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Laboratory and Field Study on Compaction Quality of an Asphalt Pavement

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Abstract: Compaction of hot mix asphalt (HMA) layer is a process of densification through the application of vibratory, dead weight and/or pneumatic tires compactors. These processes are employed independently or in combination, depending on factors such as type of asphalt mix, layer thickness, and weather conditions, to achieve desired density of HMA pavement layers. Appropriate compaction (desired density) of the asphalt mixture is one of the important factors that influence long term performance of an asphalt pavement. During the compaction of HMA layer using vibratory rollers, the applied load and vibration energy cause reorientation and interlocking of asphalt coated aggregates resulting in increase in density. Good compaction is necessary for achieving target specifications such as required density of asphalt layers, stiffness, or volumetric properties of the asphalt mix. These specifications are designed to maximize the resistance of the pavement to deformation, cracking, raveling, moisture damage, and rutting. In the United States of America, target specifications for quality control and assurance of asphalt pavements are usually given in terms of the density of roadway cores extracted from the completed pavement. This paper investigates the level of compaction (in terms of density), that is achievable both in the laboratory and in the field. Compaction quality as a function of compaction time/roller passes and pavement thickness is studied. In addition, the uniformity of compaction over the entire length of the pavement, and the variation in density laterally across the pavement are examined during pavement construction in the field. The results of this study provide insight into the compaction quality that can be achieved during construction. Such information would is helpful for a successful design and the implementation of emerging technologies such as Intelligent Compaction.

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***Key words**: Asphalt compaction; Asphalt thickness; Compaction versus passes; Quality during compaction.*

Introduction

Hot mix asphalt (HMA) pavements are expected to perform well over their lifetime under a variety of traffic and climatic conditions. While proper mix design and selection of the aggregates and asphalt binder greatly influence the quality of the pavement, the quality of the finished pavement ultimately depends on the construction practices that are adopted and the quality control procedures implemented during the construction process. A well designed asphalt mix won't perform as expected unless it is adequately compacted in the field [1-12]. Several quality measures were developed over the past two decades to control the compaction process and assure that all aspects of asphalt production and placement met the specifications [1-5, 13-14]. The majority of Quality Control / Quality Assurance (QC/QA) procedures address the placement of the asphalt mat and its compaction in the field. In the United States of America, the air void content of a compacted asphalt pavement is the most commonly used quality measure, by both the state Department of Transportation, as well as by the contractors. In practice, the target density is specified as a percentage of the Maximum Theoretical Density (MTD) of the asphalt mix. For example 95% density implies that the pavement is compacted to 95% of its theoretical maximum density or that the pavement has 5% air voids in terms of volume. The density of a roadway core extracted from the completed pavement is also used by Department of Transportation inspectors for acceptance testing of the finished pavement [3, 6-8, 15-19].

While the importance of the compaction of asphalt pavements is well understood, there is a lack of quantifiable data about the quality of compaction (compaction density) that is actually achieved in the field. In this paper, the compaction quality (density) that can be achieved during laboratory and field compaction is studied. Data is collected from several laboratory tests and real life road construction projects and factors such as volumetric design of asphalt mix, aggregate size, roller passes, density, mix temperature, thickness of pavement layers, confinement, and weather conditions that affect the compaction of pavements are analyzed to understand their impact on the quality of compaction. These results are then used to provide an insight into the compaction quality that can be achieved during construction.

Laboratory Achievable Compaction Quality

Compaction of asphalt mix commonly used in Oklahoma (Superpave mix with 19 mm nominal maximum aggregate size), was carried out in the laboratory to study achievable quality during the compaction. The main objectives of the laboratory tasks were to

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(1) study variability in density along thickness of a compacted slab (2) study effect of compaction time on density, (3) study effect of lift thickness on density. The samples were compacted using an Asphalt Vibratory Compactor (AVC) manufactured by Pavement Technology Inc., to replicate a vibratory roller used in the densification process of pavements during road construction (see Fig. 1). The AVC is a vibratory plate compactor that can compact mix specimens for a specified duration of time through the application of vibratory energy at different amplitudes and frequencies. Variation of the amplitude and frequency can be used to replicate the compaction obtained by different rollers in the field while the duration of compaction can be used to replicate the number of roller passes on a given stretch of the pavement. It is to be noted that Superpave Gyratory Compactor (SGC) is commonly used to compact HMA samples in the laboratory. However, unlike the AVC, the SGC does not allow the compaction of asphalt specimens at different amplitudes and frequencies. The compaction using the SGC is semi-static under a 600 kPa pressure while the compaction using the AVC is dynamic with different combinations of frequencies and amplitudes. Therefore, the compaction process in the AVC can be said to be similar to the compaction of asphalt pavements during their construction [20]. The AVC was therefore selected for investigating the effect of different process parameters on the compaction of asphalt specimens.

The loose HMA mix (Table 1, Superpave mix with 19 mm nominal maximum aggregate size) is placed in an oven till equilibrium at compaction temperature was achieved.6.5 kilograms of the asphalt mix is then placed in the rectangular mold of the AVC. The mold is 125 mm wide, 300 mm long, and 75 mm high. It is noted that a maximum of 75 mm thick sample can be prepared using the current AVC mold. Therefore, the effect of frequency and amplitude studied in this study is limited to a 75 mm thick HMA layer. The AVC base plate and mold were kept in the oven at compaction temperature. After pouring the mix, the mold is placed in the AVC and the machine parameters, such as the time of compaction, frequency and amplitude of vibrations, are set prior to starting the compactor. After compaction is complete, two cylindrical cores of 100 mm diameter are cut from a single rectangular specimen of the asphalt mix. The bulk specific gravity of the cores is measured using AASHTO T-166 [21] method to determine the density/air void content of the sample. The theoretical maximum specific gravity of the selected mix is determined in accordance with AASHTO T-209 [21]. The ratio of bulk specific gravity and theoretical maximum specific gravity is used to represent the percent density (% compaction) of the compacted specimen.

Fig. 1. Laboratory Asphalt Vibratory Compactor (AVC).

Table 1. Gradation of Superpave Mix (NMAS 19 mm).

Sieve Size (mm)	Passing (%)
25.4	100
19	98
12.5	88
9.5	72
4.75	40
2.36	30
1.18	21
0.6	16
0.3	11
0.15	8
0.075	4.2

Asphalt Vibratory Compactor

Asphalt Vibratory Compactor (AVC) can be used in the laboratory to prepare cylindrical and rectangular specimens of HMA. The vibratory compactor uses amplitude, frequency and pressure as input parameters to control the amount of compaction [20]. The compaction of HMA layer in the field is usually performed using static, vibratory, or pneumatic tire compactors. These rollers may be used individually or in combination, depending upon the type of the mix, layer thickness, and weather conditions, to achieve desired density in the HMA pavement layer. Usually in the United States of America, vibratory rollers are used for breakdown rolling and accomplish most of the compaction. For a specified roller, the amount of compaction or percentage density achieved is a function of the weight of the compactor as well as the amplitude and frequency of vibrations. Since an AVC can be operated by changing the compactive pressure, it is possible to create similar settings to the ones used by the compactors in the field, and simulate the compaction achieved on during the construction of roads. The compaction achieved in the laboratory using the AVC can be modified by changing magnitude of frequency, amplitude and time of compaction. Since the cross-sectional area of the mold is fixed, the final volume of the specimen is a function of the height of the compacted specimen. Thus the volume, and thereby the final density of the specimen, can be controlled by controlling the displacement of the compaction head. The duration of compaction can be set by the user to control the final height of compacted specimen [20]. The AVC is selected by this research because it can reproduce most of the physical process carried out in the field. Fig. 1 shows the used AVC at the Broce Asphalt Laboratory at the University of Oklahoma.

Variability in the Achieved Density During Compaction

Hot Mix Asphalt (HMA) has two fundamental ingredients: aggregates and asphalt binder. The HMA mixture is designed to conform to the specific requirements of the road/highway under different traffic and climatic conditions. Properties of the aggregates that affect the performance of the mix are source, gradation, maximum size, toughness, abrasion resistance, durability, soundness, shape, texture, and cleanliness. Likewise, properties of the asphalt binder that are usually considered are type, asphalt content, durability, rheology, purity, and additional modifying agents. While a good and well-designed mix is necessary for the pavement to be durable, resist deformation, and to perform well, a high quality mix by itself is not sufficient to obtain the required properties in the finished pavement. To the contrary, the bearing capacity of finished pavement is highly influenced by the compaction process.

In order to isolate the effect of the construction process on the quality that is obtained as a result of compaction, the effect of changes in the mix on compaction was first studied in the laboratory. For example, if an asphalt mix is well designed, correctly produced in the plant, and compacted at the right temperature, how would the density vary inside the asphalt pavement during its compaction? To answer this question, 12 different specimens of a HMA mix with 19 mm nominal maximum aggregate size (NMAS), gradation provided in Table 1, were compacted using the AVC for 30 seconds as per manufacture's recommendation to achieve desirable density [20]. After compaction was completed, each slab sample was cut into three different portions: top, middle and bottom. Each part was separately tested to calculate its density/air void content. Fig. 2 shows the density / air void content measured for top, middle, and bottom portions.

Effect of Compaction Time on Compaction Density

At the beginning of a road construction job, the rolling pattern, that is, the roller path and number of passes required to achieve a given target density (i.e., % compaction in range of 92% to 96% of maximum theoretical density), is first established. The rolling pattern that results in the specified density of the pavement (% compaction) is then used for the remainder of the construction with the assumption that the rolling pattern produces identical results on the entire extent of the project. In order to validate this assumption, 28 beam samples of a selected mix (Table 1) with 19 mm NMAS were compacted in the laboratory using the AVC over several time periods: 40, 45, 50, 55 and 60 seconds. The progressively increased time periods are intended to simulate the breakdown rolling and number of roller passes on the asphalt mat. A larger time period of compaction replicates a larger number of passes. The measured densities of the cores compacted at different time periods are shown in Fig. 3.

Variation of Compaction Density with Sample Thickness

The depth of penetration of the compaction energy imparted to the asphalt mat by the vibratory roller depends on the weight of the roller as well as the amplitude and frequency of the vibrations. For a given setting of amplitude and frequency, the density achieved depends on the thickness of the mat and the underlying pavement layers. Therefore, the thickness of the pavement under compaction affects the amount of energy absorbed versus the energy dissipated into the underlying layers.

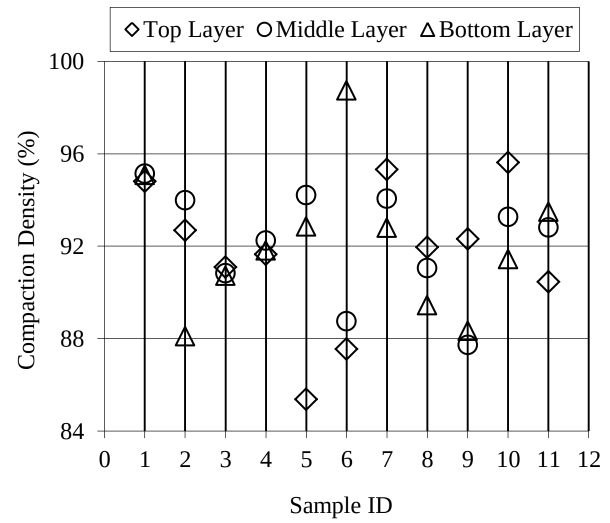

Fig. 2. Distribution of Compaction Density for Laboratory Sample.

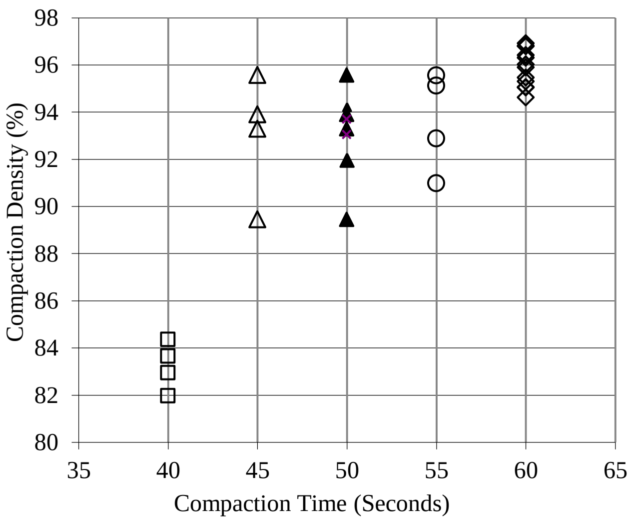

Fig. 3. Compaction Density Versus Compaction Time.

Four sets of 19 mm HMA samples were compacted in the AVC for 60 seconds. As discussed in previous section, 60 seconds is enough time to reach target density for the selected mix and specimen thickness used in this study. Each set of samples were prepared using a different quantity of the mix in order to represent different lift thickness. Fig. 4 shows the density / air void content of each sample after completion of compaction.

Field Achievable Compaction Quality

Laboratory testing of an asphalt mix provides critical information on the effect of the mix parameters on the pavement performance and the optimum performance that can be achieved in the field Good construction techniques, augmented by good quality control procedures, are necessary for the pavement to meet the long term performance goals. Quality control in the field is accomplished through the extraction of roadway cores and/or point-wise measurement of the pavement density using a density gauge.

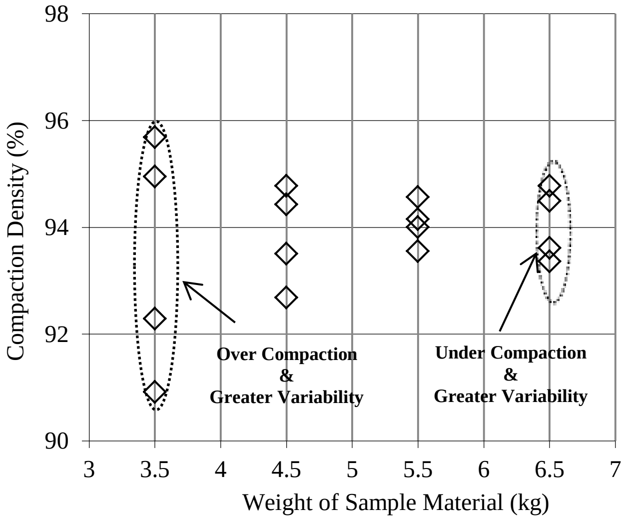

Fig. 4. Sample Thicknesses vs. Compaction Density.

Fig. 5. CMP and DOT Cores' Locations.

Table 2. DOT vs. CMP Cores

	Density		Error
	DOT	CMP	DOT vs. CMP
Maximum	95.9	96.4	1.9
Minimum	91.4	91.8	-1.9
Mean	93.7	93.9	-0.3
Std. Dev.	0.99	1.04	0.79

Table 3. Propagation of Compaction over Successive Roller Passes.

	Non-Nuclear Density Gauge (%)						
Location	1	2	3	4	5	6	7
Pass 1	93.9	93	93.1	94.8	94.7	93	93.2
Pass 2	95	93.3	92.1	94.3	94.6	95.7	95
Pass 3	94.5	94.8	95.2	92.9	93.9	95.2	94.7
Pass 4	95.9	95.8	95.6	95.4	95.5	94.7	95.2

Variation of Compaction Density

The variation of density in a finished asphalt pavement was studied during the resurfacing of Interstate I-86 in New York State near Hornell. First, a thin (5/8 in) lift of Nova Chip was milled from a layer of the pavement. The remainder of the faulted concrete pavement was then rubblized and proof rolled. Any soft areas were replaced with screened gravel and a lift of 25 mm mix. The prepared pavement (either rubblized or undercut) was then paved with a 65 mm thick base layer comprising of 25 mm HMA, followed by two 50 mm thick asphalt layers using 19 mm HMA, and finally a 40 mm thick asphalt layer using 9.5 mm HMA. While Quality Control is a main concern for the contractor, Quality Assurance is a priority for the Department of Transportation (DOT) inspectors and other contracting agencies. At the end of each day, cores were extracted from randomly chosen locations on the completed pavement. New York State Department of Transportation (NYSDOT) inspectors marked four cores for every 1000 tons of constructed asphalt [22]. Additionally, companion cores were marked adjacent to each NYSDOT core and were used by the contractor for quality control (see Fig. 5). The density measured at these locations are shown in Table 2, where 'DOT' indicates the density measured from the core locations specified by the NYSDOT state agency and 'CMP' indicates the density measured from the companion cores.

Density Measurement Laterally Across the Pavement

During the construction of interstate I-86 in New York, density measurements using a calibrated non-nuclear density gauge (NDG) were taken at 50 meter intervals after the final roller pass. At every 50 meter marker, four measurements were taken across the mat from the outside shoulder to the inside joint between the lanes.

Compaction Density versus Number of Roller Passes

The density achieved during the construction of an asphalt pavement as a function of the roller pass was studied during the construction of State Highway SH-99 near Seminole Oklahoma. About five miles of full-depth asphalt pavement was constructed and SH-99 was expanded from two to four lanes. First, a 200 mm stabilized subgrade with 12% fly ash was compacted and prime coat was applied immediately after the final compaction. A 200 mm aggregate base was placed on top of the compacted sub-grade. A 19 mm Recycle mix was then placed at a thickness of approximately 76 mm on top of the compacted base layer. The breakdown rolling was performed by an Ingersoll-Rand DD118 dual drum vibratory compactor and the compaction level after each roller pass was measured using a non-nuclear density gauge at different locations. The roller followed the same path during the forward and reverse motion of all passes. Results are presented in Table 3 and plotted in Fig. 6.

Compaction Density versus Thickness of Pavement Layers

Core density values were collected from five different job sites to study the effect of lift thickness on the achievable compaction levels during construction. All the cores were collected from intermediate layers constructed using 19 mm HMA pavement. A total of 60 core density values were gathered where some of them are the average of a set of DOT and CMP cores. The recommended minimum lift

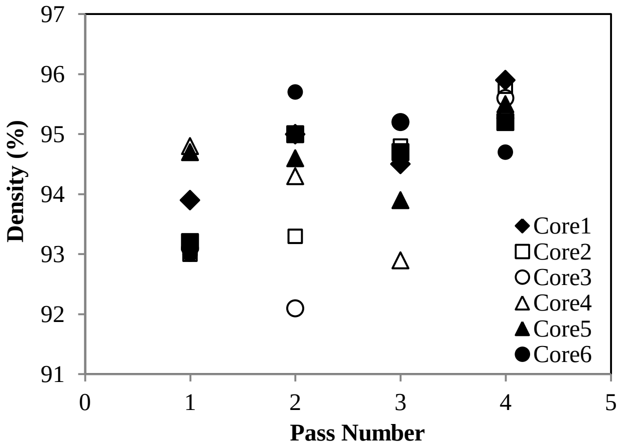

Fig. 6. Measured Compaction Density Values After Each Roller Pass at Seven Different Locations.

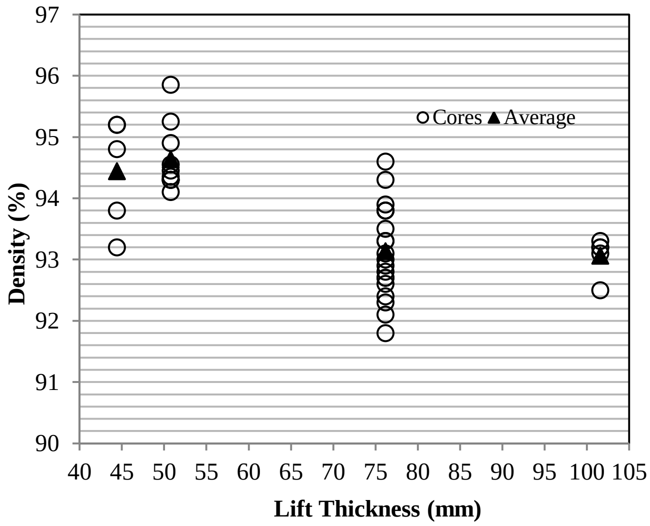

Fig. 7. Achievable Compaction Levels Based on Lift Thickness.

thickness for a 19 mm HMA pavement is between 50 and 75 mm [23]. Fig. 7 shows the influence of an asphalt pavement thickness against compaction level and compaction consistency.

Discussion of Results

Variability in the Achieved Density During Compaction (Laboratory Compaction)

It can be observed in Fig. 2 that the three portions of a slab specimen do not always have the same density. Almost half of the tests results showed that the density of the top portion is the lowest. In conclusion, the compaction process does not always result in higher density in the top portion and progressively decrease toward the bottom portion. In contrast, density in the portions of an asphalt pavement randomly changes during compaction, due to the continuous reorientation of aggregates and the randomness of aggregate shapes and texture.

Effect of Compaction Time on Compaction Density (Laboratory Compaction)

First, as the compaction time increases, the density of the asphalt mix increases, thereby indicating a decrease in the air void content of the sample (see Fig. 3). It can also be noticed that the density of an asphalt mix does not increase linearly with time. It can also be observed from the figure. that after 60 seconds of compaction, the target density is consistently reached (within 2%). While it is possible to get good compaction by increasing compaction time (the number of roller passes), such an increase could possibly result in over compaction of the mix and should be avoided in practice. As a consequence, fewer roller passes are selected to meet the QA specification but at risk of increased variability in the achieved density. For example, compaction of a sample greater than 45 seconds can ensure that density would be in range of the target density (i.e., 92% to 96% of maximum theoretical density). The variability in compaction density is lower as the compaction time increases.

Variation of Compaction Density with Sample Thickness (Laboratory Compaction)

Fig. 4 shows the influence of an asphalt pavement thickness on compaction level and compaction consistency. For the selected mix used in this study, it was found that the compaction at a the lower limit of recommended thickness (3.5 kg in Fig. 4 corresponding to a lift thickness of 50 mm) can possibly result in over compaction of the mix and also result in greater variability in the achieved density. On the other hand, compaction at the upper limit of the recommended thickness (6.5 kg corresponding to a lift thickness of 75 mm) would result in under compaction and greater variability in the achieved density (NAPA 2001). This is an important issue to be considered as the viscous flow of asphalt mixture results in variable thickness of the pavement. This problem is further exacerbated when the pavement has unconfined edge. However, it is to be noted that these findings are limited to the mix type selected in this study (Superpave 19 mm and 75 mm thickness of sample). Further, the procedure adopted in this study closely represents the construction pattern followed in the United States. Since construction practices vary from region to region, additional studies are necessary before these results can be generalized to other asphalt mixes or construction practices not addressed in this study.

Variation of Compaction Density (Field Compaction)

It is apparent from Figs. 8, 9 and Table 2 that a difference of up to 1.9% can exist between locations on the finished pavement that are less than 200 mm apart. The results are consistent with the laboratory results explained in the previous sections. Even though all the ingredients of the asphalt mix are blended together, the mix is not uniform, and results in a random distribution of aggregates. Furthermore, degradation of aggregates may result in the variability in density for two adjacent spots. Thus, closely located regions on the asphalt mat could have a relatively large difference in air void content.

Student t-test analysis was conducted to check if the difference in density for DOT and CMP cores is statistically significant. The null hypothesis for this analysis is: "the difference in the mean of density

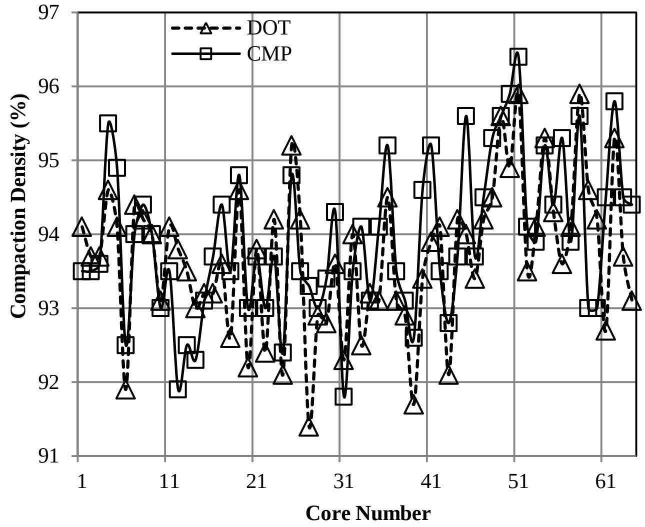

Fig. 8. Laboratory Measured Density Values of NYSDOT Cores Versus Companion Cores.

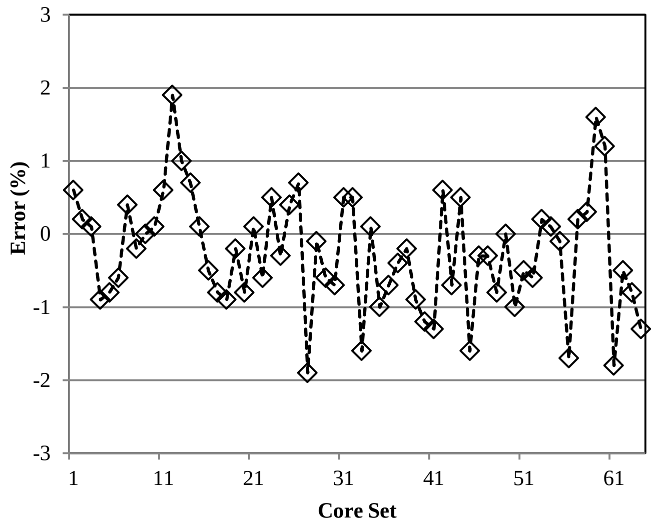

Fig. 9. Error between Laboratory Measured Density Values of NYSDOT Cores vs. Companion Cores.

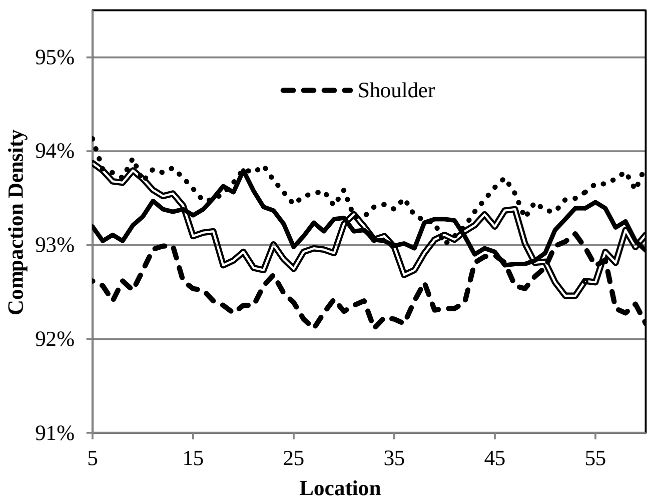

Fig. 10. 2D Density Distribution over the Road Using a Non-Nuclear Density Gauge.

for DOT and CMP cores is equal to zero ($H_0 = \mu_{DOT} = \mu_{CMP}$)". An alternative hypothesis (H_a) is: "the mean of density was not equal". The test was conducted at a significance level of 0.05. The p-value < 0.05 indicates rejection of the null hypothesis. The p-value for the present case was found to be 0.01 (i.e., $p < 0.05$), indicating that statistically significant difference existed between the density measured for DOT and CMP cores. The difference in the density for closely associated cores can result into the different performance of pavement.

Density Measurement Laterally across the Pavement (Field Compaction)

Fig. 10 shows that lower densities can be observed on the outside shoulder while the inside joint is higher and the middle section of the pavement is the highest density. This data shows that there is significant variation across the width of the pavement and that lack of confinement towards the shoulder has a significant effect on the density achieved in the field.

Compaction Density versus Number of Roller Passes (Field Compaction)

From Fig. 6 it is observed that most of the compaction took place during the first pass. Also, more passes are required to increase the density and make compaction more uniform.

Compaction Density versus Thickness of Pavement Layers (Field Compaction)

Based on the limited scope of this study of one selected mix, it was found that quality of compaction may depend on the thickness of a pavement layer. It is recommended that a further study be conducted to verify the findings.

Conclusions

In this paper, achievable compaction quality (compaction density) both in the laboratory and in the field is presented. First, the uniformity of compaction over the entire length of the pavement and the variation in density laterally across the pavement are examined. It was found that density in the layers of an asphalt pavement randomly changes during compaction, due to the continuous reorientation of aggregates and the randomness of aggregate shapes and texture. In addition, a difference of up to 1.9 % can exist between locations on the finished pavement that are less than 200 mm apart. Secondly, compaction quality as a function of compaction time / roller passes was studied. It was observed that the density of an asphalt mix does not increase linearly with time. Additionally, most of the compaction took place during the first pass. Also, more passes are required to increase the density and make compaction more uniform. Finally, compaction quality as a function of pavement thickness is considered for a selected Superpave mix of 19 mm nominal maximum aggregate size. It was found that for the mix used in this study, compaction at the lower limit of recommended thickness (50 mm) can possibly result in over compaction of the mix while compaction at the upper limit of the recommended thickness (75 mm) would result in under compaction. However, it is noted that this compaction behavior depends on many factors such as type of mix, binder type, weather conditions; therefore, it is recommended that a study be conducted to evaluate effect of layer thickness of compaction of HMA layer. A statistical analysis showed that a significant difference existed between the density measured for DOT and CMP cores. It shows that the difference in the density for closely associated cores can result into the different performance of pavement.

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