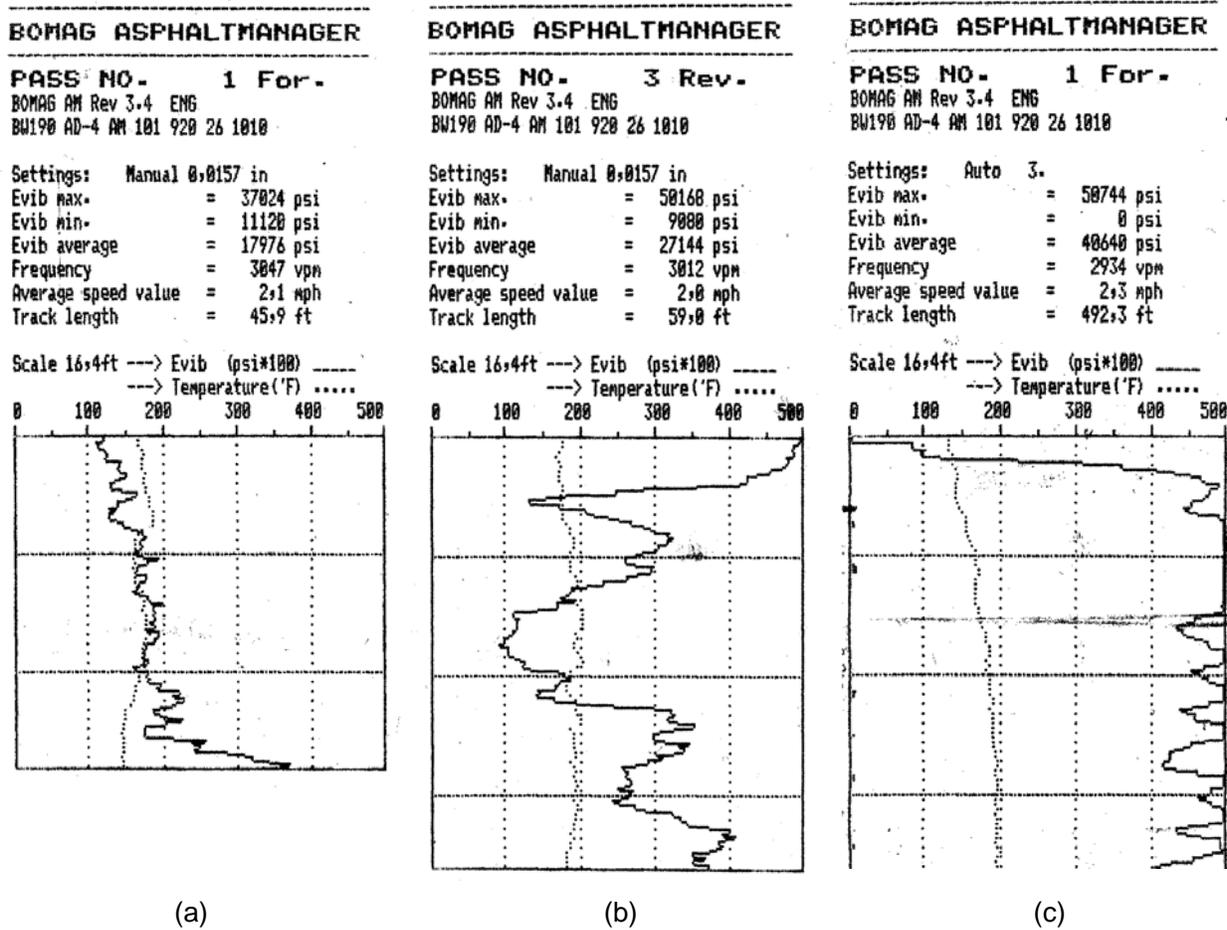0   100   200   300   400   500

(c)

Figure 5. Typical Roller Stiffness and Surface Temperature Printouts. (a): Steady increase in stiffness as roller progresses approximately 50 ft along roadway. (b): Large variation in stiffness as roller progressed approximately 60 ft along roadway. (c): Saw-tooth pattern of stiffness, evidently occurring because roller was jumping as it attempted to change force applied to asphalt mix.

The temperature plots indicated temperatures in the vicinity of 200°F on the last pass when the stiffness readings were taken. This temperature may be too low to obtain a good stiffness/density correlation. At low temperatures, the movement of the roller drum and related accelerometer readings may be influenced more by the underlying structure than by the asphalt surface being compacted.

A correlation was developed between the stiffness and density values, shown in Figure 6. The correlation within the range of values obtained was poor, with an R^2 value of only 0.27. If a wider range of values was available, the correlation may have been better. It is obvious that the stiffness measuring system was not able to differentiate between several units of density at a high level of roller stiffness where the optimum target density occurs. Obviously, temperature could have a large effect on the stiffness measurements since asphalt stiffness changes as temperature changes. Table 3 shows that the surface temperature varied from 163°F to 226°F for the final roller pass on the tests where stiffness was recorded. Station 9, which had the lowest temperature, also had the lowest density and stiffness readings. If the temperature is too low, it
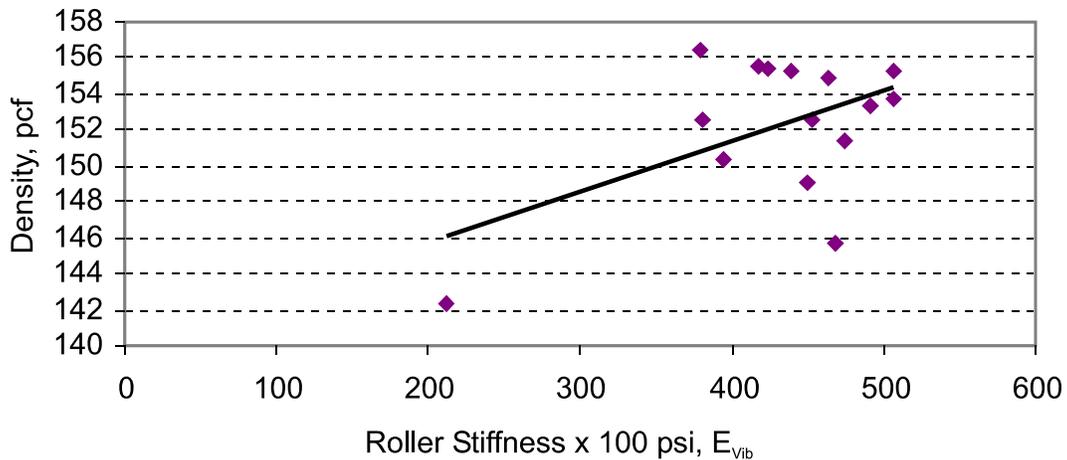
Figure 6. Roller Stiffness versus Nuclear Density of Compacted Surface Layer

is difficult to achieve adequate density, and low density generally results in low stiffness. However, the other stiffness levels do not seem to be directly related to density or temperature.

There are two complications when trying to use measured stiffness as an indicator of density, which is usually an acceptance quality indicator. Two factors that can influence the stiffness measurements are the temperature and the stiffness of the underlying structure. Measurements need to be taken at approximately the same asphalt temperature, and the stiffness of the underlying structure needs to be uniform so that its influence on stiffness readings will be uniform. Perhaps the variation shown in the stiffness printout of Figure 5(b) was being influenced by the variation of the total pavement structure.

SUMMARY OF FINDINGS

The two sections of surface mix compacted by the IC and the conventional breakdown rollers possessed similar properties. The average density and variability of density of the two sections were not statistically different, and the permeability of the two sections was similar. Both rollers required the same number of passes to reach optimum density; therefore, there was no increase in efficiency through the use of the IC roller for compaction of the asphalt mix at this location. The IC roller may not have been able to capitalize on its "intelligent" features to provide more compactive effort when needed because of the thinness and fineness of the mat being placed. A thicker, coarser mat such as with a stone matrix asphalt might have produced different results.

One of the primary hopes for this project was that the IC roller could possibly be used to measure the density of the compacted pavement. However, the correlation of the stiffness measured by the IC roller and the density measurements was poor. Three possible reasons for the lack of correlation were the effect of decreasing mat temperature on asphalt stiffness, the variation in stiffness of the underlying layers, and the use of an incorrect roller "hammer" setting.

This study also pointed out other weaknesses that should not be repeated in future investigations of IC, particularly in the upcoming national pooled fund study. VTRC has a representative on the panel for this study who will be able to relate the results of the current study. Although the paving contractor for this project went beyond his normal obligations in volunteering his cooperation in the experiment, some of the conditions for the experiment were less than desirable. It would be preferable to include the experimentation in the original paving contract in order to be able to specify proper experimental conditions. In addition, a new construction project would eliminate the possibility of the underlying structure influencing compaction or stiffness readings.

Another important factor in any future experimentation is that an appropriate roller representative(s) be present to make sure that the equipment is operating correctly. It is important that the equipment representative(s) be responsible for obtaining the optimum level of performance. Although this project did not produce encouraging results for the potential of IC asphalt rollers, it should not discourage future studies.

CONCLUSIONS

- *The IC roller was not more efficient than the conventional vibratory roller.* The IC roller may not have been able to capitalize on its "intelligent" features to provide more compactive effort when needed because of the thinness and fineness of the mat being placed in this study. A thicker, coarser mat such as that obtained with stone matrix asphalt might have produced different results.

- *The correlation between IC stiffness measurements and pavement density was poor.* Three possible reasons for the lack of correlation were the effect of the decreasing temperature of the mat on stiffness, the variation in stiffness of the underlying layers, and the use of an incorrect roller "hammer" setting.

- *As noted in the previous conclusions, proper project selection and conduct of IC experiments are important.* A new construction project would eliminate the possibility of the underlying structure influencing compaction or stiffness readings, and the presence of knowledgeable equipment personnel on the project would ensure proper operation of the equipment.

- *The IC method of compaction is not ready for use in asphalt construction at this time.*

- *Although the results of this project were not encouraging with regard to the potential use of IC rollers in asphalt construction, they should not discourage additional studies and should aid in the planning of an imminent national pooled fund study.*

RECOMMENDATIONS

1. VTRC should continue to follow research on IC and provide input through its involvement in the national pooled fund study.[6]

2. In future investigations, such as the national pooled fund study, the experimental weaknesses revealed in this study should not be repeated.

COSTS AND BENEFITS ASSESSMENT

The particular IC roller used in this study did not show the anticipated benefits. Efficiency did not increase with the IC roller, which might have led to a decrease in the contractor's construction cost. Further, no increase in average density or decrease in variability of density was realized with the IC roller, which would have translated to improved product quality. Further, there was no indication that roller stiffness measurements could be used in end-result acceptance of density, which would possibly have simplified acceptance procedures. However, the research did provide some guidance for future national studies.

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