Intelligent Compaction, Does It Exist?

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ABSTRACT

There has been great emphasis in the last few years on the need to develop an “Intelligent Compaction” system to improve the efficiency and effectiveness when double drum vibratory rollers are used to compact an asphalt concrete mixture. The primary problem is that there are many variables that affect the ability of the compaction equipment to properly densify the mix. One of the most important variables is the temperature of the mix, which is a constantly changing mix property. In addition, the modulus, stiffness, or strength of an asphalt concrete mix measured at one temperature may not be related to the modulus, stiffness, or strength of the mix when the compaction process is finished.

This paper describes two field test sections that were constructed in order to advance the development of an Intelligent Compaction system for the compaction of asphalt concrete mixes. Data from the test sections showed that the number of roller passes over each point in the pavement surface can be monitored, the surface temperature of mix can be measured, and a relative stiffness value for the mix can be determined during the compaction process.

RÉSUMÉ
1.0 INTRODUCTION

The buzz word in the asphalt paving industry currently is “Intelligent Compaction” (IC). The question that must be answered, however, is whether or not intelligent compaction actually exists and what the term actually means.[1,2,3,4,5,6,7] According to the Federal Highway Administration (FHWA) in the United States, the goal of IC is to eventually measure the modulus of materials during compaction, but at this time the purpose is to find a surrogate for density.

There are many variables that affect the ability of the compaction equipment to properly densify an asphalt concrete mixture when placed on the roadway. Among those variables are the type and shape of the coarse and fine aggregate used in the mix, the type and amount the asphalt binder, the type of mix, the type and condition of the underlying pavement layers, the thickness of the layer being placed, as well as environmental factors such as ambient air temperature. The most important variable, however, is the continuously changing temperature of the asphalt concrete mix during the compaction process.

In order to achieve the desired level of density in the asphalt concrete mix, two factors must be taken into account. The first is the number of passes that a roller operator makes over each point in the pavement surface as well as the temperature of the asphalt concrete mix when those roller passes are made. The second is being able to determine those locations where additional roller passes are needed because the desired level of density has not yet been achieved.

One question which must be addressed is whether or not some sort of modulus value or stiffness value that is measured in the asphalt concrete mix at a temperature of 120ºC is related to the modulus value or stiffness value that is measured at a temperature of 90ºC or 70ºC. An asphalt concrete mix gets stiffer as it gets colder. The temperature of the mix as well as the number of roller passes made at each particular temperature will determine the final density of the mix. Can one assume that the stiffness measured after three passes of the roller when the mix temperature is 120ºC will be related to the stiffness measured after five passes of the roller when the mix temperature is 90ºC? That assumption, however, is probably not true. Too many variables affect the increase in density achieved with each pass of a particular roller at a given temperature.

2.0 FACTORS AFFECTING MODULUS, STIFFNESS, AND/OR STRENGTH

One of the original desires of the FHWA was to use IC during construction to predict the final “modulus” value in the asphalt concrete mix [8]. The problem is, however, that the modulus value to be measured was never defined. What modulus? Resilient modulus, dynamic modulus, creep modulus or some other modulus value? Recently the FHWA has decided to drop the term “modulus” from the discussion of intelligent compaction and substitute the word “stiffness”.

The problem is that stiffness can not really be defined any better than modulus could be. Stiffness measured how? Occasionally it has been stated that the “strength” of the mix is what needs to be measured. What is really desired to be predicted or measured is the ultimate density of the asphalt concrete mix when the compaction process is finished.

There are many factors that affect the modulus or stiffness of an asphalt concrete mixture. Among those factors are the properties of the asphalt concrete mix, the type and density of the underlying base course material, the thickness of the asphalt concrete layer, and the environmental conditions at the time of paving. If any of these factors change, the final modulus or stiffness or strength of the mix will be directly
affected. In addition, the final stiffness of the mix is affected by the type of rollers, the number of rollers, and the rolling patterns used during the compaction process.

2.1 Asphalt Concrete Mix and Pavement Variables

There are a wide variety of asphalt concrete mixtures currently being used in North America. Among those mix types are dense graded mixes, open graded mixes, and stone mastic (matrix) asphalt (SMA) mixes. Within the realm of dense graded mixes, some of the mixes are fine graded mixes, some are coarse graded mixes, and some are very densely (uniformly) graded mixes. Some of the open graded mixes are used for friction course layers while some are used as a permeable base course layer. SMA mixes, which are usually very dense graded, typically have a significantly different gradation than normal dense graded asphalt mixes and an increased amount of mineral filler as part of the gradation. Gap graded asphalt concrete mixes are also used by some agencies.

There are also many types and grades of asphalt binder materials currently being used. A few of those binder materials are still graded using the penetration system, some are still viscosity (AC) graded, while most meet at least some of the criteria for a Performance Graded (PG) asphalt binder. Further, some of the asphalt binders are polymer modified, using either elastomeric or plastomeric materials. Asphalt rubber binders are also used in some asphalt concrete mixtures. Each of these types and grades of asphalt binder materials will affect the degree of stiffness obtained in the asphalt concrete mix, both at the time of construction and throughout the compaction process.

There are a wide variety of aggregate types currently being used across North America. Some of those materials are sedimentary, some are igneous, and some are of glacial origin (gravel). In addition, the absorption, soundness, angularity, surface texture, and degree of flat and/or elongated particles all affect the properties of the different aggregate materials and, therefore, the properties of the asphalt concrete mix into which they are incorporated. In particular, the amount of crushed coarse and fine aggregate in the mix has a direct affect on the modulus, stiffness, or strength of the resulting mixture.

The volumetric requirements for the various asphalt concrete mixes vary widely. In many jurisdictions, voids in mineral aggregate (VMA), voids filled with asphalt (VFA), and air void (AV) content requirements are included as part of the mix specification limits. In some places, Hveem mix design methods are still popular and, in general, the Hveem mix design system does not require the calculation of the VMA or VFA values in the mix. It is well known, however, that the volumetrics of the asphalt concrete mix have a direct affect on the performance of the mix under traffic. The volumetrics, however, also have a very dramatic affect on the stiffness of the mix during the compaction operation and on the ability of the contractor to achieve the desired level of compaction.

The environmental conditions at the time of mix placement can directly influence the amount of compaction obtained by affecting the time available to compact the mix--the cooling rate of the mix. Air temperature, base temperature, wind velocity, and solar flux or cloud cover (to a minor degree) all govern the cooling rate of the mix and the ability of the contractor to obtain density in the asphalt concrete mix. The environmental conditions are different on each project and will affect the level of density obtained with each pass of the compaction equipment.

The effect of the base type and condition is also a factor which affects the level of stiffness or compaction achieved in the new asphalt concrete mix. The amount of compactive effort needed depends, in part, on whether the new asphalt concrete layer is placed on top of subgrade soil, an aggregate base course, cold mix asphalt, cracked asphalt concrete, new asphalt concrete, or a portland cement concrete pavement.
layer. In addition, the thickness of the asphalt concrete layer being placed also is a factor to be considered when attempting to compact the mix. Thinner asphalt concrete layers will cool faster than thicker layers.

### 2.2 Mix Temperature

It has been stated that the three most important factors that affect the ability of a contractor to achieve the desired level of density in an asphalt concrete mix are, in order of importance, temperature, temperature, and temperature. It is this fact that makes intelligent compaction such a difficult concept to put into action. Although it seems simple at first glance, it is very difficult, if not impossible, to achieve in the real world because the modulus, stiffness, and/or strength of an asphalt concrete mix is directly related to the temperature of the mix at the time that the modulus, stiffness, and/or strength value is measured.

Asphalt concrete mixes can be divided into two primary categories as far as the resistance to compaction is concerned. Some mixes are stiff and are difficult to compact. Some mixes are tender and move excessively under the action of steel wheel rollers. The tender mixes generally will check or crack in the “middle temperature zone”. Instead of gaining density when the mix is rolled in the middle temperature zone, density is often lost when the mix moves in front of the steel wheels on a double drum vibratory roller or a static steel wheel roller.

The roller pattern used to compact a stiff mix is typically significantly different than the roller pattern used to compact a tender mix. Because of the three temperature zones usually found when compacting a tender mix, the modulus, stiffness, or strength measured at one temperature or a series of different temperatures may not be related at all to the final density of the mix.

The temperature of the asphalt concrete mix is continually changing during the rolling process. The rate of cooling of the mix is related to a number of factors such as the thickness of the layer being compacted, the temperature of the mix at the time it is extruded from under the screed on the paver, the properties of the asphalt concrete mix (dense graded or open graded), as well as the environmental conditions such as air temperature and wind velocity.

Temperature is the primary factor that makes prediction of the ultimate density of the mix when the rolling is completed so difficult to judge during the actual rolling process itself. The modulus, stiffness, or strength measured at one mix temperature is not the same as the modulus, stiffness, or strength measured at a different temperature.

### 2.3 Roller Patterns

There are four different types of rollers commonly used to compact newly placed asphalt pavement layers. Those four types are double drum vibratory rollers, pneumatic tire rollers, vibratory pneumatic tire rollers, and static steel wheel rollers. In addition, these types of rollers are used in different positions behind the paver, usually termed the breakdown position, the intermediate position, and the finish position.

When vibratory rollers are employed to compact an asphalt concrete mix, a number of variables are under the control of the roller operator. The operator can select the vibratory frequency used, the amplitude used, as well as the speed of the roller. The combination of frequency and speed is related to the number of impacts that the roller makes per lineal foot of the pavement length. The number of impacts per foot has a direct affect on the density obtained as well as the smoothness obtained. Depending on the width of the roller and the width of the lane being compacted, there will be a number of transverse locations where
the roller drum will overlap from one pass to the adjacent pass. This overlap will obviously affect the amount of density achieved at different locations across the width of the mat.

Stiff asphalt concrete mixtures are those mixes that typically contain a high percentage of crushed fine aggregate and/or a polymer modified asphalt binder. For a stiff mix, which does not exhibit a “bow wave” in front of the steel wheels on a roller, one of three roller patterns is normally used. The most common, but least efficient, is to place a double drum vibratory roller in the breakdown position followed by a pneumatic tire roller in the intermediate position, followed by a static steel wheel roller in the finish position. A better alternative is to place a pneumatic tire roller in the breakdown position followed by a double drum vibratory roller in the intermediate/finish position. If the vibratory roller follows directly behind the pneumatic tire roller, usually no finish roller is needed. Another very efficient roller pattern is to employ two double drum vibratory rollers in an echelon configuration directly behind the paver. Because the breakdown rolling is completed by the two rollers when the mix temperature is high, no additional rolling is typically necessary. The double drum vibratory breakdown rollers act as their own finish rollers.

For tender asphalt concrete mixtures, a bow wave normally occurs in front of the drums of a steel wheel roller. The mix “checks” or cracks when compaction is attempted. For a tender mix, one which exhibits checking or cracking when compacted using a vibratory or static steel wheel roller, one of three roller patterns is normally used. The most common, but least efficient, is to place a double drum vibratory roller in the breakdown position followed by a pneumatic tire roller in the intermediate position, followed by a static steel wheel roller in the finish position. Another possibility, but one which typically does not permit the desired level of density to be obtained, is to put a double drum vibratory roller in the breakdown position, do not use any roller in the intermediate position, and then to use a static steel wheel roller in the finish position. A better, more efficient roller pattern is to employ two double drum vibratory rollers in an echelon configuration directly behind the paver, similar to a stiff mix. In this last case, all compaction needs to be completed before the mix temperature drops into the middle tender zone.

If the mix is stiff, the modulus, stiffness, or strength measured at a relatively high temperature may or may not be related to the value measured at an intermediate temperature or a relatively low temperature. For a mix that is tender, however, the modulus, stiffness, or strength measured at a relatively high temperature (above the middle tender temperature zone) will typically not be related to the value measured at an intermediate temperature or a relatively low temperature.

### 2.4 Mix Variables and Mix Temperature

Given all of the mix variables that affect the properties and characteristics of an asphalt concrete mix, it should not be surprising that it is very difficult for a roller operator to understand ahead of time what roller pattern to use for the mix being placed that day. The selection of a roller pattern that was effective yesterday may not be the most efficient roller pattern to use today if one or more of the mix properties or the weather conditions have changed.

Temperature, however, is the one primary factor that makes prediction of the ultimate density of the mix when the rolling is completed so difficult to judge during the actual rolling process itself. Any modulus, stiffness, or strength value that is measured at one temperature during the compaction process may not, and probably will not, have any direct relationship to any modulus, stiffness, or strength value that is measured at any other temperature or to the final density of the mix when the compaction process is completed and the mix is “cold”.
The factors that must be addressed in the development of any Intelligent Compaction system are:

- How do you verify the accuracy of the value measured by the roller?
- What do you compare that roller derived value to?
- Any value measured by the roller must be compared to some other value, but at best it is only a relative comparison at a particular time and temperature.
- Once the mix has cooled, it is too late for any additional compactive effort to be applied.

3.0 ROLLER DERIVED MEASUREMENTS

3.1 Intelligent Compaction Capabilities

It is possible to equip a double drum vibratory roller to obtain a number of different measurements during the compaction process. First, it is possible to determine the speed of the roller and where the roller has gone--how many roller passes have been made over each point in the pavement surface. Second, it is possible to determine the temperature of the surface of the asphalt concrete mix at the time that the compactive effort is applied by the roller. Third, it is possible to determine a relative, surrogate value of the stiffness of the asphalt concrete pavement layer.

3.2 Monitoring Roller Location (GPS)

Operating a roller can be a very boring job. It is certainly repetitive. Keeping track of the number of times that a roller has covered a particular location on the surface of the pavement is very difficult. The result is non-uniform compactive effort and, therefore, non-uniform density in the asphalt concrete mix being compacted. The non-uniformity extends both transversely across the pavement width as well as longitudinally down the length of the roadway.

Intelligent compaction equipment can incorporate the use of a Global Positioning System (GPS) to track the number of roller passes made over each point on the surface of the asphalt concrete mixture. The GPS system can be used to determine whether or not the operator of the roller has made the same number of roller passes over each edge of the lane being constructed as well as in the center of the lane. The GPS system can thus show the roller operator where additional passes of the roller are needed to attempt to achieve the required level of density uniformly in the asphalt concrete mix.

3.3 Monitoring Mix Temperature

The IC roller can be equipped with a temperature measuring device to determine the surface temperature of the asphalt concrete mix being compacted. The location of the thermometer on the roller is important since water is typically being applied to the drums on a steel wheel roller as the roller moves down the roadway. Some of that water will end up on the pavement surface and will influence the temperature being measured.

Since mix temperature is the most important factor that controls the ability of the compaction equipment to achieve the required level of density, providing the roller operator with information on the surface temperature of the mix is critical data that can be very useful to the operator. This is particularly true when the asphalt concrete mix is “tender” and moves under the double drum vibratory roller in the middle temperature zone. Knowledge of the surface temperature of the mix allows the roller operator to apply the compactive effort (roll the tender mix) in the upper temperature zone and/or in the lower temperature zone and avoid the middle, tender temperature zone.
Knowing the surface temperature where the tender zone begins and ends allows the roller operator to avoid creating the bow wave in the mix and then checking and/or shoving the mix. Since different asphalt concrete mixes, with different mix properties, have tender zones that begin and end at different surface temperatures, monitoring the pavement temperature permits the roller operator to find, and then avoid, the middle or tender temperature zone.

3.4 Monitoring Mix “Stiffness”

As an asphalt concrete mix gets colder, it gets stiffer. As an asphalt concrete mix gets denser, it gets stiffer. Unfortunately, at this time, there is no foolproof way to determine what the final density of an asphalt concrete mix will be based on some value measured during the compaction process. This is mainly due to the fact that the temperature of the mix plays such a significant part in the ability to compact the asphalt concrete mix.

The stiffness of an asphalt concrete mix, during compaction, is typically monitored by placing an accelerometer on the double drum vibratory roller. The accelerometer measures the rebound of the drum when the drum comes in contact with the surface of the asphalt concrete mix. The harder (stiffer) the surface of the mix, the more rebound that is measured by the roller drum. As the mix gets more dense, and/or gets colder, the accelerometer measures the amount of rebound and displays a value to the operator of the roller. Unfortunately, the rebound number does not tell the roller operator whether the mix has been properly compacted or if the mix has become too cold to compact further.

The one advantage of the use of the accelerometer is that the information allows the roller operator to detect differences in the stiffness of the asphalt concrete mix at different locations in the pavement surface. If, for example, the rebound deflection is greater in one place than in an adjacent location, the roller operator can make an additional roller pass or passes over the less stiff pavement surface. Thus the roller operator can make an effort to achieve a more uniform level of density across the width and down the length of the pavement lane.

As discussed above, however, the amount of rebound at a particular mix temperature is not necessarily related to the final density that will be obtained in that mix. Any measurement of any type taken at a particular temperature will not necessarily be related to any measurement taken the same way on the same mix, but at a different temperature. This is because the stiffness, or modulus, or strength of an asphalt concrete mix is dependent not only on the density of the material, but also on the temperature of the material.

4.0 MEASURING MIX “STIFFNESS”

Assume that a double drum vibratory roller has made three passes over a given point on the surface of a newly placed asphalt concrete mix. Assume that a nuclear or non-nuclear gauge is then used to take a density measurement at a predetermined location. The question becomes “What does the gauge reading mean and how do you use the measured value?” A second question is “What is the relationship of a gauge reading after three passes to the gauge reading after five passes or after seven passes of the roller over the same point in the pavement surface.

Correlations between gauge readings and the final density of an asphalt concrete mixture are usually done when the compaction operations have been completed on a test strip constructed at the beginning of the project. Cores are cut from the test section, the theoretical maximum density (TMD) of the mix is determined in the laboratory, and a comparison is made between the bulk density of the compacted cores
and the lab TMD value. The percentage of air voids in the mix is then calculated. Finally, a comparison is made between the gauge readings and the core densities so that the nuclear or non-nuclear gauge readings can be used to predict the core density of the mix. It is pointed out, however, that this correlation is done after the compaction process has been completed, not during the process.

Any gauge reading must be somehow correlated to the number of roller passes over a point as well as the surface temperature of the mat when the gauge reading is taken. That correlation, however, must also be correlated with the stiffness reading that is measured by the acceleration of the vibrating drum on the roller. Each different combination of the number of passes and the temperature of the mat would have to be correlated with the drum measured stiffness value. A new correlation would be needed if either the number of roller passes changed or the temperature of the mat changed (which, of course, it will, continuously). Thus nuclear gauge readings or non-nuclear gauge readings would have to be taken continuously for every pass or every other pass of the roller over the pavement surface. Yet, even if that were done, there would still be no correlation between the gauge readings and the final density of the mix when the compaction process was completed.

Assume that three passes of a double drum vibratory roller were made on the pavement surface when the mix temperature was between 140°C and 130°C and three additional passes were made over the same location when the mix temperature was between 120°C and 110°C. Would the stiffness of the mat be expected to be the same if the first three passes were made over the mat when the mix temperature was between 110°C and 100°C and the next three passes were completed when the mix temperature was under 80°C? Probably not. The stiffness value determined from the acceleration (rebound) of the steel drum, however, might be the same since the lower temperature would result in a stiffer mix.

It was stated in some early FHWA literature on the goal of intelligent compaction that it would be desirable for the roller to be able to automatically adjust the compactive effort applied to the asphalt concrete mix as the mix increased in density. Thus, as the mix became stiffer, the applied force of the vibratory drums could be changed and less force directed to the pavement surface. Indeed, some roller manufacturers have developed vibratory rollers that are capable of automatically redirecting the vibratory force as the mix gets stiffer (as the amount of rebound of the drum increases).

By reducing the compactive effort, however, significant efficiency is lost. By reducing the compactive effort at the lower mix temperatures, three passes of the double drum vibratory roller might need to be made over the pavement surface to achieve the desired level of density compared to one pass of the same roller if the compactive effort remained the same. In addition, while the extra roller passes are being completed, the mix is continuing to cool, further increasing the possibility that the desired level of density may not actually be obtained. It does not seem to be very efficient to decrease the compactive effort, increase the number of roller passes, and still expect to have a cost effective compaction process.

5.0 MEASURING RELATIVE STIFFNESS WITH A VIBRATORY ROLLER

The measurement system consists of three primary parts. The first is a high accuracy GPS unit capable of monitoring the precise location of the roller across the width of the lane being paved as well as down the length of the roadway. It is capable of recording and displaying the number of roller passes made over each point in the pavement surface. The second component is an infrared temperature gauge to measure the temperature of the asphalt concrete pavement surface. The third component is a “stiffness” sensor to determine the amount of acceleration of the steel drum as the roller moves across the surface of the mix. All the data is recorded by an on board computer and displayed for the roller operator in real time. Shown in Figure 1 is an example of a double drum vibratory roller with typical IC equipment.
Data Collection

- High Accuracy GPS tracks Roller Position
- Number of Roller Passes
- Distribution of Stiffness
- Surface Temperature

Sakai Heavy Industries, Ltd. has tested two versions of accelerometer based sensors to measure the relative stiffness of an asphalt concrete mix during the compaction process. The Alfa – System was tested in 2006 in California, and the CCV system was tested in June of 2007 in Florida. The test results using the two systems are discussed in this paper.

5.1 GPS System

The GPS components include both a base station (antenna, GPS receiver, and radio modem transmitter) and a mobile station attached to the roller (antenna, GPS receiver, radio modem receiver, radio modem transmitter, and a computer). The GPS base station is positioned over a known x-y-z coordinate.
The bias between the known coordinate and the measured coordinate at the base stations is calculated to determine the accurate position of the mobile GPS station on the roller through a radio modem transmitter. An on-board computer at the operator’s station displays the distribution of the number of roller passes—the number of roller passes over each point in the pavement surface and the rolling pattern that is being used by the roller operator. A schematic diagram of the basic system is shown in Figure 2 with the GPS mobile and base stations setups.

5.2 Temperature Measurement System

Mounted on the front end of the roller is an infrared temperature gauge which is used to measure the surface temperature of the asphalt concrete mix. It is important to note that the position of the device across the front of the drum will depend, in part, on the width of the roller compared to the width of the paving lane.

If, for example, the roller is 2.12 m wide and the lane being paved is 3.66 m wide, the double drum vibratory roller can cover the whole width in two passes, one on the left side of the lane and one on the right side of the lane. The position of the temperature gauge is relatively unimportant. If, however, the drum on the steel wheel vibratory roller was only 1.71 m wide, then three passes of the roller would be needed to completely cover the lane width. In this latter case, the temperature gauge (infrared gauge) should be positioned near the center of the width of the roller drum to better monitor the temperature of the mix for all three roller passes.

The temperature data is displayed for the roller operator on the same monitor that shows the position of the roller on the asphalt concrete mix surface. That data, particularly if the roller operator is attempting to compact a tender mix, will allow the operator to avoid trying to roll the mix when the mix temperature is in the middle tender temperature zone.
5.3 Stiffness Sensors

5.3.1 The Compaction Control Value (CCV) Sensor

CCV monitors the waveform measured by the accelerometer as vibration acceleration changes with the increase in compaction. As the drum, lifts, falls, and collides with a surface as it is compacted, various frequency components are generated and combined with the fundamental frequency. These changes in vibration acceleration are digitized and a calculation is used to obtain the CCV, as shown in Figure 3. The acceleration signal is processed using the Fast Fourier Transform (FFT) method and the fundamental frequency $F_0$ of the vibrating drum is detected. By filtering with band pass filters which correspond to six frequencies ($1/2 F_0$, $F_0$, $3/2 F_0$, $2 F_0$, $5/2 F_0$, $3 F_0$) the acceleration amplitude spectrum ($A_1$ - $A_6$) at each frequency is detected as shown in Figure 3. Based on the detected amplitude spectrum CCV is determined by the following formula: $CCV = \{(A_1+A_3+A_4+A_5+A_6) / (A_1+A_2)\} \times 100$. The value obtained is dimensionless.

The CCV is displayed on a screen as a bar graph with the value directly under the drum at the top of the screen, the screen moves down as the roller moves forward giving a visual representation in real time. The unit can show softer areas, stiffer areas and uniformly compacted areas as shown in Figure 4.
5.3.2 The Alfa–System Sensor

The Alfa-System sensor, described in 5.0, was developed in Japan by the Obayashi Company and the Maeda Company. The value, “E”, is obtained based on the two-degree-of-freedom model between the vibratory roller and the underlying pavement surface as shown in Figure 5. The parameters and constants in the equations are the mass of the drum frame, the mass of the vibratory drum, the drum width, the centrifugal force, the frequency, and the Poisson ratio of the material. The equation used to calculate the “E” value is also shown in Figure 6.

\[
E = \frac{2 \cdot (1 - \nu^2)}{B \cdot \pi} \left( \frac{4 \cdot F_1 + 1}{1 - 0.32 \alpha + \sqrt{0.1024 \alpha^2 - 1.64 \alpha + 1}} \right) \cdot m_2
\]
\[
\alpha = 1 - \left( \frac{F}{(m_1 + m_2)g} \right)^3
\]

In the equation, the term \( F_1 \) is calculated using the equation shown in Figure 6. The “E” value correlates with the relative degree of compaction and is given by both harmonic and sub-harmonic wave spectra of drum acceleration analyzed by the Fast Fourier Transform (FFT) method and the mechanical parameters of the roller being used.

The Alfa-System is applicable to different types of asphalt concrete mixtures and to specific roller models by inputting the mechanical parameters of the roller into the equation. The acceleration response of the vibrating drum is directly affected by the condition of the material being compacted and the specifications of the particular roller model. The Alfa-System provides an “E” value in terms of N/m².
6.0 CALIFORNIA TEST PROJECT

In May 2006, a test project using the Alfa-System sensor was conducted on an asphalt concrete paving project in California. The job was on a four lane portion of State Route 68, between Salinas and Monterey. The test area was approximately 1.8 km in length and consisted of two travel lanes totalling 7.2 m in width. One test section was on the outside driving lane and the second test section was on the inside passing lane. The project consisted of a 75 mm thick overlay of an existing asphalt pavement surface.

6.1 Job Mix Formula Data

The asphalt concrete mix used was a 19 mm nominal maximum aggregate size coarse graded mixture. The job mix formula data is shown in Table 1, including the aggregate gradation, asphalt binder content, and theoretical maximum density (TMD). The binder content was based on the dry weight of the aggregate only and not on the total weight of the mix. The PBA-6a binder is a polymer modified material.

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6.2 Breakdown Rolling

6.2.1 Breakdown Rolling Pattern

A high frequency double drum vibratory roller, shown in Figure 7, was instrumented for measurement of the location of the roller passes, the number of roller passes, and the relative stiffness of the asphalt concrete mix. The operating weight of the roller was 12,930 kg and the width of the steel drum was 2.0 m. The roller was operated at a frequency of 4,000 vibrations per minute (vpm) and at an amplitude of 0.33 mm during breakdown rolling. The same roller was operated at a frequency of 2,500 vpm for finish rolling, again at an amplitude of 0.33 mm. The frequency and amplitude settings, as well as roller speed, were selected by the paving crew based on their past experience with this particular asphalt concrete mix.
It is noted also that the roller patterns used by the two different roller operators—in the breakdown rolling position and in the finish rolling position—were chosen by each operator. No attempt was made to control the paving operation or interfere with the normal routine of the paving crew. Thus no special instructions were given to the roller operators. (In hind-sight, this was probably a mistake given the roller pattern used by the breakdown roller operator.)

During breakdown rolling, the operator used a rolling pattern as indicated schematically in Figure 8, as measured by the GPS system on the roller. In the first (forward) pass, a short straight stretch along the left side of the lane was completed. When the roller direction was reversed, however, the roller operator moved to the right side of the lane with a big curving pass, and then went forward again, using an even bigger curving pass on the right side of the lane to catch up with the paver. This pattern, which was then repeated on a new section of pavement, resulted in a very non-uniform distribution of roller passes across the width of the paved lane.

Figure 9 illustrates the distribution of the roller passes as recorded during breakdown rolling. It shows only one 200 m long section of the outside lane. Paving and rolling operations proceeded from right to left across Figure 9. The upper side of the diagram represents that outside or shoulder edge of the lane. The lower edge of the diagram corresponds to the longitudinal joint between the outside and the inside lane. It can easily be seen that the number of roller passes over each point in the pavement surface was
anything but consistent. As a matter of fact, they were consistently inconsistent. Many more roller passes were made close to the longitudinal joint and in the middle of the lane compared to the outside (shoulder) edge of the lane.

![Figure 9. Distribution of Roller Passes During Breakdown Rolling](image)

### 6.2.2 Breakdown Rolling Mix Temperature Measurement

Figure 10 is a diagram of the asphalt pavement surface temperature measured by the infrared temperature gauge on the double drum vibratory roller during the breakdown rolling pattern shown in Figure 9, above. It is apparent that the temperature varied between 130°C and 60°C. This wide difference is most likely the result of the varying number of roller passes made over each point in the asphalt concrete pavement surface.

![Figure 10. Distribution of Pavement Surface Temperatures during Breakdown Rolling](image)
6.2.3 Relationship between the Roller Measured Value and Density

Shown in Figure 11 is the distribution of the roller measured value, “E”, (based on the acceleration of the steel drum) for the breakdown vibratory roller. The relative stiffness is higher along the longitudinal joint which corresponds to the increase in the number of roller passes made in that location by the roller. The “E” values range from 30 MN/m^2 to 70 MN/m^2, as measured by the difference in the acceleration values of the vibratory drum. The variation in the relative stiffness at different locations along the length of the pavement is directly related to the highly variable breakdown rolling pattern.

An attempt was made to correlate the “E” value (relative stiffness) measured during breakdown rolling with the final density of the asphalt concrete mix. No control was exercised over intermediate and finish rolling, however, and the total number of roller passes over each point on the pavement surface was unknown. Although the GPS data was used to select the location to cut cores from the final, compacted pavement surface, the lack of knowledge of the rolling patterns used by the intermediate and finish rollers made the correlation exercise meaningless. A poor correlation, $r^2 = 0.56$, was determined when a comparison was made between the relative stiffness values and the TMD of the cores.

6.3 Finish Rolling

6.3.1 Finish Rolling Pattern

The finish roller did a significantly better job in accomplishing the final compaction of the asphalt concrete mix in the passing lane. The distribution of the roller passes for this roller is shown in Figure 12. This pavement is not the same section used for the breakdown roller test area. The finish roller made relatively straight passes down the length of the test section. The distribution of the roller passes over each point in the pavement surface, however, is still not as uniform as it should be to produce consistent density values across the width of the lane.
6.3.2 Finish Rolling Mix Temperature Measurement

As expected, the asphalt concrete mix surface temperature was significantly lower during finish rolling than during breakdown rolling. Figure 13 provides a distribution of the temperature values, which vary from a high of 90°C to a low of 50°C (which is a very low temperature to attempt to gain density in the asphalt concrete mix). The range of temperatures measured during the finish rolling is somewhat narrower than the range of temperatures seen during breakdown rolling.

![Figure 13. Distribution of Pavement Surface Temperatures during Finish Rolling](image)

6.3.3 Relationship between the Roller Measured Stiffness Value and Density

Figure 14 shows the distribution of the roller measured relative stiffness value “E”, for the finish vibratory roller. The relative stiffness is higher in the middle of the lane and next highest along the longitudinal joint between the passing and driving lanes where the drum overlaps the cold pavement. The lowest relative stiffness values were found along the side of the pavement adjacent to the inside shoulder.

The “E” values range from 30 MN/m² to 70 MN/m², same as measured by the breakdown roller in the adjacent lane. Since it is not known what roller pattern was used by the breakdown roller over this test section, it is not known whether the variation in the breakdown rolling pattern had an affect on the relative density of the asphalt concrete pavement after the finish rolling was accomplished. The stiffness values measured during finish rolling in the lower temperature range showed no correlation with density.

![Figure 14. Distribution of Relative Stiffness Values after Finish Rolling](image)
6.4 Conclusions

The following conclusions were reached in regard to this initial intelligent compaction field test work:

- The GPS system could be used to determine the distribution of the roller passes over the asphalt concrete pavement surface.
- The surface temperature of the asphalt concrete mix could be measured.
- The difference in the relative stiffness of the asphalt concrete mix in different locations could be determined.
- Intelligent compaction rollers being developed will not be able to achieve uniformly compacted asphalt concrete pavements until consistent rolling patterns at high temperatures are used during the compaction process.

7.0 FLORIDA TEST PROJECT

In June 2007, a second test project using the Sakai CCV system and software developed by the Trion Corporation was tested on an asphalt concrete paving project in Florida. The test section site was a portion of an approach road to a new bridge that was under construction. The test area was approximately 0.2 km in length and consisted of a variable width section of roadway. The actual test lane was 3.7 m wide.

7.1 Job Mix Formula Data

The asphalt concrete mix used was a 12.5 mm nominal maximum aggregate size, relatively fine graded mixture that plotted just above the maximum density line. The job mix formula data is shown in Table 2, including the aggregate gradation, asphalt binder content, and theoretical maximum density (TMD).

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Table 2. Job Mix Formula Data (FL)
7.2 Rolling Pattern

7.2.1 Breakdown and Finish Rolling Pattern

Two high frequency double drum vibratory rollers, shown in Figure 15, were employed to compact the asphalt concrete mix on this short test section. Each of the two rollers was equipped with GPS, temperature measurement devices, and the CCV system to measure the acceleration of the roller drum. The rollers were operated at a frequency of 4,000 vibrations per minute and an amplitude of 0.33 mm during both breakdown rolling and finish rolling.

![Two Sakai SW 850 High Frequency Double Drum Vibratory Rollers](image1)

The combined number of roller passes made by the two rollers is shown in Figure 16. It is seen, that even in this short test section, the number of roller passes made over each point in the pavement surface was not consistent.

![Rolling Pattern Recorded during Breakdown and Finish Rolling](image2)
7.2.2 Pavement Surface Temperatures

Figure 17 shows the distribution of the asphalt pavement surface temperature measured by the infrared temperature gauge on the roller during the first vibratory pass during breakdown rolling. The temperature varied between 135 °C and 95 °C on one side of the lane, where the first roller pass was made, and between 120 °C and 90 °C on the other side.

![Figure 17. Distribution of Pavement Surface Temperatures during 1st passes of the Breakdown Roller](image)

7.2.3 Relationship between CCV and Density

Shown in Figure 18 is the distribution of the dimensionless roller measured relative stiffness value or CCV, after compaction had been completed by both vibratory rollers. As can be seen, the relative stiffness varies significantly along the length and width of the test section. This is due in large part to the variation in the condition of the sandy subbase soil underneath the layers of asphalt concrete mix and to the variation in the density of the underlying asphalt concrete layers. The subbase material had been displaced by the haul trucks and the paver during the placement of the bottom layers of mix and the thickness and density of those layers were variable.
Interestingly, the CCV for the asphalt concrete surface course layer was greater at the beginning of paving compared to the end of the paver pass. This is true even though the breakdown double drum vibratory roller was kept close behind the paver at all times. The CCV values shown were recorded during the final pass of the finish roller. The CCV varies from less than 4 to more than 7. Once rolling was completed, ten cores were cut from the test section, as illustrated in Figure 19. The core locations are also marked on Figure 18.

A correlation was made between the measured CCV values (relative stiffness) and the density of the cores cut from the compacted pavement layer. That exercise resulted in a fair correlation, $r^2 = 0.69$. It is noted that the final density of the asphalt concrete surface course layer was poor, ranging for the ten cores from a low of 89.1 percent to a high of 91.0 percent of the theoretical maximum density value for this particular asphalt concrete mix. This correlation is detailed in Figure 20.
The following conclusions were reached in regard to this second intelligent compaction field test work:

- The GPS system could be used to determine the distribution of the roller passes over the asphalt concrete pavement surface.
- The system was able to monitor the temperature of the pavement surface during compaction.
- The difference in the relative stiffness of the asphalt concrete mix in different locations could be determined.
- The test data showed that the level of compaction achieved was less than desired. Additional roller passes could not be made due to the condition of the sandy subbase material.
- The development of intelligent compaction rollers needs to be continued. If possible, a way needs to be found to relate the relative stiffness value determined during construction to the final density of the mix once compaction is completed.

Use of the GPS system alone should greatly improve ability of an asphalt paving contractor to meet the minimum density specifications on an asphalt paving job simply by allowing the roller operator to know how many passes he or she has made over each point in the pavement surface. A more uniform
application of the compactive effort across the width and down the length of the roadway should make a significant improvement in the consistency in the density obtained.

By knowing the temperature of the surface of the asphalt concrete mix, the roller operator will gain an understanding of the importance of temperature in the ability to achieve the desired level of density in the mix. In addition, knowledge of the mix surface temperature will keep the roller operator from using a steel wheel roller to attempt to compact a tender mix if the mix temperature is in the middle tender temperature zone.

Having real time information available on the relative stiffness of the asphalt concrete mix being compacted will allow the operator to make additional roller passes over the softer areas while the mix temperature is still high. The operator can react immediately and correct a problem while he or she is still able to do so.

Although there is currently no way to directly relate the relative stiffness value at some temperature directly to the final density of the mix, that does not necessarily mean that such a relationship will not be developed in the future. New technologies such as high accuracy GPS, faster computers, better software and wireless communication now make it possible to utilize the data that can be collected by a roller during compaction in new ways. Does Intelligent Compaction exist? No, not really, not yet, but the compaction process is getting a lot smarter.
REFERENCES


