The Journal of Engineering Research Vol 7, No. 1 (2010) 11-21

Estimating Optimum Compaction Level for Dense-Graded Hot-Mix Asphalt Mixtures

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Received 3 March 2008; accepted 18 May 2009

تحديد المستوى الامثل للدمك المخبري للخلطات الأسفلتية ذات الكثافة العالية

خالد الشامس ، لؤي محمد

الخلاصة: يعد الدمك (الضغط) المخبري من الخطوات الاساسية في تصميم الخلطات الاسفلتية. الدمك المخبري ينبغي أن يؤدي الى انتاج عينات أسفلتية ذات خصائص هندسية مشابهه للمادة الأسفلتية الناتجة من الدمك الذي تحدثه معدات الضغط المستخدمة في تشييد الطريق. هذه الدراسة تقدم طريقة مبتكرة لتحديد المستوى الامثل للدمك المخبري للخلطات الأسفلتية ذات الكثافة العالية و ذلك باستخدام فحوصات مخبرية متطورة. الدراسة شملت تصميم و تحليل خصائص ١٢ خلطة أسفلتية مختلفة و أيضا الاستعانة بجهاز متطور لقياس توزيع الضغط داخل العينة أثناء الدمك.

المفردات المفتاحية: الرصف، أسفلت، الدمك، خلطة أسفلتية

Abstract: A critical step in the design of asphalt mixtures is laboratory compaction. Laboratory compaction should reflect field compaction and should produce mixtures that are economical and possess high structural stability. During the compaction process, asphalt mixtures are subjected to certain amount of compaction energy in order to achieve the required density. The Superpave volumetric mix design is based on compacting HMA mixtures to a specified compaction level described by the number of gyrations from the Superpave gyratory compactor (SGC). This level is termed Ndes and represents the required energy (based on the traffic level expected) to densify the mixture to a 4% air voids level. This paper re-examines the Superpave compaction requirements through extensive laboratory investigation of the response of a number of asphalt mixtures to the applied compaction energy. It also presents an alternative method to estimate the number of gyrations at which a mixture first reaches an optimum aggregate interlock and hence prevents overcompaction problems that might result in unstable aggregate structures or dry asphalt mixtures. A total of 12 HMA mixtures were studied. During compaction, force measurement was made using the pressure distribution analyzer (PDA). The compaction characteristics of the mixtures were analyzed using data from the PDA and the traditional Superpave Gyratory Compactor (SGC) results.

Keywords: Locking point, Mix design, Asphalt mixtures, Pavement materials, Laboratory compaction

1. Introduction

Hot mix asphalt (HMA) is the most common material used for paving applications. It consists primarily of an asphalt binder and mineral aggregates. The binder acts as a gluing agent that binds aggregate particles into a cohesive mass. When bound by an asphalt binder, a mineral aggregate acts as a stone framework that provides strength and toughness to the system. Several mixture design methods have been developed over time, in an effort to create a mixture that is capable of providing acceptable performance based on certain predefined set of criteria. The most recently developed mixture design method is the Superpave method. Superpave stands for Superior Performing Asphalt Pavements and represents a basis for specifying component materials, asphalt mixture design and analysis, and pavement performance prediction. It includes several processes and decision points. A key feature in the Superpave system is laboratory compaction. In the mix design procedure, a Superpave gyratory compactor (SGC) is used to carry out the compaction of the asphalt mixture specimens in the laboratory. SGC was found to be effective in simulating field compaction and ensuring that the properties of the samples compacted in

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the laboratory are to some extent, similar to the mix placed in the field (Cominsky, 1994). Figure 1 is a schematic illustration of the SGC and Fig. 2 presents a typical output from it. A hydraulic or mechanical system applies a load to the loading ram, which applies 600 kPa compaction pressure to the specimen. The loading ram diameter nominally matches the inside diameter of the compaction mold, which is normally 150 mm for design purposes. The SGC base rotates at a constant rate of 30 revolutions (gyrations) per minute during compaction, with the compaction mold positioned at a compaction angle of 1.25º. The ram pressure is monitored by a pressure gauge during compaction. As the specimen densifies, the pressure gauge and loading ram maintain compaction pressure. The specimen height during compaction is monitored and recorded.

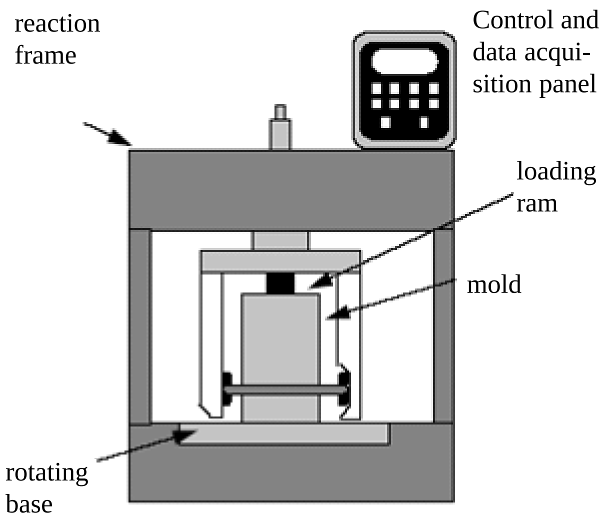

Figure 1. Superpave Gyratory Compactor (Asphalt Institute, 2001)

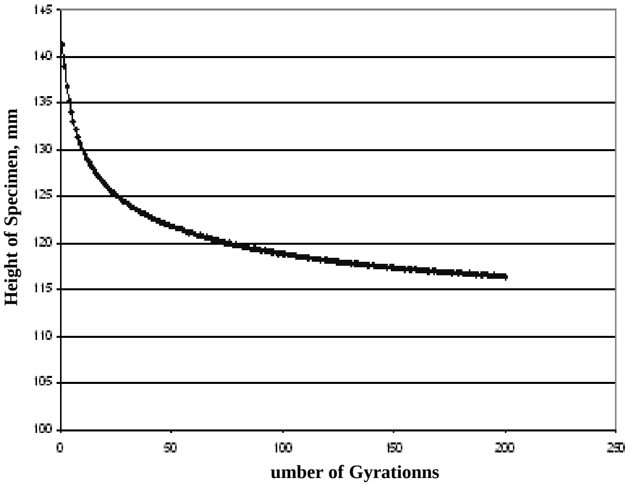

Figure 2. Typical data output from the SGC

In the Superpave system, asphalt mixtures are designed at a specific level of compactive effort. This is a function of the design number of gyrations (N_{design}). The design number of gyrations depends upon the traffic level for which the mix is designed. Traffic is represented by the design-equivalent single axle loads (EASLs). Four traffic categories ranging from 0.3 to greater than 30 million EASLs are used. Higher compaction energy is applied to mixtures in the heavy traffic category. The analysis of the compacted samples is done in terms of percentage of the theoretical maximum specific gravity of the mixtures.

The data from the SGC are generally used in computing volumetric properties such as density or air void content as a function of compaction gyrations. However, several attempts have been recently made to analyze the densification curve obtained from the SGC in order to evaluate the asphalt mixtures' workability and resistance to permanent deformation. The initial number of gyrations ($N_{initial}$) and the slope of the initial portion of the SGC compaction curve have been hypothesized to reveal certain mixture properties such as tenderness of the mixtures and the strength of aggregate structure (McGennis, 1995).

Vavrik (Vavrik, *et al*. 2000) suggested the evaluation of mixture compaction characteristics based upon the locking point or the point during compaction at which the mixture exhibits a marked increase in resistance to further densification. The Alabama Department of Transportation (Alabama DOT, 2002) have adopted the locking point mix design concept. They define the locking point as the point where the sample being gyrated loses less than 0.1 mm in height between successive gyrations. Similarly, the Georgia Department of Transportation (Georgia DOT, 2003) use the concept of locking point in designing HMA mixtures. They define the locking point as the number of gyrations at which, in the first occurrence, the same height has been recorded for the third time. For Georgia, typical locking points are reported to be in the range between low 60's to high 80's measured with the Superpave gyratory compactor. Recently, the Oregon Department of Transportation changed the Superpave design gyration levels for mixes used in the state highway system (Asphalt, 2007). Oregon highway mixes will be designed at 4.0 percent air voids at 65, 80, and 100 gyrations. For highways with low truck volumes (ODOT level 2), gyrations have been rolled back from 75 to 65. Mixes to support moderate truck traffic (ODOT Level 3) will be designed at 80 gyrations instead of 100. Interstate and other highways with heavy truck traffic (ODOT level 4) will be built with mixes designed at 100 gyrations rather than 125 gyrations.

Guler *et al*. (Guler, *et al*. 2000) developed a gyratory load cell and plate assembly (GLPA) for measuring HMA shear resistance during compaction with any SGC. It is a thin cylindrical device that is inserted on top of the mixture in the compaction mold that gives a continuous measure of shear resistance under gyratory loading during compaction. They hypothesized that bulk shear resistance from the GLPA is a good indicator of the compactability of HMA mixtures and their potential resistance to rutting under traffic. It was concluded that the device offers potential as a low-cost tool to complement volumetric properties from the SGC by evaluating the compactability of asphalt mixtures as well.

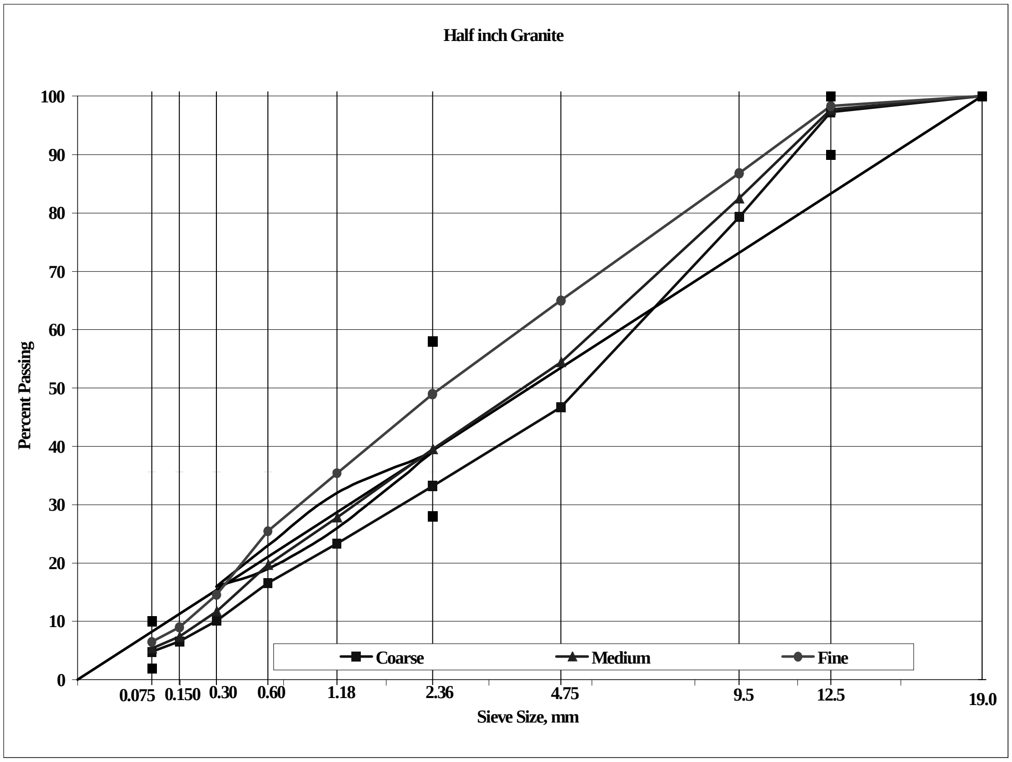

Figure 3. Example of aggregate structure used in the study

2. Objective and Scope

The primary objective of this study was to develop a method for estimating the number of gyrations at which an asphalt mixture reaches its optimum aggregate interlock. To achieve this objective, an extensive laboratory investigation was carried out to study the response of a number of asphalt mixtures to the applied compaction energy when compacted in the Superpave gyratory compactor (SGC). A total of 12 HMA mixtures were evaluated. During compaction, force measurement was made using a small device inserted in the compaction mold called the pressure distribution analyzer (PDA). The compaction characteristics of the mixtures were analyzed using data from the PDA and the traditional Superpave Gyratory Compactor (SGC) results. The following sections describe in detail the materials used and the methodology applied to achieve the objective of the study.

3. Materials

An asphalt mixture is a composite material that is largely made of two main components, aggregate and asphalt cement. Sources of aggregate were selected to encompass a wide range of aggregates commonly used in asphalt mixtures. Three aggregate types were used. These are:

- Hard aggregates; crushed granite (GR)
- Water-absorptive, high-friction aggregate; sandstone (SST) and
- Low friction low-water-absorption aggregate; limestone aggregate (LS).

Different stockpiles from each type of aggregates were acquired. Natural coarse sand was used whenever necessary in the final design blends. Aggregates were acquired in 50-gallons barrels and kept properly sealed from any moisture intrusion. Detailed laboratory evaluation procedures of individual stockpiles were conducted to determine the basic aggregate properties such as specific gravity, gradation, and other Superpave consensus properties.

Larger-sized stockpiles were sieved into individual size fractions. Materials retained on 1", 3/4", 1/2", 3/8", No. 4, and passing No. 4 sieves were stored in separate containers so that the required gradations could be batched directly from the individual size fractions. This method of aggregate separation, while somewhat time and labor-intensive, allows for strict control and exact replication of mixture's aggregate gradation. Three aggregate structures were designed for each aggregate type: coarse (C), medium (M), and fine (F). Figure 3 shows an example of the aggregate structures used in the study. SB polymer-modified asphalt binders PG76-22M were used in all the mixtures evaluated in this study.

4. Mixture Design

Mixture design was performed on all the aggregate structures that were formulated. The Superpave mixture design method was followed except for the VMA requirement. All the mixtures were designed for high-volume traffic (N_{des} = 125 gyrations at 1.25° angle of gyration). The optimum asphalt content was determined as the asphalt content required to achieve 4.0 percent air voids at N_{des}. Optimum asphalt contents ranged from 3.0% to

Table 1. Job mix formula - 12.5 mm mixes - N_{des} = 125 Gyrations

Mixture name[1]	**LS Coarse**	**LS Medium**	**LS Fine**	**SST Coarse**	**SST Medium**	**SST Fine**	**GR Coarse**	**GR Medium**	**GR Fine**
Mix type	12.5 mm	12.5 mm	12.5 mm	12.5 mm	12.5 mm	12.5 mm	12.5 mm	12.5 mm	12.5 mm
Binder type	PG 76-22M	PG 76-22M	PG 76-22M	PG 76-22M	PG 76-22M	PG 76-22M	PG 76-22M	PG 76-22M	PG 76-22M
	Design AC content, volumetric properties, and densification								
% G_{mm} at N_I	85.1	86.2	88.0	86.0	86.4	88.0	87.3	87.3	87.1
% G_{mm} at N_M	97.2	97.4	97.3	97.0	97.1	97.4	97.5	97.2	97.0
Design binder content, %	5.1	4.0	3.5	5.1	3.6	3.9	4.8	4.5	4.3
Design air void, %	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
VMA, %	12.8	14.5	16.6	12.3	11.8	13.8	12.7	11.3	10.9
VFA, %	71.0	62.7	58.5	69.0	50.0	54.0	66.2	62.4	60.6
Metric (U.S.) Sieve	Gradation, (% passing)								
19 mm (¾ in)	100	100	100	100	100	100	100	100.0	100.0
12.5 mm (½ in)	97.1	97.0	97.2	96.0	96.6	97.2	97.3	97.7	98.3
9.5 mm (3/8 in)	80.3	80.2	81.7	80.7	83.8	86.5	79.3	82.5	86.8
4.75 mm (No.4)	46.9	55.2	59.8	48.6	57.6	64.7	46.7	54.4	65.0
2.36 mm (No.8)	31.5	39.6	46.1	32.8	41.6	48.4	33.2	39.5	49.0
1.18 mm (No.16)	21.8	27.9	34.7	22.2	31.5	36.9	23.3	27.8	35.4
0.6 mm (No.30)	15.3	19.7	25.6	16.2	23.7	27.8	16.6	19.7	25.5
0.3 mm (No.50)	9.3	11.1	14.4	12.1	15.9	17.7	10.1	11.7	14.6
0.15 mm (No.100)	6.6	7.4	9.3	6.7	11.2	12.1	6.6	7.4	9.0
0.075 mm (No.200)	5.5	6.0	7.2	4.2	8.4	9.1	4.8	5.4	6.5

[1] LS: Limestone, SST: Sandstone, GR: Granite

5.1% . The coarse mixtures had higher optimum asphalt contents for all the aggregate types considered. Tables 1 and 2 provide the job mix formula for each of the designed mixtures.

5. Mixtures Compactability

The densification curve obtained from the SGC was used to evaluate mixture resistance to the compaction energy applied by the SGC. The behavior of the mixtures during compaction was also captured using the pressure distribution analyzer (PDA). This is a simple accessory that measures the force applied to the mixtures using three load-cells equally spaced at an angle of 120°. The load-cells allow measuring of the variation of forces during gyration such that the position or eccentricity of the resultant force from the gyratory compactor can be determined in real time. The two-dimensional distributions of the eccentricity of the resultant force can be used to calculate the effective moment required to overcome the internal shear frictional resistance of mixtures when tilting the mold to conform to the 1.25° angle. Based on the data from the load-cells, the two components of the eccentricity of the total load relative to the center of the plate (e_x and e_y) can be calculated. The calculations are simply done with general moment equilibrium equations along two perpendicular axes passing through the center of one of the load-cells as shown in Fig. 4 using the following equations:

$$\Sigma M_x = 0 \Rightarrow e_y \tag{1}$$

Table 2. Job mix formula - 25.4 mmmixes - N_{des} = 125 Gyrtions

Mixture name	**LS Coarse**	**LS Medium**	**LS Fine**
Mix type	25.4	25.4 mm	25.4 mm
Binder type	PG 76-22M	PG 76-22M	PG 76-22M
Design AC content, volumetric properties, and densification			
% G_{mm} at N_I	85.0	88.8	89.1
% G_{mm} at N_M	97.7	97.4	97.4
Design binder content, %	3.8	3.0	3.3
Design air void, %	4.0	4.0	4.0
VMA, %	11.1	9.6	10.0
VFA, %	63.5	58.2	60.5
Metric (U.S.) Sieve	Gradation, (% passing)		
37.5 mm (1½ in)	100	100	100
25 mm (1 in)	92.4	92.6	95.2
19 mm (¾ in)	78.8	79.3	86.5
12.5 mm (½ in)	64.7	66.0	76.9
9.5 mm 3/8 in)	52.5	56.1	65.8
4.75 mm (No.4)	36.4	43.2	50.3
2.36 mm (No.8)	24.5	32.7	38.1
1.18 mm (No.16)	15.8	24.3	28.2
0.6 mm (No.30)	10.6	17.6	20.4
0.3 mm (No.50)	7.7	8.7	10
0.15 mm (No.100)	6.1	5.2	5.9
0.075 mm (No.200)	5.1	4.2	4.8

$$\Sigma M_y = 0 \Rightarrow e_x \qquad (2)$$

$$e = \sqrt{e_x^2 + \left(r_y - e_y\right)^2} \qquad (3)$$

P_1, P_2, P_3 are load-cell forces; e_x and e_y are x- and y-components of the eccentricity, e; and ry is the location of the plate center point with respect to the x-axis.

The frictional shear resistance of the asphalt mixture can be calculated using the following relationship:

$$FR = \frac{Re}{AH} \qquad (4)$$

where,

FR = the frictional resistance
R = Resultant Force
e = eccentricity
A = cross-section area
H = sample height at any gyration cycle.

Two specimens per mixture were tested for compactability in both SGC and PDA devices.

Figures 5 and 6 present an example of the behavior of the asphalt mixtures during the compaction process using the data from both SGC and PDA devices. The figures show the rate of change in specimen height (from the SGC) and the frictional resistance (from the PDA). It is clear that the mixture reaches a condition where applying additional compaction energy results in little or no effect in further densifying the mixture. The point at which the mixture starts exhibiting this level of compaction resistance is termed the locking point of the mixture and is defined as follows:

SGC Locking Point : The SGC locking point is the number of gyrations after which the rate of change in height is equal to or less than 0.05 mm for three consecutive gyrations (Fig. 5).

PDA Locking Point: It is defined as the number of gyrations at which the rate of change of frictional resistance per gyration is less than 0.01 (Fig. 6).

The locking point data presented in Figs. 7 and 8 for both the SGC and the PDA respectively indicate that it takes more energy to densify coarse mixtures compared to the medium and fine mixtures. As the aggregate gradation becomes finer, the compactability of the mixtures generally improves. Locking points are much lower than the design number of gyrations recommended by the current Superpave design system. The highest locking point is about 70% of the recommended design number of gyrations for the heavy-traffic category (N_{des}=125). Figure 9 presents the good correlation between the locking points determined from the SGC and those determined from the PDA. On average, the PDA locking points were about 4 gyrations lower than those determined from the SGC data.

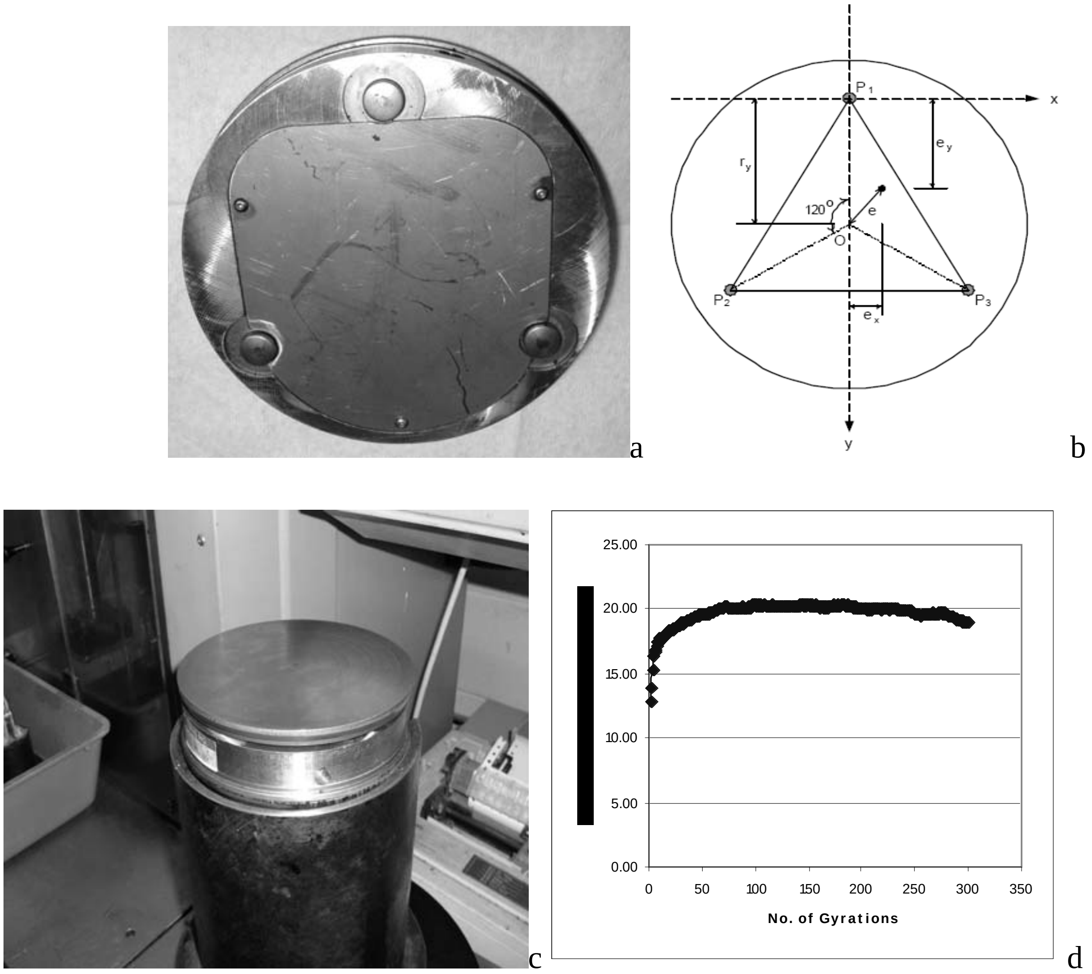

Figure 4. Pressure distribution analyzer (a) The PDA device (b) Analysis of forces (c) Inserting the PDA in the compaction mold (d) Typical results

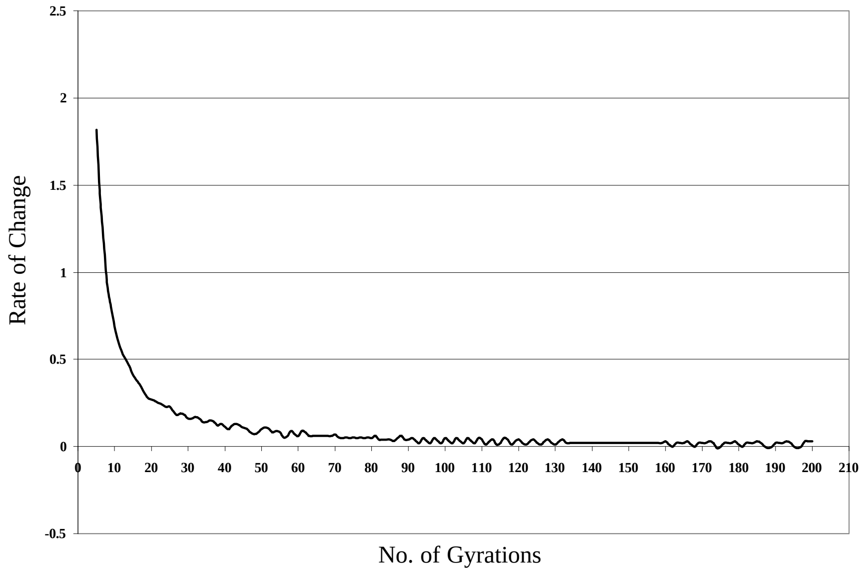

Figure 5. Rate of change of the height SGC compaction

6. Physical Properties of Mixtures at their Locking Point

A limited number of mixtures were selected for mixture design using the locking point concept as opposed to the traditional Superpave Ndes. Graphical comparisons of some physical properties from both sets of mixtures are presented in Figs. 10 through 12. As anticipated, com-

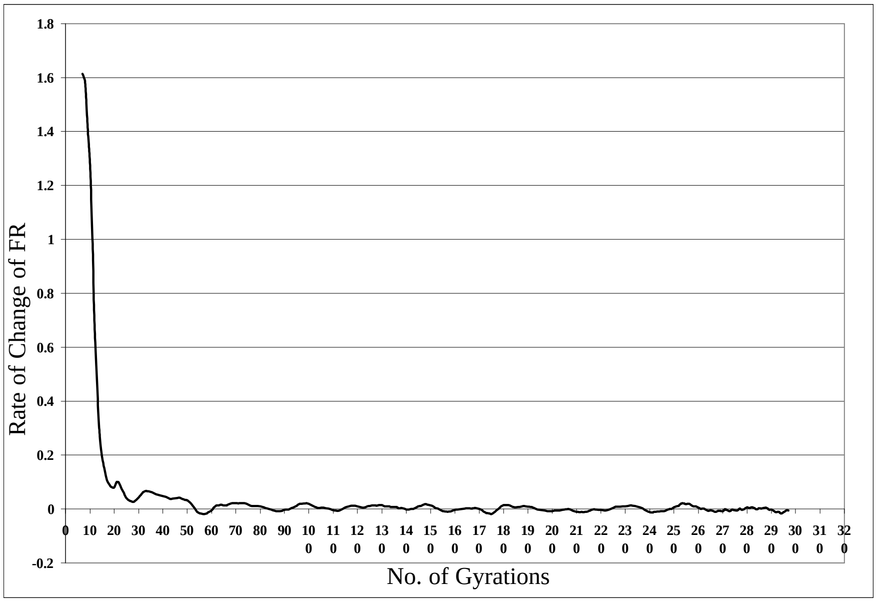

Figure 6. Rate of change of frictional resistance SGC compaction

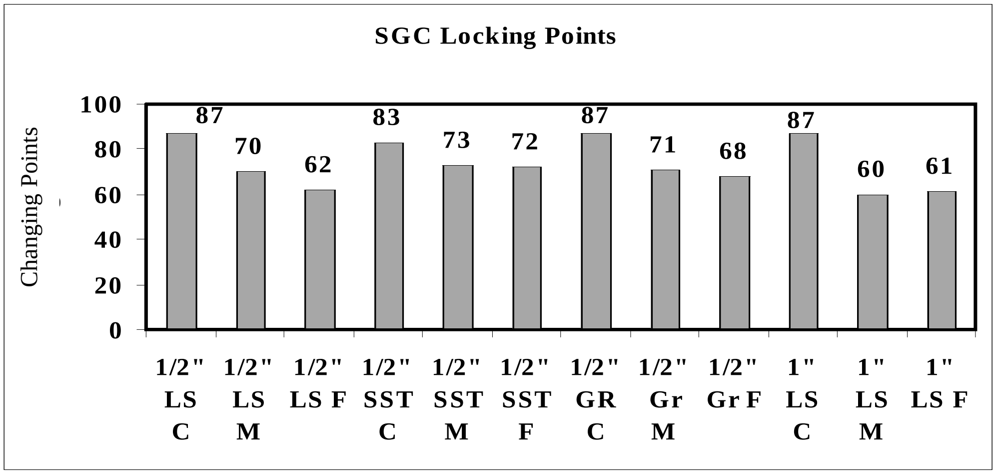

Figure 7. SGC locking point results

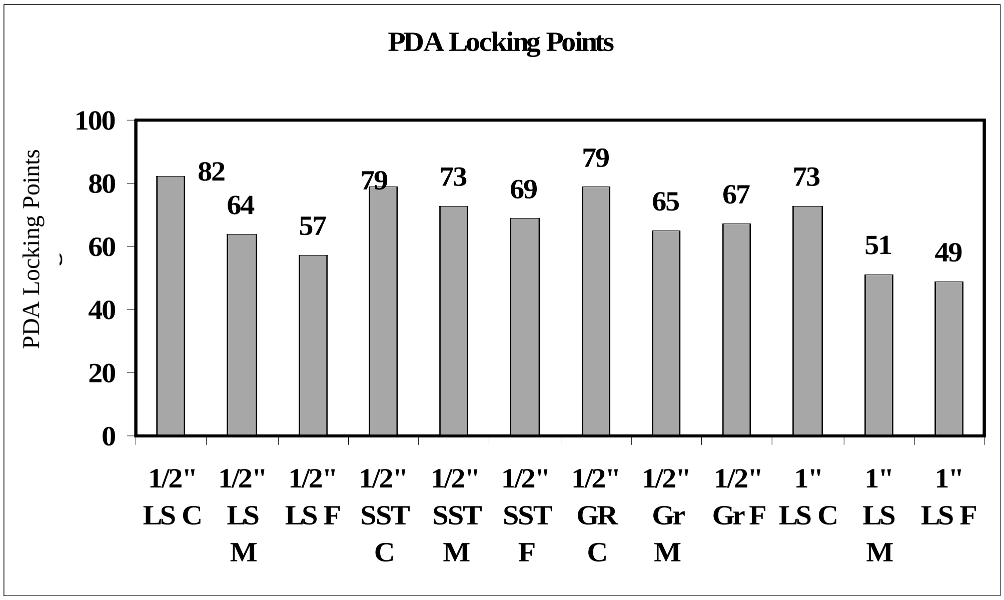

Figure 8. PDA locking point research

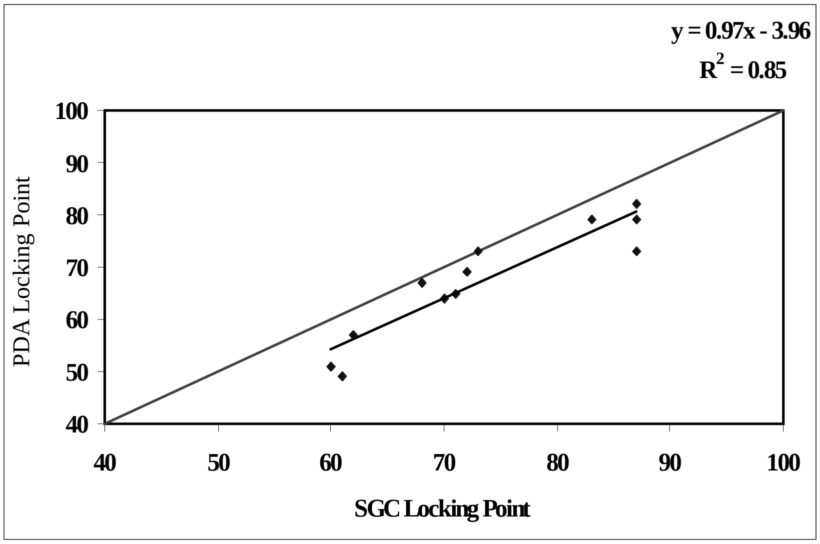

Figure 9. SGC and PDA locking points correlation

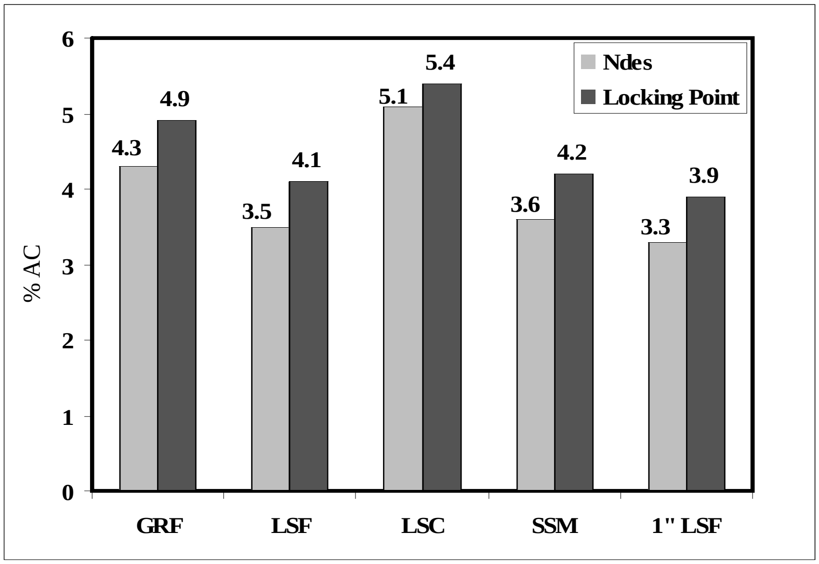

Figure 10. Comparison of the design asphalt content

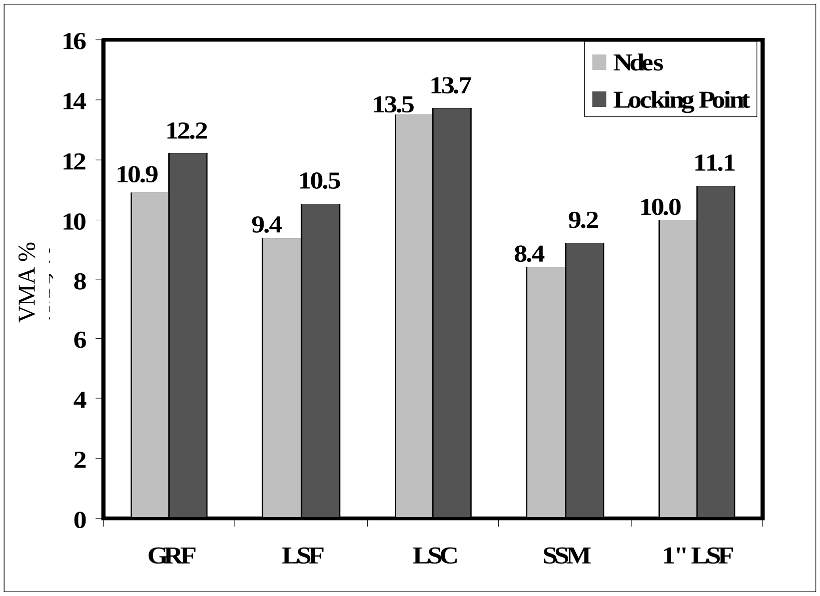

Figure 11. Comparison of the VMA results

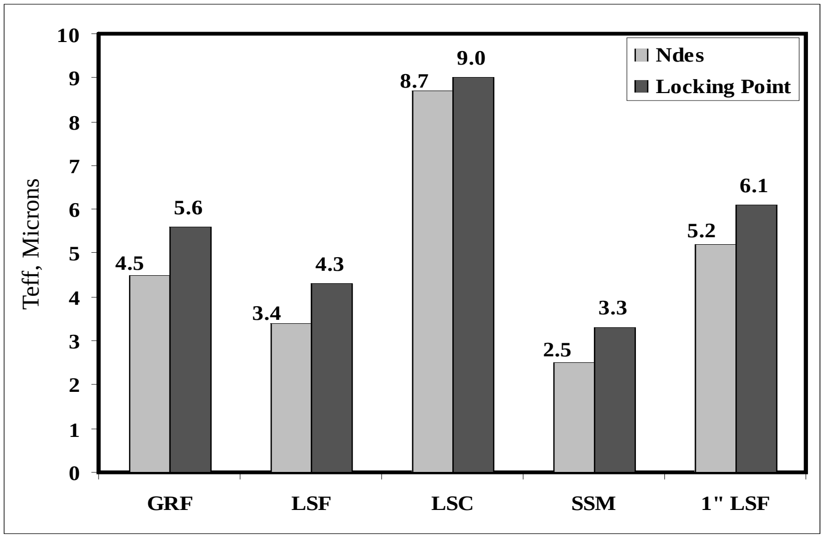

Figure 12. Comparison of the effective film thickness

pacting mixtures to their locking point yielded higher design asphalt contents than those obtained when Superpave-design number of gyrations was used. The asphalt content for mixtures designed using the locking point ranged from 3.9% to 5.4% compared to 3.3% to 5.1% for the same mixtures designed using the traditional Ndes. It is worth noting that except for the half-inch coarse limestone mixture, there was about 0.6% increase in asphalt content for all other mixtures when they were designed using their locking points at the same level of 4.0% air void. The Voids in Mineral Aggregates (VMA) values were 1.1% to 1.2% higher for the mixtures designed at the locking point except for the medium sandstone mixture in which there was 0.8% increase. Higher asphalt contents naturally resulted in higher VFA, lower Dust/Pbeff ratio, and hence higher effective film thickness for the mixtures in consideration.

7. Estimating Locking Point

To facilitate the design process, a multiple linear regression model was developed using SAS software (SAS 2002) to estimate the locking point of the mixture based on certain properties that are thought to influence the performance of the mixture during compaction. The response parameter used was the locking point (LP). Since the compaction process is always performed at elevated temperatures, the influence of aggregate structure is thought to be more pronounced than that of the binder although the binder will still maintain some lubrication effect that might contribute to the mixture's response to the applied compaction energy. Several parameters were first introduced in the model including different characteristics of the gradation curves of the designed aggregate structure as well as binder content. A stepwise variable selection procedure was first performed on a general model that contains those variables. The purpose of such a procedure is to remove insignificant variables from the general model. The regression analysis was then conducted on the reduced model using the stepwise variable selection procedure. Three parameters were used in the regression analysis which were significant when included in the model as independent variables. These were:

- Volume of coarse aggregate in the aggregate structure (VCA). The designer can determine the VCA in the dry condition of aggregate by performing a unit weight test on the combined material retained on No. 4 Sieve for a given blend according to AASHTO T-19 test procedure (AASHTO T-19, 2004), along with determining the combined specific gravity for this material.
- Percent Passing #200 sieve for the aggregate structure in consideration. This parameter is termed as "P_{200}".
- Estimated initial asphalt content (AC).

The predictive model used is:

$$LP = 1.38 * VCA + \left(0.62 * P_{200} * AC\right) - 6.86 \qquad (5)$$

where LP, VCA, P_{200}* AC are:

LP = Locking Point to be estimated
VCA = Volume of coarse aggregate in the aggregate structure
P^{200} * AC = the interaction between the effect of the amount of material passing #200 sieve in the aggregate structure and the estimated asphalt content.

The results of the regression procedure are shown in Table 3. The F- Value for the model was 45.44 with a P-value of <0.0001. This indicates that the model is significant in describing the relationship between the response variable and the independent variables. All the parameter estimates for the predictor variables in the model were significant at the 95% significance level selected for the analysis. The model was also checked for any co-linearity between the predictor variables. When there is a perfect linear relationship among the predictors, the estimates for

Table 3. Linear Regression analysis to estimate locking point

Analysis of Variance

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	2	1413.28	706.64	45.44	<.0001
Error	11	171.08	15.55		
Corrected Total	13	1584.36			
Root MSE	3.94	**R-Square**	0.89		
Dependent Mean	71.21	**Adj R-Sq**	0.87		
Coeff Var	5.54				

Parameter Estimates

Variable	**DF**	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr > |t|**	**Tolerance**	**Variance Inflation**
Intercept	1	-6.86	8.43	-0.81	0.4329	.	0
VCA	1	1.38	0.15	9.04	<.0001	0.99	1.00
DAC	1	0.62	0.18	3.45	0.0055	0.99	1.00

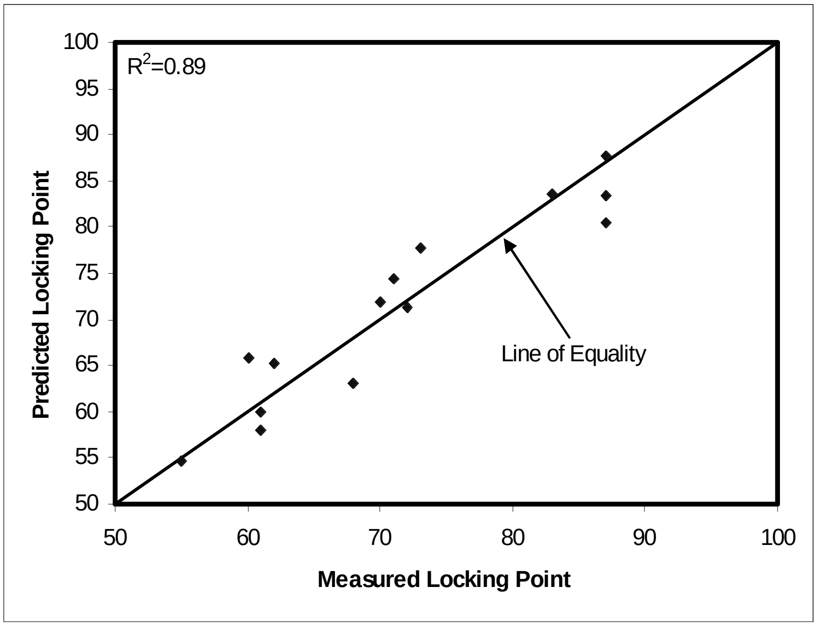

Figure 13. Accuracy of the locking point estimation model

a regression model cannot be uniquely computed. The term co-linearity describes two variables that are near-perfect-linearity combinations of one another. When more than two variables are involved, it is often called multi-co linearity, although the two terms are often used interchangeably.

The primary concern is that as the degree of multi-co linearity increases, the regression model estimates of the coefficients become unstable and the standard errors for the coefficients can get wildly inflated.

The 'vif' option was used to check for multi-co linearity. If stands for *variance inflation factor*. As a rule of thumb, a variable whose 'vif' value is greater than 10 may merit further investigation. A comparison between the measured and predicted response variable is shown in Fig. 13.

8. Conclusions

The several key findings of this study may be summarized as follows:

- Data from the SGC provide valuable information on the compactability of asphalt mixtures.
- Both SGC and PDA results suggest that coarse mixtures are more difficult to compact compared to the medium and fine ones. This emphasizes the importance of relating the level of applied compaction energy to some specific attribute of the asphalt mixtures and not basing it solely on the expected traffic level as currently practiced in the Superpave mixture design methodology.
- The compaction data also suggest that the current recommended Superpave design number of gyrations is too high and subject the mixtures to unnecessary high compaction loads for extended periods of time, which might have an adverse effect on the final mixture volumetrics.
- There was a strong correlation between the data from the SGC and PDA. This suggests the data from the SGC provides a good indication of mixture compactability.
- A statistical estimation model was developed based on parameters that have a significant effect on the compactability of asphalt mixtures. This model can help mix designers in establishing the optimum compaction levels for their mixtures.

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