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EFFECT OF END-POINT COMPACTION ON SUPERPAVE HOT MIX ASPHALT (HMA) MIX DESIGNS

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16. Abstract

In the Superpave hot mix asphalt (HMA) mix design system, gyratory specimens are compacted to varying levels of initial ($N_{initial}$), design (N_{design}) and maximum ($N_{maximum}$) gyrations. Initially, in the Superpave system, specimens were compacted to $N_{maximum}$ and their volumetric properties back-calculated at N_{design}. However there can be errors in the HMA volumetric properties at N_{design}, as a result of the back calculation.

This study was conducted to determine differences in volumetric properties and design asphalt content for commonly used HMA mixes in Mississippi. Forty-eight mixes were first designed by compacting directly to N_{design}. Afterwards specimens were compacted to N_{design} and $N_{maximum}$ at the determined design asphalt content. Volumetric properties of specimens compacted directly to N_{design} were compared to those back calculated from $N_{maximum}$. Additionally, the Corelok vacuum sealing procedure, along with the conventional water displacement technique, was used to determine the bulk specific gravity of all compacted specimens. An evaluation of the effect of the Corelok device on the mix design asphalt content and VMA was conducted.

Differences in the volumetric properties, as a result of compacting specimens directly to N_{design}, will result in a reduction of 0.14 percent design asphalt content and 0.29 percent voids in the mineral aggregate (VMA).

By using the Corelok device and compacting specimens directly to N_{design} overall average increases in the design asphalt content and VMA of 0.15 and 0.35 percent, respectively, were observed.

17. Key Words Superpave, gyratory compactor, hot mix asphalt, $N_{initial}$, N_{design}, $N_{maximum}$, Corelok	18. Distribution Statement Unclassified		
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TERMS, ACRONYMS, AND DEFINITIONS

Term	Acronym	Definition
Hot Mix Asphalt	HMA	Mixtures of aggregate and apshalt binder produced at elevated temperatures in asphalt plants.
Superior Performing Asphalt Pavements	Superpave	Product of the Strategic Highway Research Program and the new mix design system for hot mix asphalt, replacing the Marshall mix design system.
Air Voids	AV	Total volume of air located between coated aggregate particles within a compacted HMA mix. Also referred to as Voids in the Total Mix (VTM).
Voids in the Mineral Aggregate	VMA	Volume of intergranular void space between aggregate particles of compacted HMA mixtures that includes air voids and effective asphalt binder content, expressed as a percentage of the total sample volume.
Voids Filled with Asphalt	VFA	Portion of the total volume of intergranular void space or VMA filled with effective asphalt binder.
Theoretical Maximum Specific Gravity	G_{mm}	Ratio of HMA mix mass to volume without any air present.
Bulk Specific Gravity of the Compacted HMA Mix	G_{mb}	Ratio of HMA mix mass to volume, including air.
Aggregate Apparent Specific Gravity	G_{sa}	Ratio of aggregate dry mass to solid aggregate volume.
Aggregate Bulk Specific Gravity	G_{sb}	Ratio of aggregate dry mass to solid aggregate volume + surface permeable voids.
Percent of Theoretical Maximum Specific Gravity	$\%G_{mm}$	Percent HMA mix compaction relative to the theoretical maximum specific gravity.
Design Asphalt Content	DAC	Asphalt content of a paving mixture at which 4 percent air voids are achieved.
$N_{initial}$	$N_{initial}$	Number of revolutions of the Gyratory compactor representing the compactibility of the paving mixture behind the spreader.
N_{design}	N_{design}	Number of revolutions of the Gyratory compactor required for design characteristics of the job-mix formula.
$N_{maximum}$	$N_{maximum}$	Number of revolutions of the gyratory compactor representing the density of a pavement layer at the end of its design life.
Nominal Maximum Aggregate Size	NMAS	One sieve size larger that the first to retain at least 10 percent of the aggregate blend.
Performance Grade	PG	Superpave nomenclature for performance graded asphalt binder. PG is used in front of two numbers to distinguish an asphalt binder's grading (e.g., PG 67-22). Replaces the conventional viscosity grading system (e.g., AC-30).
Analysis of Variance	ANOVA	Collection of statistical procedures used to evaluate the statistical significance of observed data from experiments.

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CHAPTER 1 INTRODUCTION

1.1 INTRODUCTION

In the Superpave hot mix asphalt (HMA) mix design system, gyratory specimens are compacted to varying levels of initial ($N_{initial}$), design (N_{design}) and maximum ($N_{maximum}$) gyrations. Initially, in the Superpave system, specimens were compacted to $N_{maximum}$ and their volumetric properties back-calculated at N_{design}. However, as a result of back-calculation, errors in HMA volumetric properties at N_{design} can be present. Of most concern is the change in air voids and voids in the mineral aggregate (VMA).

Because of these errors, the Mississippi Department of Transportation (MDOT) recently revised their protocol for Superpave HMA mix designs. The revised protocol requires specimens to be compacted directly to N_{design} for selecting design asphalt content.

1.2 OBJECTIVES AND SCOPE

A study has been undertaken targeted at determining the effect on Superpave design asphalt content resulting from changing end-point compaction for mix designs from $N_{maximum}$ to N_{design}. The laboratory study evaluated various factors including aggregate type, asphalt binder performance grade, N_{design} level, nominal maximum aggregate size, and aggregate gradation. Mix designs were conducted at N_{design} as the end-point of compaction. Additional specimens were compacted to $N_{maximum}$. The differences in design asphalt contents and other volumetric properties at N_{design} and $N_{maximum}$ were then analyzed.

Corelok vacuum sealing procedures were used to determine the bulk specific gravity (G_{mb}) of all compacted specimens in the study. An evaluation of the effect of the Corelok device on the mix design asphalt content and VMA was also conducted.

Results of the study provide a basis for evaluating changes in design asphalt content for the range of aggregate and asphalt combinations used throughout Mississippi.

CHAPTER 2 LITERATURE REVIEW

A literature review was conducted and is discussed as a part of this report. Literature was reviewed that pertained to development of the Superpave gyratory compaction procedure (development of N_{design}, $N_{initial}$, and $N_{maximum}$) and past evaluations of the effect of end point compaction.

The experimental approach, results, and conclusions from the initial N_{design} experiment are provided by Blackenship et al (*1*). The N_{design} experiment was undertaken to determine the number of gyrations (N_{design}) required to represent various traffic levels in different geographical regions and climates. In accomplishing this task two gyration levels were evaluated. One level was $N_{construction}$, which represented the initial laydown compaction level, $C_{construction}$, and the other level was $N_{design,}$ which represented the compaction in the wheel path under applied traffic, C_{design}. For the experiment the value of $C_{construction}$ was unknown for many of the pavements and was assumed to be 92 percent of G_{mm}. In the original experiment 27 pavement sites with 54 mixtures were to be evaluated. The sites would include three climates (hot, warm, and cool), three traffic levels (low, medium, and high), and two pavement layers (upper and lower). However, it was later decided to evaluate only pavements which had been in service for over 12 years. As a result, the number of pavements in the study was reduced to 18, with 15 being available for final evaluation. An assumption was made that all the mixtures were designed to have 3 to 5 percent air voids in the laboratory and in-place air voids of 7 to 9 percent immediately after construction

The aged asphalt was extracted from 305 mm cores taken from the various pavements. Subsequently, the aggregate was re-mixed with an unaged AC-20 asphalt cement. Prior to compaction the mixes were aged for 4 hours at 135°C. They were then compacted with 230 gyrations using the Strategic Highway Research Program (SHRP) gyratory compactor. Mixtures with 19.0 mm and less nominal maximum aggregate sizes were prepared using a 100 mm compaction mold. Mixtures with greater than 19.0 mm nominal maximum aggregate sixes were compacted in a 150 mm mold. All mixtures evaluated in the study had a fine gradation.

Analysis of test results was used to select N_{design} for a desired traffic level and an average 7-day high temperature. The authors suggested that the results and conclusions from the experiment were acceptable but more research was needed to increase the precision of N_{design}.

Cominsky et al. (2) provided the background and an overview of the Superpave mix design system as it was developed. Specifically, they provide a detailed description of how the Superpave gyratory compactor was selected for use in mix design and quality control. After considerable research and effort, SHRP researchers elected to use a gyratory compactor with operating protocols very similar to the French gyratory compactor. The final protocol specified a rotational speed of 30 rpm, a gyration angle of 1.25 degrees, a vertical pressure of 600 kPa, and a target final sample compaction height of 115 mm.

A discussion is also provided by Cominsky et al. (2) on how the gyratory compaction parameters of $N_{initial}$ and $N_{maximum}$ were established. Initially, in the Superpave procedure, $N_{initial}$ and $N_{maximum}$ were referred to as N_{89} and $N_{98,}$ respectively. As mentioned previously, the Superpave gyratory compaction procedure was modeled, in part, after the French gyratory compaction protocol. Wherein, N_{89} is set at 10 gyrations; at which the compacted specimen density must be less than 89 percent of the maximum theoretical specific gravity. The value of N_{89} does not change based upon the selected level of N_{design}. The SHRP researchers felt that the level of N_{89} or $N_{initial}$ should be a function of N_{design} and should increase as N_{design} increases. This would yield a more stable mixture for higher temperatures and traffic levels.

The N_{98} or $N_{maximum}$ was established to represent a maximum allowable density using the Superpave gyratory compactor. Researchers felt that a mix that compacts to greater than 98 percent of the maximum theoretical specific gravity in the laboratory would be prone to excessive densification or rutting in the field.

From results of the initial N_{design} experiment (SHRP-A001, Task F), a relationship between $N_{initial}$ and $N_{maximum}$ was established. Figure 2.1 illustrates the procedure used by the researchers for one mix from Arizona. Aggregate recovered from cores was re-mixed with an asphalt cement equivalent to the original asphalt cement and compacted to approximately 275 gyrations in the Superpave gyratory compactor. A plot of percent G_{mm} versus the log of gyrations provides the densification curve for the mixture. The densification curve is also referred to as the Aas-recovered@ curve on the plot. The point representing 96 percent G_{mm} and the N_{design} for the mix are plotted. The next step was to determine the intersection point of 96 percent G_{mm} and the established N_{design} value for the mix. The Aas-recovered@ compaction curve was then translated horizontally until it passes though the plotted point. In Figure 2.1, this shifted curve is referred to as the Aestimated design@ curve. Finally, lines are drawn vertically for of 89 and 98 percent G_{mm}, on the Aestimated design@ curve to the x-axis. The number of gyrations corresponding to 89 and 98 percent G_{mm} were then referred to as $N_{initial}$ and $N_{maximum}$, respectively. The ratio of the log of $N_{initial}$ and $N_{maximum}$ to the log of N_{design} was then used to determine the relationship between a given N_{design} and the corresponding $N_{initial}$ and $N_{maximum}$ values. This process was repeated for each of the mixes used in the N_{design} experiment.

Analyses indicated the average $N_{initial}$ level for the mixes evaluated in the N_{design} experiment was approximately 0.47log N_{design}, which then evolved to the currently used Superpave criteria of $N_{initial}$ = 0.45log N_{design}. Likewise, the average $N_{maximum}$ level was determined to be approximately 1.15log N_{design}, which was later specified as 1.10log N_{design}.

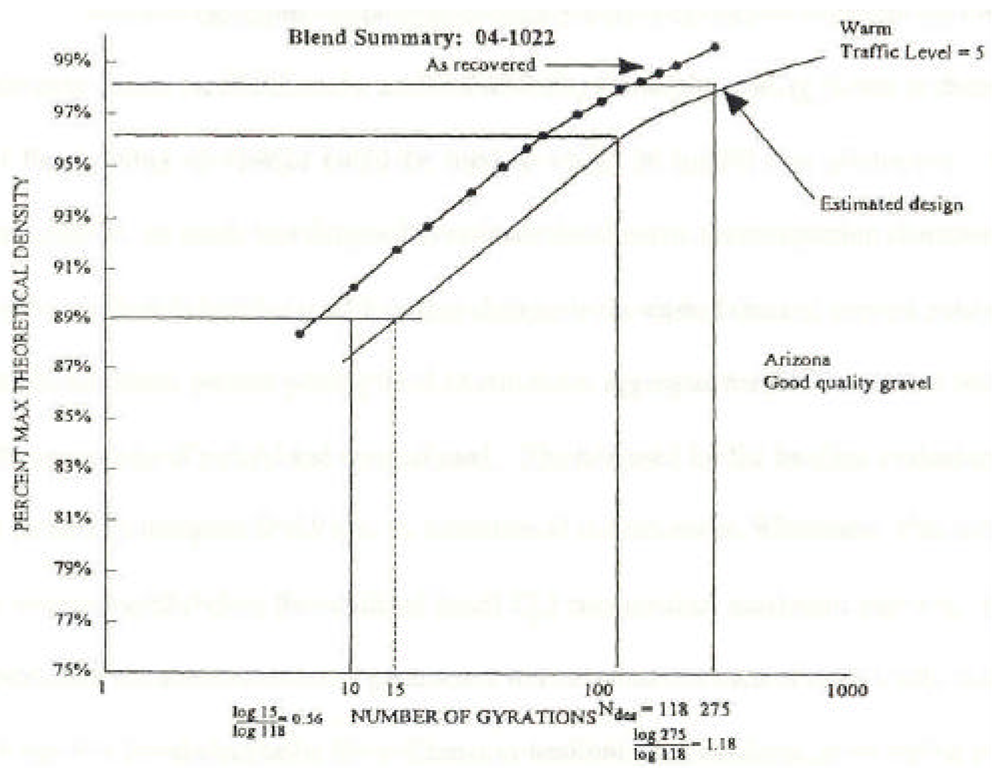

Figure 2.1 $N_{initial}$ and $N_{maximum}$ Relationship from N_{design}

In another study by Cominsky et al. (3), a description of the operational parameters of the Superpave Gyratory Compactor is provided. In the Superpave gyratory compaction procedure, the density at three specific points, $N_{initial}$, N_{design}, and $N_{maximum}$, is determined as the specimen is being compacted. Selection of N_{design} level depends on the design traffic level (ESALs) and the design seven day maximum air temperature for the project. The values of $N_{initial}$ and $N_{maximum}$ are then determined depending upon the selected N_{design} level through the following equations:

$$\log N_{initial} = 0.45 \log N_{design} \qquad \textit{Equation 2.1}$$

$$\log N_{\max imum} = 1.10 \log N_{design} \qquad \textit{Equation 2.2}$$

Values of $N_{initial}$, N_{design}, and $N_{maximum}$ were originally established based on traffic level and temperature. Design asphalt content is selected at 96 percent G_{mm} (4 percent air voids) at the given N_{design} level. Furthermore, the mixture must have densities which are less than 98 percent G_{mm} (2 percent air voids) and 89 percent G_{mm} (11 percent air voids) at $N_{maximum}$ and $N_{initial}$, respectively. A typical densification slope which is obtained from the Superpave gyratory compaction procedure is shown in Figure 2.2. In this figure, the densification slope of a gyratory compacted sample is approximately linear when plotted on a semi-log scale. This is typically assumed for gyratory compacted mixtures.

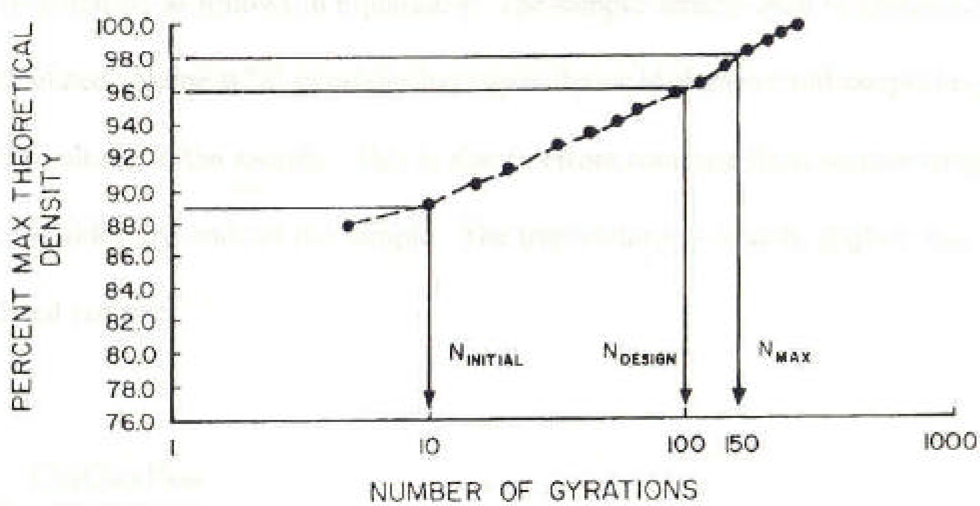

Figure 2.2 Typical Superpave Gyratory Compactor Densification Curve (3)

Originally, in the Superpave procedure, all specimens were compacted to $N_{maximum}$ and their densities at N_{design} and $N_{initial}$ determined through a back-calculation procedure. The procedure consists of first calculating an uncorrected density of the sample at a given gyration level as follows:

$$C_{ux} = \left[\frac{\frac{M_{mix}}{V_{mix}}}{G_{mm}} \right] * 100 \qquad \textit{Equation 2.3}$$

Where, C_{ux} = uncorrected sample density at a given gyration level (x), (g/cm^3),

M_{mix} = mass of mix being compacted (g),

V_{mix} = volume of mix being compacted at (x) gyrations (cm^3).

G_{mm} = theoretical maximum specific gravity of mix

This calculated uncorrected density can in turn be used to calculate the corrected specimen density as follows in Equation 2.4. The sample density must be corrected because the calculated volume at Ax@ gyrations based upon the mold diameter and sample height is not the true volume of the sample. This is due to errors resulting from surface irregularities or texture along the sides and ends of the sample. The true volume is usually slightly less than the calculated volume.

$$C_x = \frac{C_{ux} * G_{mb} * V_{mm}}{M_{mix}} \qquad \textit{Equation 2.4}$$

where,

C_x = corrected sample density at a given gyration level (x), (g/cm^3),

G_{mb} = measured bulk specific gravity of the sample at $N_{maximum}$,

V_{mm} = volume of mix at $N_{maximum}$ (cm^3),

M_{mix} = mass of mix at (x) gyrations (g)

Vavrik and Carpenter (4) conducted a study to determine the sources of inaccuracies, in both mix design and quality control testing, as a result of back-calculation of gyratory specimen density at N_{design} from densities obtained at $N_{maximum}$. The Superpave system, as originally developed, uses a back-calculation procedure in which specimen density at N_{design} is determined through the use of the specimen height and a correction factor determined at $N_{maximum}$. This correction factor is distinct for each mixture designed and will vary with asphalt content, gradation, and compactive effort.

The mixture used in this research was a 19.0 nominal maximum size dense-graded mixture, with a gradation below the Superpave restricted zone and near the coarse control points. (Note: Current Superpave specifications do not contain a restricted zone; however, the restricted zone existed in the original Superpave system). One specimen was compacted to N_{design} and one was compacted to $N_{maximum}$. Densities of specimens compacted to N_{design} and densities back-calculated from $N_{maximum}$ were compared. The results showed differences in density between 0.5 and 1.5 percent.

Due to these differences, the state of Illinois developed a method of determining the densification properties of a mixture based on analyzing all of the gyratory height data and the densification curve for a given mixture. In the procedure it is stated that the densification curve for a mixture is taken as linear up to the point of 96 percent of G_{mm} or 4 percent air voids. The majority of the back-calculation error actually occurs as the void level drops below 4 percent air voids. The Illinois method utilizes a Alocking point@ concept. This Alocking point@ is referred to as the first of three consecutive gyrations producing the same specimen height. Generally, the densification rate of the mixture is nonlinear at any further gyration levels. The Alocking point@ concept was developed by Illinois to prevent over compaction of their mixes during design. At the locking point of the mixture compaction is stopped. It is assumed that specimen densities at lower levels of compaction can be estimated correctly.

Mallick et al. (5) compared correction factors obtained at different gyration levels during compaction. As part of the study, a traprock aggregate was used in two very different gradations: a stone matrix asphalt (SMA) gradation and a conventional well-graded or dense gradation. A PG 64-22 asphalt binder was used for all mixes. Mixes were prepared at their respective design asphalt contents and compacted in a Pine SGC at different gyration levels. The gyration levels used for dense and SMA mixes were 27, 46, 66, 85, 97, 109, 120 and 132; and 40, 71, 101, 132, 153, 174, 194, and 215 gyrations, respectively. After compaction, bulk specific gravities and correction factors were determined. Next, separate specimens were compacted to the maximum level of gyrations used in the above procedure (i.e., 132 for dense, and 215 for SMA) and their bulk specific gravity and correction factors determined. The densities at lower levels of compaction were back-calculated using correction factors from the highest gyration levels and compared with directly measured densities. The results showed that correction factors were not constant at different gyration levels for the mixes evaluated. Relationships between errors in voids and correction factors versus gyrations are shown in Figures 2.3 and 2.4, respectively. As expected, the coarser mixture (SMA) exhibited the greatest difference between the back-calculated and the actual specimen densities due to the open surface texture of the mix. Also, the densities of compacted specimens at lower gyration levels were greater than the densities that were back-calculated from a correction factor determined at the maximum level of gyrations. This is attributed to the increased amount of surface irregularities or texture of the sample at the lower gyration levels relative to high gyration levels. A recommendation was made to compact specimens to N_{design} in the volumetric mix design procedure to insure the true specimen density is obtained at the design level of gyrations.

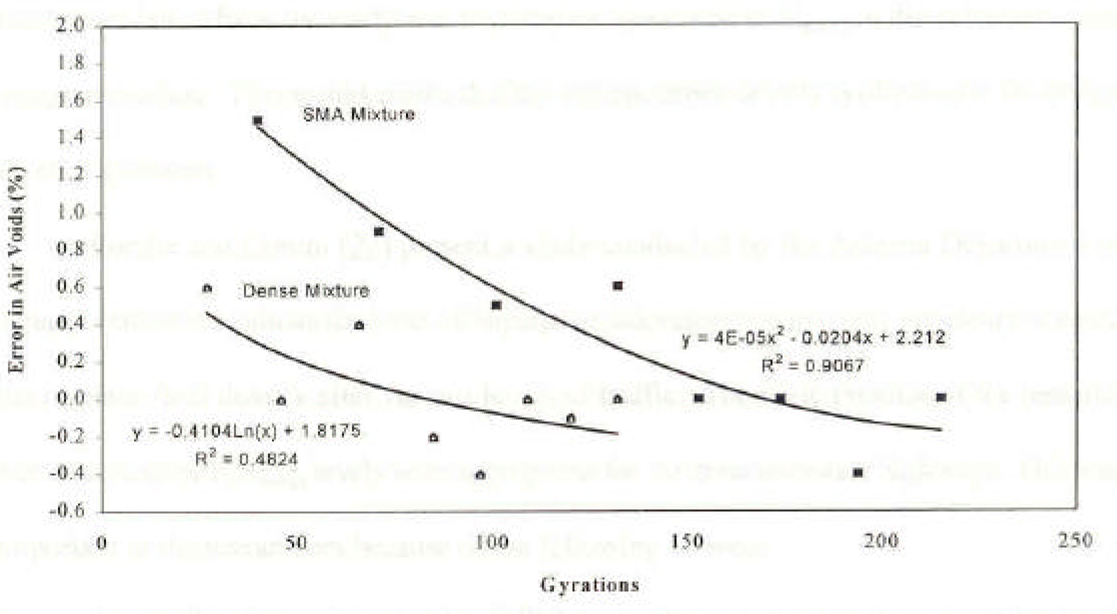

Figure 2.3 Error in Air Voids versus Gyrations (5)

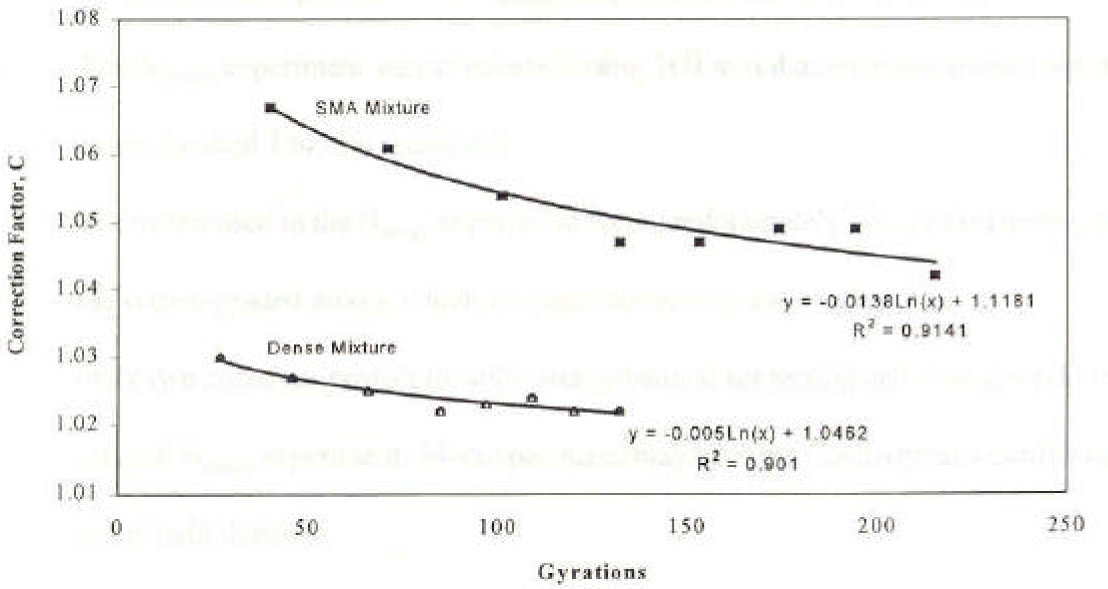

Figure 2.4 Relationship of the Correction Factor versus Gyration Level (5)

Buchanan (6) conducted research on the consolidation of the original N_{design} compaction matrix and evaluation of the gyratory compaction requirements of $N_{initial}$ and $N_{maximum}$. One specific item of interest was the evaluation of specimen density when compacted directly to N_{design} and back calculated to N_{design} from $N_{maximum}$. Specimens from different mixes were compacted directly to N_{design} and their density determined. Next, specimens were compacted to the corresponding $N_{maximum}$ value and their density back calculated to N_{design}.

The results indicated that errors up to 0.8 percent air voids could result by compacting specimens to $N_{maximum}$ and back calculating specimen density at N_{design}. A recommendation was made to compact specimens directly to N_{design} so that any error (positive or negative) in the N_{design} density would be eliminated.

CHAPTER 3 RESEARCH TEST PLAN

3.1 RESEARCH TEST PLAN

The research test plan for the study is shown in Table 3.1. Five factors were varied and their effect on mixture volumetric properties determined. These factors included aggregate type, N_{design}, asphalt binder performance grade, nominal maximum aggregate size, and aggregate blend gradation. Levels of each factors are shown in Table 3.1.

Table 3.1 Research Test Matrix

Aggregate	N_{design}	PG	NMAS	Gradation
Gravel, Sandstone, Limestone/ Gravel	96	67	12.5	Fine
				Coarse
			19.0	Fine
				Coarse
		76	12.5	Fine
				Coarse
			19.0	Fine
				Coarse
	119	67	12.5	Fine
				Coarse
			19.0	Fine
				Coarse
		76	12.5	Fine
				Coarse
			19.0	Fine
				Coarse

The aggregates used consisted of chert gravel from Columbus, Mississippi, sandstone from Russelville, Arkansas; and limestone from Birmingham, Alabama. Additionally, recycled asphalt pavement (RAP) was obtained from Columbus, Mississippi. One percent hydrated lime was added to all study mixes. Aggregate blends were developed comprised of predominately gravel, sandstone, and approximately a 50/50 blend of limestone and gravel. For the gravel mixes, 8 to 10 percent recycled asphalt pavement (RAP) was added. However, due to variability of the RAP, a decision was made not to use the RAP in the sandstone and limestone/gravel mixes.

Subsequently, the aggregate blends in the study will be referred to in the remainder of the study as gravel, sandstone, and limestone/gravel for simplicity. For each of the aggregate types, two aggregate gradations, fine-graded and coarse-graded Superpave blends, were evaluated. In the original Superpave system, fine and coarse-graded aggregate blends were distinguished by the restricted zone, with fine and coarse-graded blends passing above and below the restricted zone, respectively. However, the restricted zone no longer exists in Superpave specifications. Agencies now typically specify fine and coarse-graded blends based on blend percentages passing a certain sieve [generally a smaller sieve size (e.g., 2.36 mm)], with fine-graded blends having a greater percent passing than coarse-graded blends. In this study, efforts were made to develop fine and coarse-graded blends for each aggregate type that were distinctly different, especially between the 2.36 mm and the 0.150 mm sieves. However, due to stockpile limitations, the difference between fine and coarse-graded blends among the aggregate types varies.

A breakdown of the various aggregate stockpile percentages used for each of the aggregate blends is shown in Table 3.2, while the overall aggregate blend gradations are provided in Table 3.3 and Figures 3.1 and 3.2.

Table 3.2 Stockpile Percentages for Aggregate Blend Gradations

Aggregate Stockpile	Aggregate Blend											
	Gravel				Sandstone				Limestone / Gravel			
	12.5 CG	12.5 FG	19.0 CG	19.0 FG	12.5 CG	12.5 FG	19.0 CG	19.0 FG	12.5 CG	12.5 FG	19.0 CG	19.0 CG
1 inch Gravel	0	0	31	40	0	0	0	0	0	0	0	0
3/4 inch Gravel	23	24	50	32	0	0	0	0	26	10	40	34
1/2 inch Gravel	30	0	5	0	0	0	0	0	21	19	0	0
3/8 inch Gravel	31	40	0	0	0	0	0	0	0	0	0	0
RAP	10	10	8	10	0	0	0	0	0	0	0	0
Sand	0	10	0	9	10	10	10	10	12	20	14	15
57 Limestone	0	0	0	0	0	0	0	0	0	0	10	8
67 Limestone	0	0	0	0	0	0	0	0	0	0	0	0
78 Limestone	0	0	0	0	0	0	0	0	22	20	15	12
8910 Limestone	5	15	5	8	0	18	0	18	18	30	20	30
67 Sandstone	0	0	0	0	15	15	30	35	0	0	0	0
78 Sandstone	0	0	0	0	37	0	28	0	0	0	0	0
89 Sandstone	0	0	0	0	23	43	15	23	0	0	0	0
8 Sandstone	0	0	0	0	0	0	0	0	0	0	0	0
1/4 x 0 Sandstone	0	0	0	0	14	13	16	13	0	0	0	0
Hydrated Lime	1	1	1	1	1	1	1	1	1	1	1	1

Table 3.3 Study Aggregate Blend Gradations

Sieve Size (mm)	Percent Passing											
	Gravel				Sandstone				Limestone / Gravel			
	12.5 mm		19.0 mm		12.5 mm		19.0 mm		12.5 mm		19.0 mm	
	Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse
25			100	100							100	100
19	100	100	99	99	100	100	100	100	100	100	98	97
12.5	95	95	89	86	94	94	86	88	96	93	86	84
9.5	87	86	78	72	88	88	76	79	87	80	75	70
4.75	59	52	51	42	58	51	50	45	64	50	55	46
2.36	37	32	33	27	40	29	36	27	47	34	40	33
1.18	26	21	23	19	30	22	28	21	36	26	31	26
0.6	19	16	17	15	25	19	23	18	29	21	25	21
0.3	14	11	12	11	18	14	16	14	17	12	15	13
0.15	10	8	9	8	11	9	10	8	9	8	9	8
0.075	7.7	6.4	6.9	6.1	7.5	5.9	7.1	5.8	7.1	5.9	7.1	5.9

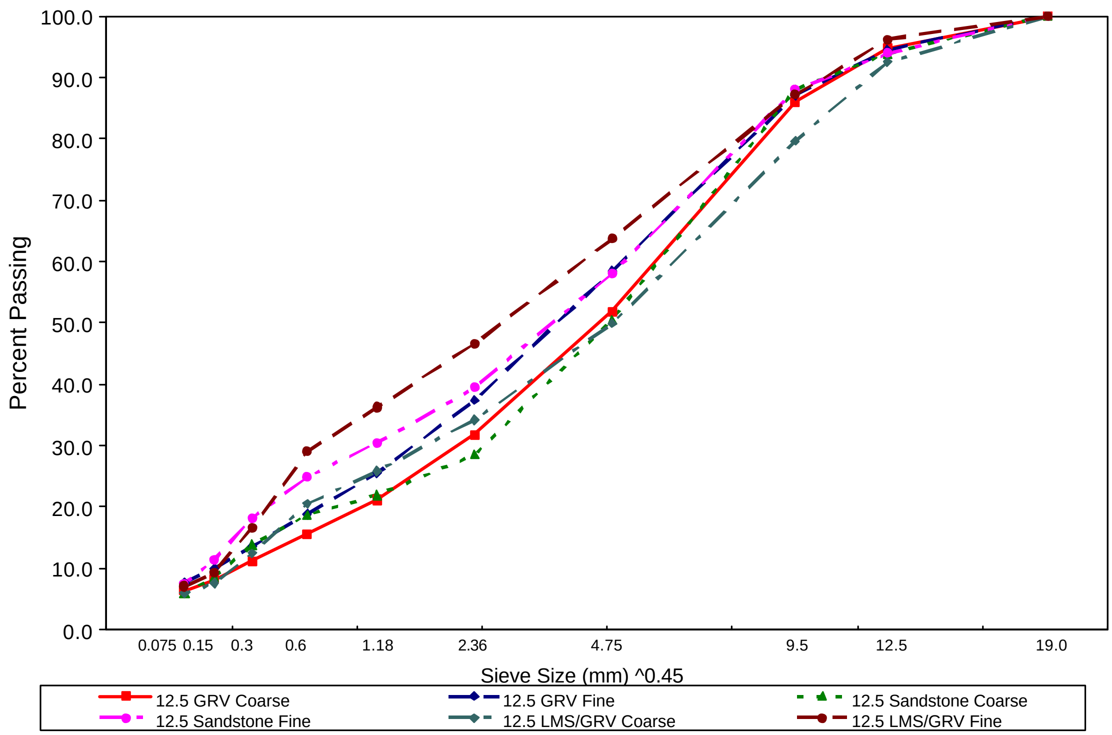

Figure 3.1 12.5mm NMAS Aggregate Blend Gradations

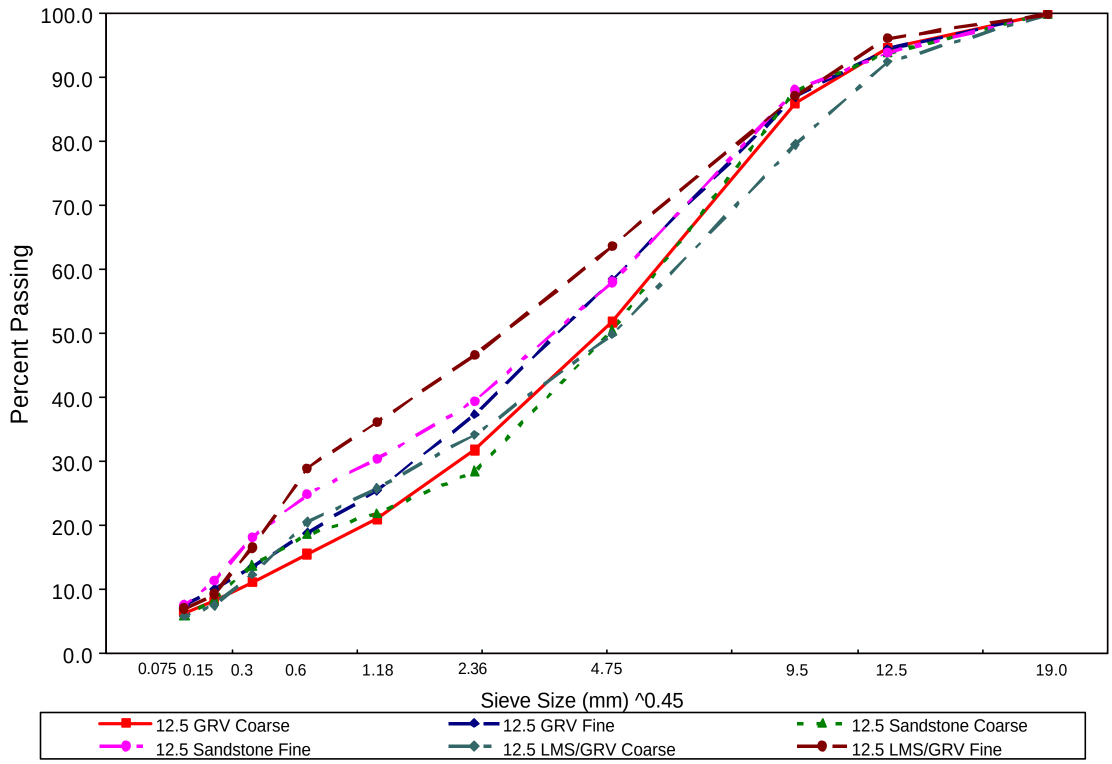

Figure 3.2 19.0 mm NMAS Aggregate Blend Gradations

Superpave mix designs were conducted for each study mix combination in accordance with MDOT MT-78 (7) protocols. The PG 67-22 and PG 76-22 asphalt binders were provided by Ergon, Inc. The target mixing and compaction temperatures for the two asphalt binders are provided in Table 3.4. All mixing was conducted using a bucket mixing device as shown in Figure 3.3.

Table 3.4 Target Mixing, Curing, and Compaction Temperatures

Asphalt Binder	Temperature, C (F)		
	Mixing	Curing	Compaction
PG 67-22	155 (310)	152 (305)	146 (295)
PG 76-22	163 (325)	160 (320)	155 (310)

Figure 3.3 Project Mixing

A standard procedure was used for preparing the PG 76-22 asphalt binder. Per Ergon's recommendations, the asphalt binder was heated to 150°C (300°F) and stirred continuously using a low shear mixer for 1 hour prior to incorporation with aggregates.

All aggregates in the study were heated to 175°C (345°F) for four hours prior to mixing. The mixing time varied but was normally approximately 2 to 3 minutes to insure adequate coating of the aggregate particles. After mixing, specimens were placed in pans which were placed in an oven set at 5°C (10°F) above the compaction temperature for 1.5 hours for short-term aging.

After short-term aging, specimens were compacted to the specified number of gyrations in a Pine Superpave Gyratory Compactor (Model AFGC125X), shown in Figure 3.4. After compaction, the bulk specific gravity of the compacted HMA mix (G_{mb}) was determined and the air voids, VMA, VFA, $\%G_{mm}$ at $N_{initial}$ determined.

Figure 3.4 Pine Superpave Gyratory Compactor

Design asphalt content (DAC) was selected for all mixes at approximately four percent air voids. At the DAC for each mix, triplicate specimens were compacted both to N_{design} and to $N_{maximum}$. The volumetric properties of specimens compacted to $N_{maximum}$ were then determined through back-calculation at N_{design}. The G_{mb} at N_{design} was determined through the use of Equation 3.1.

$$G_{mb}N_{design} = G_{mb}N_{\max imum}\left(\frac{HeightN_{\max}}{HeightN_{design}}\right) \qquad \textit{Equation 3.1}$$

where,

$G_{mb}N_{design}$ = Compacted bulk specific gravity at N_{design},

$G_{mb}N_{maximum}$ = Compacted bulk specific gravity at $N_{maximum}$,

$HeightN_{max}$ = Sample height at $N_{maximum}$,

$HeightH_{design}$ = Sample height at N_{design}.

CHAPTER 4 TEST RESULTS AND ANALYSIS

4.1 AGGREGATE PROPERTIES

All aggregates selected for evaluation in this study are commonly used for HMA production in Mississippi. Various physical properties of the coarse and fine aggregates are provided in Table 4.1. The table shows that the four aggregates selected for evaluation exhibit a wide range of physical properties, such as specific gravity, absorption, particle shape, and angularity.

Aggregate absorption will significantly affect the mixture design asphalt content, along with its volumetric properties after compaction. Aggregate particle shape and angularity will influence the densification rate and mixture surface texture of the mixture during compaction and thus the mixture volumetric properties.

Table 4.1 Physical Properties of Aggregate Blends

Property	Gravel				Sandstone				Limestone / Gravel			
	12.5 mm		19.0 mm		12.5 mm		19.0 mm		12.5 mm		19.0 mm	
	Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse
Apparent Specific Gravity, G_{sa}	2.641	2.652	2.628	2.637	2.670	2.683	2.675	2.678	2.679	2.672	2.675	2.672
Bulk Specific Gravity, G_{sb}	2.437	2.470	2.430	2.448	2.527	2.557	2.546	2.552	2.595	2.570	2.590	2.574
Absorption (%)	3.17	2.78	3.10	2.92	2.12	1.84	1.89	1.84	1.21	1.48	1.24	1.42
Fractured Faces (%)[1]	95/90	95/90	95/90	95/90	100/100	100/100	100/100	100/100	98/93	98/93	98/93	98/93
Uncompacted Voids (%)	44.2	44.0	43.9	43.8	48.5	47.4	48.4	47.5	45.6	45.7	45.6	45.5

Note: 1) 1 or more fractured faces / 2 or more fractured faces

4.2 REASONS FOR ERROR IN BACK CALCULATED VOLUMETRICS

One of the major reasons for there to be differences in volumetrics of specimens compacted directly to N_{design} as opposed to those back calculated to N_{design} from $N_{maximum}$ is the change in surface texture of a HMA specimen from N_{design} to $N_{maximum}$. During compaction, surface irregularities, voids, or texture will typically decrease. This decrease is rapid during initial compaction and then slows toward the end of compaction. The change in surface texture from N_{design} to $N_{maximum}$ can be significant and results in density differences.

Theoretically, the back calculated density at N_{design} can not be less than the direct calculated density. In fact, if there is no test variability and the sides of the HMA specimens are perfectly smooth or if the surface texture is the same at N_{design} and $N_{maximum}$, the direct and back calculated density should be the same.

Obviously, the compacted specimen surface texture of a given mix will be dependent upon the aggregates shape and texture, gradation, and size. For example, a coarse-graded mix would be expected to exhibit a larger density difference at N_{design} than would a fine-graded mix. As a mix's surface texture approaches that of a smooth sided cylinder, the amount of error from the back-calculation procedure is reduced.

Figure 4.1 illustrates two specimens: one coarse-graded and one fine-graded. It is evident that the coarse-graded sample has a far greater amount of surface voids than the fine-graded sample. With more surface texture present there is a greater probability that the surface texture will change during compaction. This change in surface texture is the driving force behind the density differences.

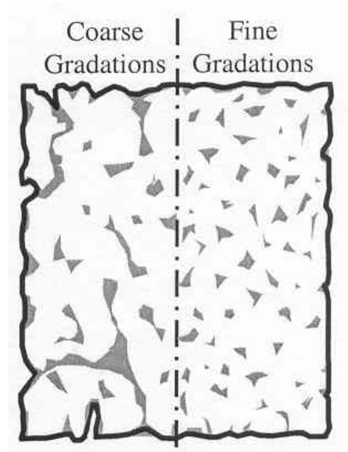

Figure 4.1 HMA Specimen with Coarse versus Fine-Gradations Schematic (8)

4.3 COMPARISON OF N_{design} DIRECT VOLUMETRICS TO N_{design} BACK CALCULATED VOLUMETRICS

Hot mix asphalt (HMA) mixture volumetrics results are presented, analyzed, and discussed in the following sections of the report. Volumetric properties of $N_{initial}$ density, N_{design} density, and voids in the mineral aggregate (VMA) for each of the study mixes are provided in Tables 4.2, 4.3, and 4.4, for the Gravel, Sandstone and Limestone/Gravel mixes, respectively. Gyratory compaction heights, G_{mb}, and G_{mm} data for all specimens compacted to N_{design} and $N_{maximum}$ are provided in Appendix A.

4.3.1 N_{design} Density

The density of specimens compacted to directly to N_{design} (referred to as actual) and density back calculated to N_{design} from $N_{maximum}$ are presented in Tables 4.2, 4.3, and 4.4. The average change in density (actual – back calculated) for each of the mixes is also provided Figures in 4.2, 4.3, and 4.4 for the gravel, sandstone, and limestone/gravel mixes, respectively. Several trends are evident from Figures 4.2 to 4.4. For the vast majority of the mixes (gravel = 75 percent, sandstone = 88 percent, and limestone = 56 percent), it appears that compaction directly to N_{design} resulted in a higher density than back calculating the density from $N_{maximum}$.

For the gravel mixes in Figure 4.2, the results indicate little change in the actual and back calculated density differences of the fine and the coarse-graded mixes. Additionally, there was little change between the 12.5 and the 19.0 mm NMAS mixes. There does appear to be slightly lower differences for mixes compacted to N_{design} of 119 relative to 96. This is not a surprise since the change in surface texture of the sample is likely to decrease with further compaction. At some point during compaction, likely very near the point of maximum compaction, the change in surface texture will be zero and any further surface texture change will be a result of aggregate breakdown and not particle reorientation.

All four of the mixes which had positive density differences were PG 76 mixes. The actual difference was very small (average of 0.12 percent density) and can probably be explained due to compaction and testing variability. There also appears to be less overall difference between the PG 67 mixes than the PG 76 mixes.

The sandstone results shown in Figure 4.3 are for the most part similar to the gravel results in that almost all of the mixes show a positive density difference. Unlike the gravel mixes, there appears to be more of a difference between the fine and coarse-graded mixes, with the coarse-graded mixes having a slightly greater difference. There does not appear to be a definite trend between the PG, NMAS, or the N_{design} factors. As with the gravel mixes, negative differences of the two sandstone mixes were very low (average of 0.18 percent density).

Limestone/gravel results are shown in Figure 4.4 and are in general agreement with the results for the previous two aggregate types. It is interesting that the magnitude of the density differences is less with the limestone/gravel aggregate. This may be due in part to the blend gradation or perhaps the smooth surface texture or particle shape of the limestone aggregate. The magnitude of negative density differences is small (average of 0.13 percent density) when compared to the positive density differences for the limestone/gravel mixtures.

The relationship between the direct and back calculated density at N_{design} is given in Figure 4.5. There is a good relationship (R^2 = 0.70) between the direct and back calculated densities. The data indicates that as the direct density at N_{design} increases the difference between it and the back calculated density also increases. The relationship may be explained by the fact that some of the mixes densified less than others between the levels of N_{design} and $N_{maximum}$. A sample experiencing less densification could be expected to have less change in surface texture, and thusly less difference between the direct and back calculated densities.

Table 4.2 Volumetric Properties for the Gravel Mixes

Aggregate	N_{design}	PG Binder	Nominal Maximum Aggregate Size (mm)	Gradation	Design AC (%)	Volumetric / Compaction Properties: %G_{mm} at $N_{initial}$ Back-Calculated from: N_{design}	$N_{maximum}$	Difference	%G_{mm} at N_{design}: Actual	Back-Calculated	Difference	%G_{mm} at $N_{maximum}$	VMA at N_{design}: Actual	Back-Calculated	Difference
Chert Gravel	96	67-22	12.5	Fine	5.1	87.15	86.95	0.20	96.16	95.60	0.56	97.07	13.33	13.83	-0.50
				Coarse	7.9	85.92	85.75	0.17	95.79	95.22	0.57	96.79	17.02	17.52	-0.50
			19	Fine	5.3	86.84	86.69	0.15	95.96	95.25	0.71	96.70	13.11	13.75	-0.64
				Coarse	7.1	86.52	85.91	0.61	96.07	95.16	0.91	96.30	16.35	17.09	-0.74
		76-22	12.5	Fine	5.4	87.19	86.63	0.56	96.03	95.26	0.77	96.43	14.08	14.77	-0.69
				Coarse	7.6	86.25	85.92	0.33	95.89	95.28	0.61	97.15	17.72	18.25	-0.53
			19	Fine	5.4	87.36	86.72	0.64	95.85	95.23	0.62	96.41	13.83	14.39	-0.56
				Coarse	6.7	86.60	86.42	0.18	95.92	95.78	0.14	97.07	16.39	16.51	-0.12
	119	67-22	12.5	Fine	4.9	86.57	86.51	0.06	95.92	95.59	0.33	97.03	13.10	13.40	-0.30
				Coarse	7.7	85.57	85.09	0.48	96.08	95.35	0.73	96.82	16.29	16.91	-0.62
			19	Fine	5.2	86.33	85.72	0.61	95.92	94.91	1.01	96.31	12.94	13.92	-0.98
				Coarse	7.0	85.72	85.49	0.23	95.81	95.43	0.38	96.93	16.29	16.62	-0.33
		76-22	12.5	Fine	5.4	87.14	86.92	0.22	96.18	96.26	-0.08	97.43	14.01	13.95	0.06
				Coarse	7.2	84.79	84.85	-0.06	95.91	95.99	-0.08	97.20	16.92	16.85	0.07
			19	Fine	5.4	86.82	87.21	-0.39	96.05	96.24	-0.19	97.28	13.65	13.49	0.16
				Coarse	6.4	86.02	86.11	-0.09	95.84	95.97	-0.13	97.14	15.86	15.75	0.11

Table 4.3 Volumetric Properties for the Sandstone Mixes

Aggregate	N_{design}	PG Binder	Nominal Maximum Aggregate Size (mm)	Gradation	Design AC (%)	Volumetric / Compaction Properties: $\%G_{mm}$ at $N_{initial}$ Back-Calculated from:			$\%G_{mm}$ at N_{design}			$\%G_{mm}$ at $N_{maximum}$	VMA at N_{design}		
						N_{design}	$N_{maximum}$	Difference	Actual	Back-Calculated	Difference		Actual	Back-Calculated	Difference
Sandstone	96	67-22	12.5	Fine	4.6	86.76	86.66	0.10	94.73	94.63	0.10	95.78	13.70	13.78	-0.08
				Coarse	5.4	86.00	85.22	0.78	96.63	96.00	0.63	97.66	14.41	14.96	-0.55
			19	Fine	4.2	86.29	86.53	-0.24	94.39	94.52	-0.13	95.69	13.12	13.00	0.12
				Coarse	5.0	86.00	85.37	0.63	96.34	95.69	0.65	97.32	13.78	14.36	-0.58
		76-22	12.5	Fine	5.0	88.10	87.53	0.57	96.04	95.45	0.59	96.52	13.37	13.90	-0.53
				Coarse	5.3	85.09	84.95	0.14	95.04	94.77	0.27	96.27	15.54	15.78	-0.24
			19	Fine	4.2	87.67	87.45	0.22	95.89	95.53	0.36	96.71	11.86	12.19	-0.33
				Coarse	5.5	87.11	86.62	0.49	97.20	96.33	0.87	97.78	14.08	14.85	-0.77
	119	67-22	12.5	Fine	4.3	86.36	86.75	-0.39	94.68	94.91	-0.23	96.04	13.10	12.88	0.22
				Coarse	5.3	85.80	85.43	0.37	96.95	96.41	0.54	98.06	13.86	14.35	-0.49
			19	Fine	4.1	86.46	85.74	0.72	94.55	93.96	0.59	95.15	12.87	13.41	-0.54
				Coarse	5.0	86.24	85.37	0.87	96.81	95.80	1.01	97.32	12.67	13.58	-0.91
		76-22	12.5	Fine	4.3	87.05	87.22	-0.17	94.98	94.94	0.04	95.95	12.81	12.84	-0.03
				Coarse	5.2	85.55	84.87	0.68	96.67	95.77	0.90	97.41	13.94	14.74	-0.80
			19	Fine	4.1	87.95	87.29	0.66	96.19	95.66	0.53	96.87	11.37	11.85	-0.48
				Coarse	5.2	84.78	84.44	0.34	95.01	94.70	0.31	96.17	15.36	15.63	-0.27

Table 4.4 Volumetric Properties for the Limestone/Gravel Mixes

Aggregate	N_{design}	PG Binder	Nominal Maximum Aggregate Size (mm)	Gradation	Design AC (%)	Volumetric / Compaction Properties: $\%G_{mm}$ at $N_{initial}$ Back-Calculated from:			$\%G_{mm}$ at N_{design}			$\%G_{mm}$ at $N_{maximum}$	VMA at N_{design}		
						N_{design}	$N_{maximum}$	Difference	Actual	Back-Calculated	Difference		Actual	Back-Calculated	Difference
Limestone /Gravel	96	67-22	12.5	Fine	4.3	87.12	87.18	-0.06	95.13	95.13	0.00	96.18	13.70	13.70	0.00
				Coarse	4.5	87.82	87.67	0.15	96.06	96.01	0.05	97.29	12.85	12.89	-0.04
			19	Fine	4.1	89.44	89.52	-0.08	96.88	96.91	-0.03	97.95	11.44	11.41	0.03
				Coarse	4.5	87.59	87.17	0.42	95.14	95.25	-0.11	96.47	12.67	12.57	0.10
		76-22	12.5	Fine	4.3	87.36	86.86	0.50	94.82	94.69	0.13	95.62	13.99	14.28	-0.29
				Coarse	4.6	87.23	86.97	0.26	95.47	95.20	0.27	96.32	13.59	13.84	-0.25
			19	Fine	4.5	89.06	88.75	0.31	96.46	96.08	0.38	96.98	11.86	12.20	-0.34
				Coarse	4.6	87.61	87.80	-0.19	95.28	95.51	-0.23	96.61	13.07	12.86	0.21
	119	67-22	12.5	Fine	4.0	87.71	87.57	0.14	95.52	95.45	0.07	96.58	12.71	12.77	-0.06
				Coarse	4.5	87.28	87.33	-0.05	95.62	95.79	-0.17	97.02	13.25	13.09	0.16
			19	Fine	4.0	88.70	88.04	0.66	96.89	96.49	0.40	97.71	11.22	11.58	-0.36
				Coarse	4.1	88.46	88.06	0.40	96.75	95.92	0.83	97.07	11.54	11.84	-0.30
		76-22	12.5	Fine	4.3	87.47	87.69	-0.22	95.17	95.37	-0.20	96.46	13.67	13.48	0.19
				Coarse	4.6	88.05	86.93	1.12	96.30	95.64	0.66	96.83	12.85	13.44	-0.59
			19	Fine	4.4	89.24	89.38	-0.14	96.62	96.63	-0.01	97.49	11.61	11.61	0.00
				Coarse	4.3	87.59	87.69	-0.10	95.23	95.40	-0.17	96.45	12.46	12.31	0.15

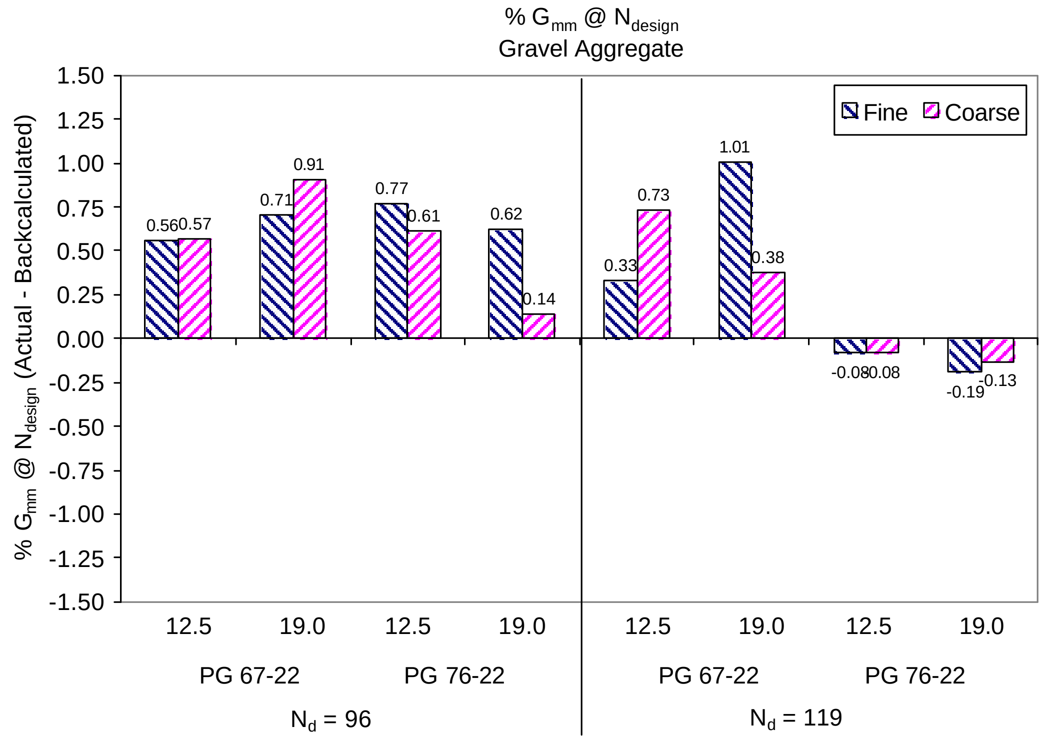

Figure 4.2 % G_{mm} at N_{design} Difference for Gravel Aggregate

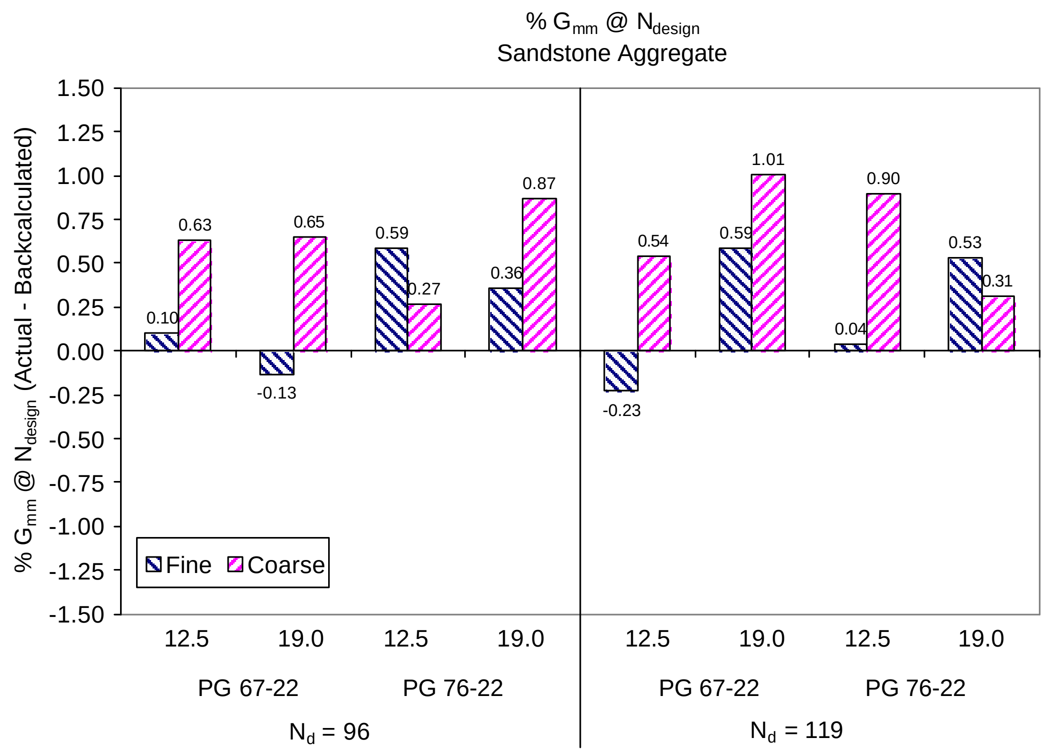

Figure 4.3 % G_{mm} at N_{design} Difference for Sandstone Aggregate

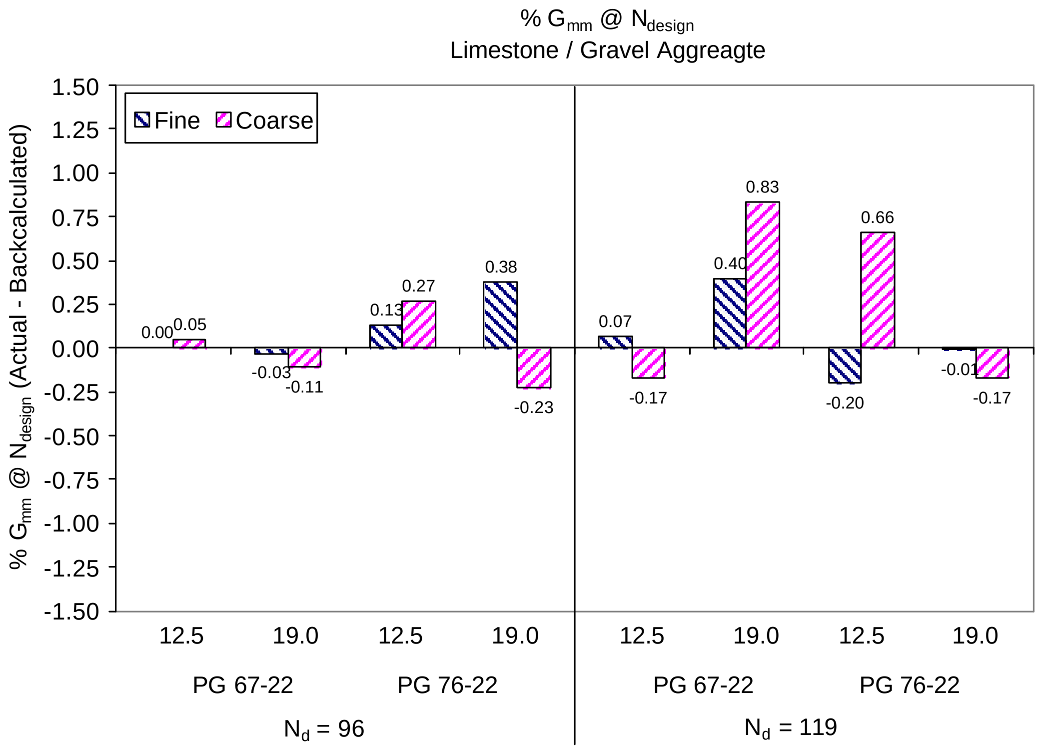

Figure 4.4 % G_{mm} at N_{design} Difference for Limestone/Gravel Aggregate

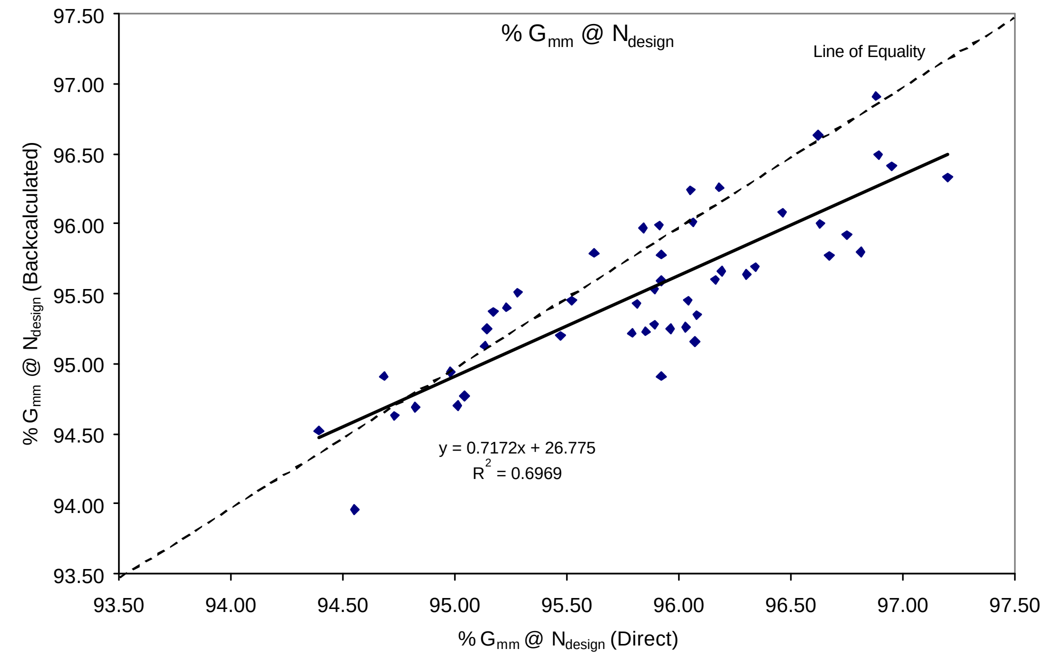

Figure 4.5 % G_{mm} at N_{design} (Back calculated versus Direct)

4.3.1.1 N_{design} Density Statistical Analysis

A multi-factor analysis of variance (ANOVA) was used to evaluate the study data. The response variables were: 1) N_{design} density difference, 2) VMA at N_{design} difference, and 3) $N_{initial}$ density difference (determined by back-calculation from N_{design} and $N_{maximum}$). All main factors (aggregate, N_{design}, PG, NMAS, and gradation) and their interactions were analyzed. All statistical analyzes were conducted at a level of significance of 5 percent using the Statistical Analysis System (SAS) Version 8.2 (9). In addition to the ANOVA, a Tukey's multiple comparison test was conducted for each response variable to determine the effects of the different factors.

ANOVA results for N_{design} density difference are provided in Table 4.5. It is evident from the analysis results that aggregate type is the most significant of the study factors. None of the other factors alone were determined to be significant, although gradation was close at a P-value of 0.081. Two-way interactions involving aggregate were significant with the exception of the aggregate*NMAS interaction. Other significant two-way interactions were PG*N_{design} and PG*NMAS. Only three of the 12 three-way interactions were determined to be significant.

Tukey's multiple comparison test results for the N_{design} density difference are provided in Table 4.6. From a review of the results, it is clear that the high significance of the aggregate factor is a result of the limestone/gravel aggregate mixes having a much lower density difference than the other two aggregates. As would be expected from the ANOVA results, there are no statistical differences among the study levels of PG, N_{design}, NMAS, and gradation.

Table 4.5 ANOVA Results for N_{design} Density Difference

Source	Degrees of Freedom	Mean Squares	F-stat	Prob > F-stat	Statistically Significant (Yes/No?)[1]
Aggregate	2	1.910	12.710	<0.0001	YES
PG	1	0.263	1.750	0.189	NO
Ndesign	1	0.269	1.800	0.183	NO
NMAS	1	0.093	0.620	0.434	NO
Gradation	1	0.466	3.110	0.081	NO
Agg*PG	2	0.948	6.330	0.003	YES
Agg*Ndesign	2	0.554	3.700	0.028	YES
Agg*NMAS	2	0.152	1.010	0.366	NO
Agg*Grad	2	0.865	5.780	0.004	YES
PG*Ndesign	1	1.100	7.350	0.008	YES
PG*NMAS	1	0.959	6.400	0.013	YES
PG*Grad	1	0.169	1.130	0.291	NO
Ndesign*NMAS	1	0.361	2.410	0.124	NO
Ndesign*Grad	1	0.223	1.490	0.225	NO
NMAS*Grad	1	0.482	3.220	0.076	NO
Agg*PG*Ndesign	2	0.055	0.370	0.689	NO
Agg*PG*NMAS	2	0.037	0.240	0.784	NO
Agg*PG*Grad	2	0.205	1.370	0.259	NO
Agg*Ndesign*NMAS	2	0.011	0.070	0.928	NO
Agg*Ndesign*Grad	2	0.029	0.190	0.824	NO
Agg*NMAS*Grad	2	0.065	0.440	0.648	NO
PG*Ndesign*NMAS	1	0.328	2.190	0.142	NO
PG*Ndesign*Grad	1	0.827	5.520	0.021	YES
PG*NMAS*Grad	1	0.056	0.380	0.541	NO
Ndesign*NMAS*Grad	1	0.662	4.430	0.031	YES
Agg*PG*Ndesign*NMAS	2	0.402	2.690	0.073	NO
Agg*PG*Ndesign*Grad	2	0.060	0.400	0.670	NO
Agg*Ndesign*NMAS*Grad	2	0.294	1.970	0.145	NO
Agg*PG*NMAS*Grad	2	0.540	3.610	0.031	YES
PG*Ndesign*NMAS*Grad	1	0.282	1.880	0.158	NO
Agg*PG*Ndesign*NMAS*Grad	2	0.002	0.020	0.903	NO
Model	47	0.336	2.720	<0.0001	YES
Error	96	0.149			

Note: 1) Conducted at a level of significance of 5 percent.

Table 4.6 Tukey's Multiple Comparison Test Results

Study Variable and Level		N_{design} Density Difference[2]	Tukey's Grouping[1]	$N_{initial}$ Density Difference[2]	Tukey's Grouping[1]	VMA Difference[2]	Tukey's Grouping[1]
Aggregate	Gravel	0.445	A	0.244	A	-0.384	B
	Sandstone	0.438	A	0.360	A	-0.393	B
	Limestone/Gravel	0.097	B	0.168	A	-0.088	A
PG	67	0.369	A	0.288	A	-0.332	A
	76	0.284	A	0.226	A	-0.245	A
N_{design}	96	0.370	A	0.290	A	-0.331	A
	119	0.283	A	0.225	A	-0.246	A
NMAS	12.5	0.301	A	0.232	A	-0.267	A
	19	0.352	A	0.283	A	-0.310	A
Gradation	Fine	0.270	A	0.196	A	-0.248	A
	Coarse	0.384	A	0.319	A	-0.328	A

Notes: 1) Level of significance = 5 percent. Levels with the same letter are not statistically different
2) N_{design} direct - N_{design} back calculated

4.3.2 Voids in Mineral Aggregate (VMA)

Also of interest is the change in the voids in the mineral aggregate (VMA) of specimens compacted to N_{design} and those back calculated from $N_{maximum}$. VMA is directly influenced by the change in the specimen G_{mb} value, as shown in the following VMA equation.

$$VMA = 100 - \left[\frac{Ps * Gmb}{Gsb}\right] * 100 \qquad \textit{Equation 4.1}$$

where,

VMA = Voids in the mineral aggregate,

P_s = Percent stone or aggregate in the mix,

G_{mb} = Bulk specific gravity of the compacted mix,

G_{sb} = Bulk specific gravity of the aggregate blend.

If a mix has a density at N_{design} direct that is greater than the density at N_{design} back calculated, the G_{mb} will obviously be higher. In the VMA equation a higher G_{mb} will produce a lower VMA value. Therefore, the relationship between VMA from specimens compacted directly to N_{design} and those back calculated from $N_{maximum}$ should follow the same trend as those for the N_{design} density analysis section.

Figures 4.6 through 4.8 illustrate the VMA differences for the gravel, sandstone, and limestone/gravel aggregate blends, respectively. From each of the figures, it is clear that the VMA trends are similar to those for the N_{design} density. Figure 4.9 illustrates the excellent relationship between the VMA at N_{design} direct and the VMA at N_{design} through back calculation from $N_{maximum}$. The regression line is almost parallel (slope = 1.026 compared to 1.000) to the line of equality. There exists a bias in the data, with the back calculated VMA being slightly higher than the direct calculated VMA.

4.3.2.1 VMA Statistical Analysis

The results of the VMA ANOVA are provided in Table 4.7. As expected the results agree well with those for the N_{design} density. The only exception is the significance of the two-way interaction of NMAS and gradation being significant, and the non-significance of the four-way interaction, AGG*PG*NMAS*GRAD.

Tukey's comparison results, shown in Table 4.6, indicate that the VMA differences for the limestone/gravel aggregate mixes are statistically different that those for the gravel and sandstone aggregate mixes. There were no statistical differences found between the project levels of PG, N_{design}, NMAS, or gradation.

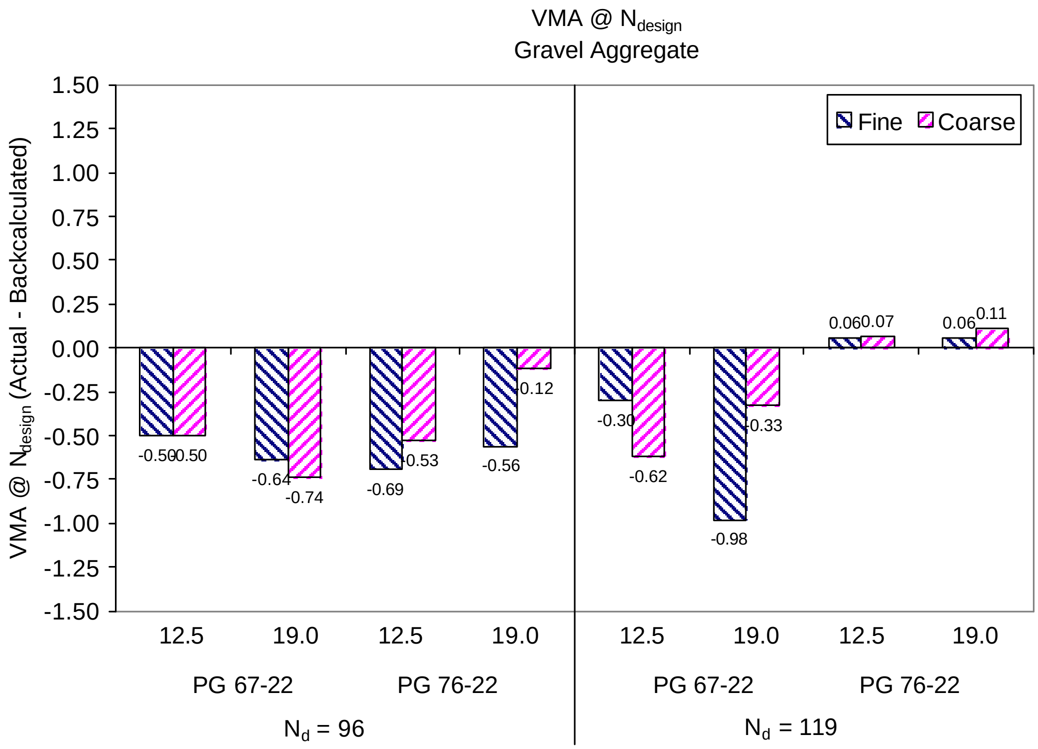

Figure 4.6 VMA Difference for Gravel Aggregate

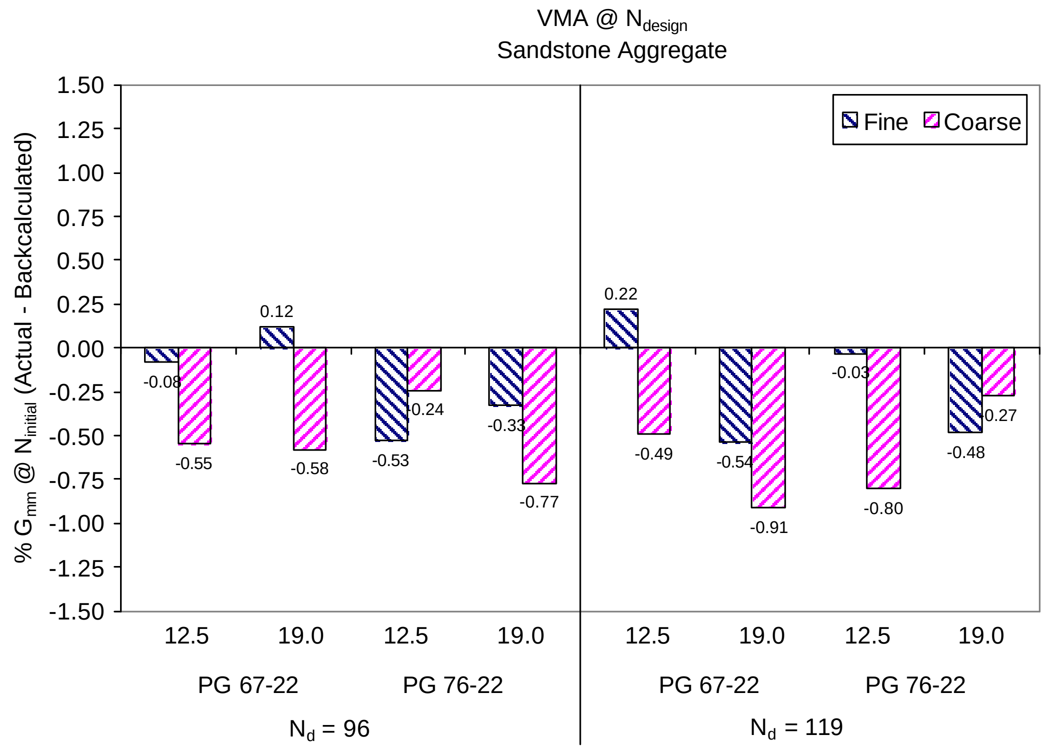

Figure 4.7 VMA Difference for Sandstone Aggregate

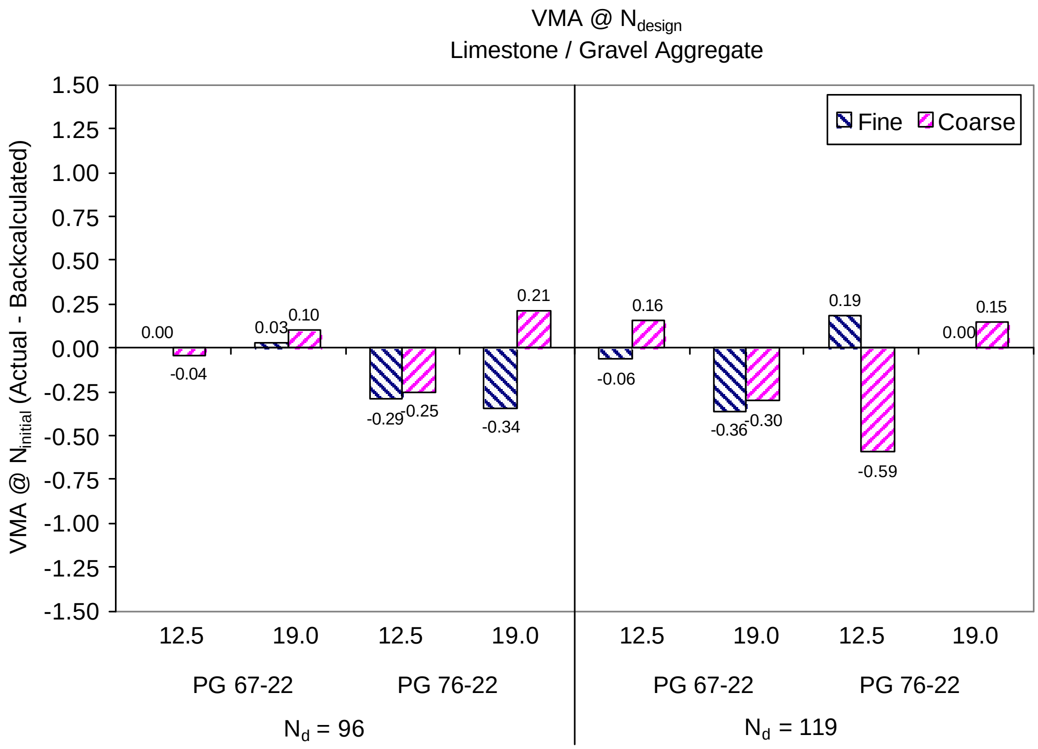

Figure 4.8 VMA Difference for Limestone/Gravel Aggregate

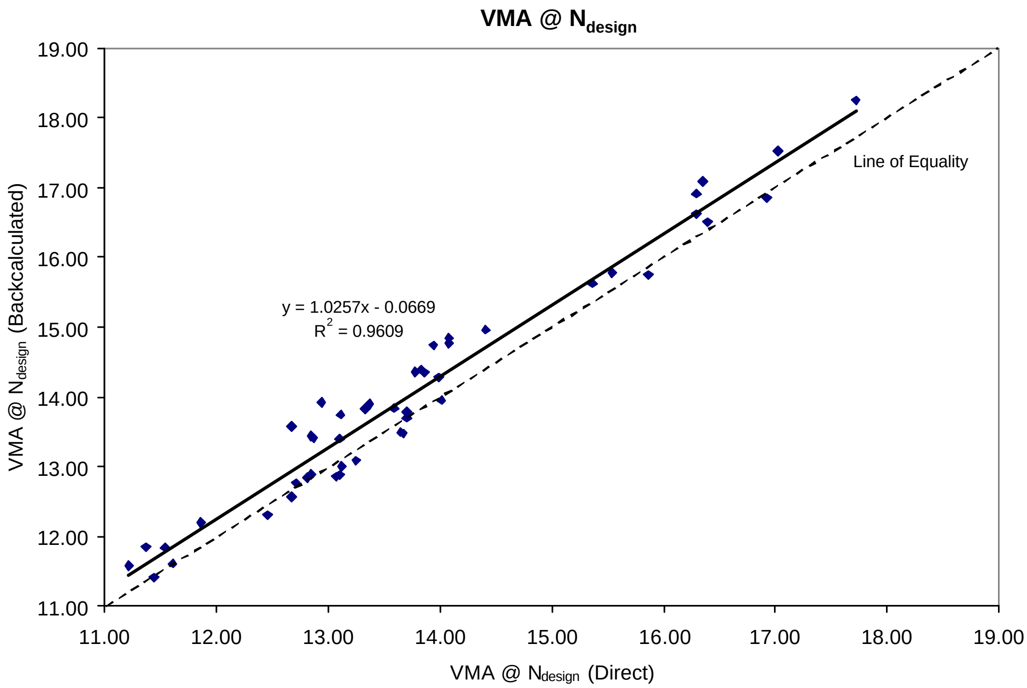

Figure 4.9 VMA (Back calculated versus Direct)

Table 4.7 ANOVA Results for VMA Difference

Source	Degrees of Freedom	Mean Squares	F-stat	Prob > F-stat	Statistically Significant (Yes/No?)[1]
Aggregate	2	1.443	11.690	<0.0001	YES
PG	1	0.273	2.210	0.140	NO
Ndesign	1	0.263	2.130	0.148	NO
NMAS	1	0.066	0.540	0.465	NO
Gradation	1	0.231	1.870	0.174	NO
Agg*PG	2	0.883	7.160	0.001	YES
Agg*Ndesign	2	0.543	4.400	0.015	YES
Agg*NMAS	2	0.134	1.080	0.342	NO
Agg*Grad	2	0.776	6.290	0.003	YES
PG*Ndesign	1	0.982	7.960	0.006	YES
PG*NMAS	1	0.917	7.430	0.008	YES
PG*Grad	1	0.158	1.280	0.261	NO
Ndesign*NMAS	1	0.236	1.910	0.170	NO
Ndesign*Grad	1	0.154	1.250	0.267	NO
NMAS*Grad	1	0.491	3.980	0.049	YES
Agg*PG*Ndesign	2	0.060	0.490	0.617	NO
Agg*PG*NMAS	2	0.038	0.310	0.738	NO
Agg*PG*Grad	2	0.162	1.320	0.273	NO
Agg*Ndesign*NMAS	2	0.030	0.240	0.786	NO
Agg*Ndesign*Grad	2	0.026	0.210	0.808	NO
Agg*NMAS*Grad	2	0.052	0.420	0.659	NO
PG*Ndesign*NMAS	1	0.328	2.660	0.106	NO
PG*Ndesign*Grad	1	0.574	4.650	0.034	YES
PG*NMAS*Grad	1	0.064	0.520	0.474	NO
Ndesign*NMAS*Grad	1	0.592	4.800	0.031	YES
Agg*PG*Ndesign*NMAS	2	0.267	2.160	0.120	NO
Agg*PG*Ndesign*Grad	2	0.046	0.370	0.690	NO
Agg*Ndesign*NMAS*Grad	2	0.228	1.850	0.163	NO
Agg*PG*NMAS*Grad	2	0.335	2.710	0.071	NO
PG*Ndesign*NMAS*Grad	1	0.204	1.650	0.197	NO
Agg*PG*Ndesign*NMAS*Grad	2	0.014	0.110	0.739	NO
Model	47	0.336	2.720	<0.0001	YES
Error	96	0.123			

Note: 1) Conducted at a level of significance of 5 percent.

4.3.3 $N_{initial}$ Density

The only valid method of determining density at $N_{initial}$ is to terminate compaction at $N_{initial}$ and determine the bulk specific gravity. However, this is not practical due to time and problems with the low mix stability at that low of a compaction level.

Current protocols involve back calculation $N_{initial}$ density from $N_{maximum}$. Back calculation would be required even if N_{design} is the terminal compaction effort. It is important to understand the magnitude of differences in $N_{initial}$ density as a result of back calculation from N_{design} relative to $N_{maximum}$ because specifications currently in place limit the amount of specimen densification which can occur at the $N_{initial}$ gyration level.

The N_{design} density of specimens compacted to N_{design} and those back calculated from $N_{maximum}$ are presented in Tables 4.2, 4.3, and 4.4. The average change in density for each of the mixes is also provided Figures in 4.10, 4.11, and 4.12 for the gravel, sandstone, and the limestone/gravel mixes, respectively.

Trends for each of the aggregates are generally similar to those for the N_{design} densities. For the gravel, sandstone, and limestone/gravel aggregate mixes approximately 88 percent, 82 percent, and 56 percent of the mixes had a density at $N_{initial}$ when back calculated from N_{design} that was higher than that back calculated from $N_{maximum}$. The reason for this once again involves the change in sample surface texture during compaction.

From Figure 4.10, almost all mixes show a positive density difference (i.e., $N_{initial}$ density from N_{design} direct greater than the $N_{initial}$ density back calculated from $N_{maximum}$). Any differences between fine and coarse-graded mixes are not clearly evident. As with the N_{design} density, there was little observed difference between 12.5 and 19.0 mm NMAS mixes, and a slightly lower difference for mixes compacted to the N_{design} of 119 relative to 96. The two mixes having a small positive density difference (average of 0.08 percent density) were PG 76 mixes.

The sandstone aggregate results, shown in Figure 4.11, are very similar to the gravel results in that almost all of the mixes show a positive density difference. There does not seem to be a distinguishable trend between any of the study factors. The average of the three mixes which had negative density differences was again very low (average of 0.32 percent).

Limestone/gravel results are shown in Figure 4.12 and agree with the results from the previous two aggregate types. As with the N_{design} density results, the magnitude of the density differences is generally less with the limestone/gravel aggregate. The mixes with negative density differences are once again very small in magnitude (average of 0.12 percent density) when compared to the positive difference mixes.

Figure 4.13 shows the relationship between the density at $N_{initial}$ back calculated from $N_{maximum}$ versus that back calculated from N_{design}. The regression line is parallel (slope = 1.011) and slightly offset to the line of equality. The results indicate that the $N_{initial}$ density back calculated from $N_{maximum}$ is slightly less than the $N_{initial}$ density back calculated from N_{design}.

4.3.3.1 $N_{initial}$ Density Statistical Analysis

The ANOVA results for $N_{initial}$ density differences are provided in Table 4.8. From Table 4.8, it appears that none of the study factors are statistically significant. However, the two-way interactions of PG*N_{design} and PG*NMAS and the three-way interactions of PG*N_{design}*Grad and N_{design}*NMAS*Grad are significant.

Tukey's multiple comparison test results for the $N_{initial}$ density difference are provided in Table 4.6. While the ANOVA results showed there to be a slight significant difference in the project data (P-value of 0.0495 at a level of significance of 0.05), the results of the Tukey's analysis do not indicate any significant difference between the overall study factors of aggregate, PG, Ndesign, NMAS, and gradation.

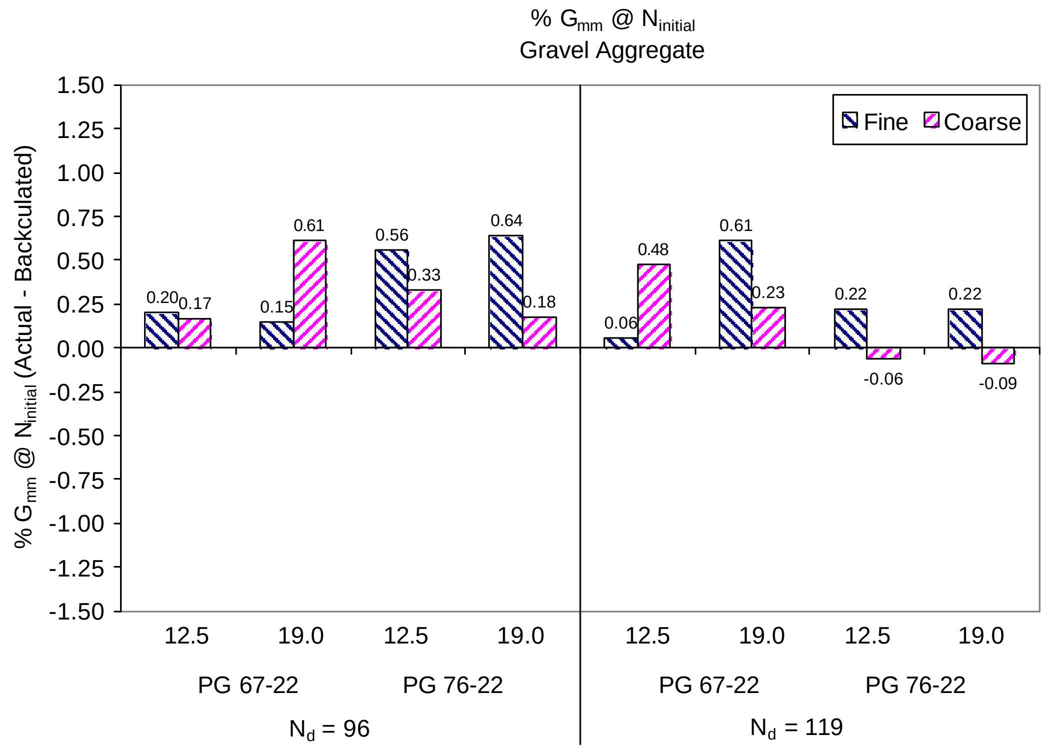

Figure 4.10 % G_{mm} at $N_{initial}$ Difference for Gravel Aggregate

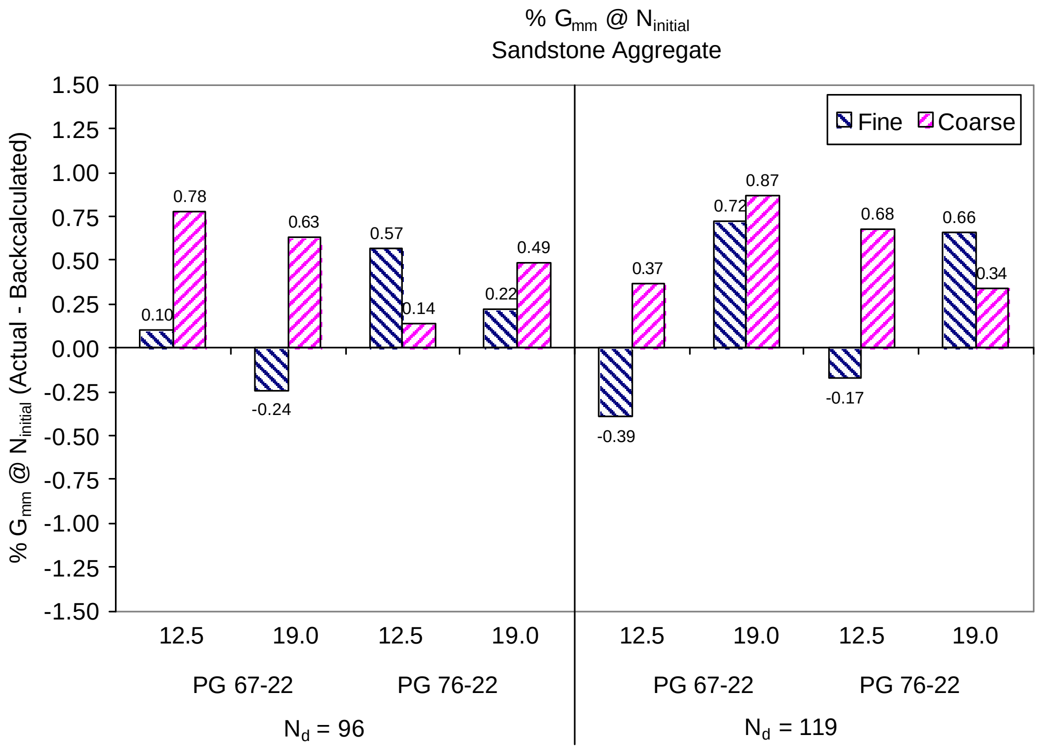

Figure 4.11 % G_{mm} at $N_{initial}$ Difference for Sandstone Aggregate

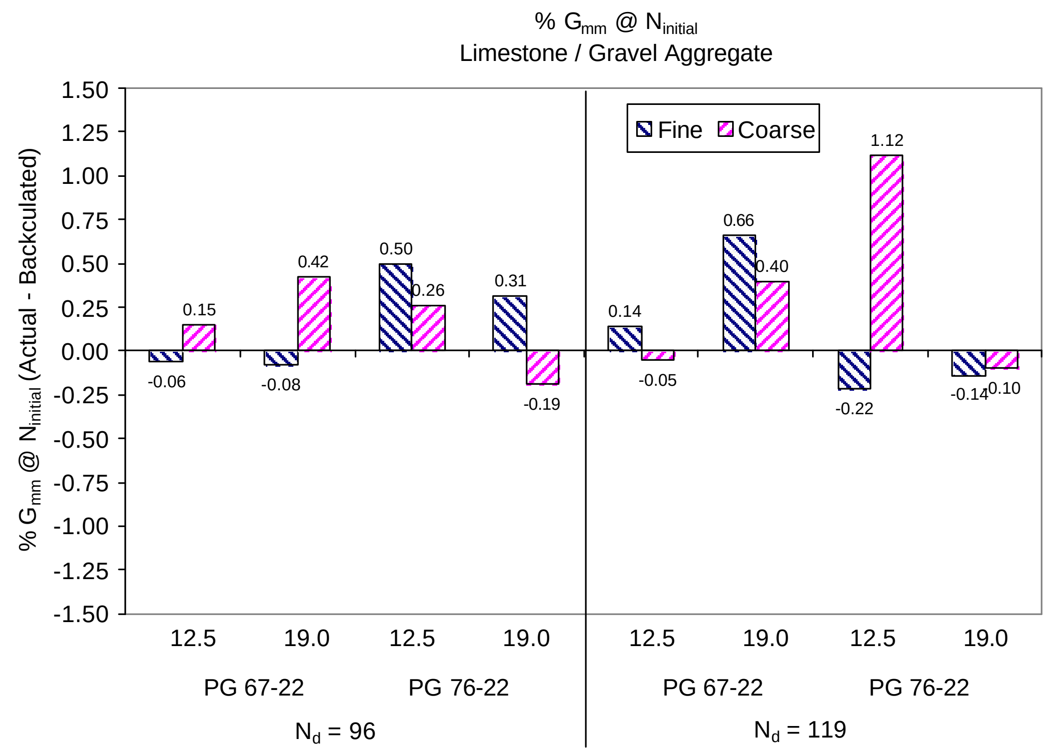

Figure 4.12 % G_{mm} at $N_{initial}$ Difference for Limestone/Gravel Aggregate

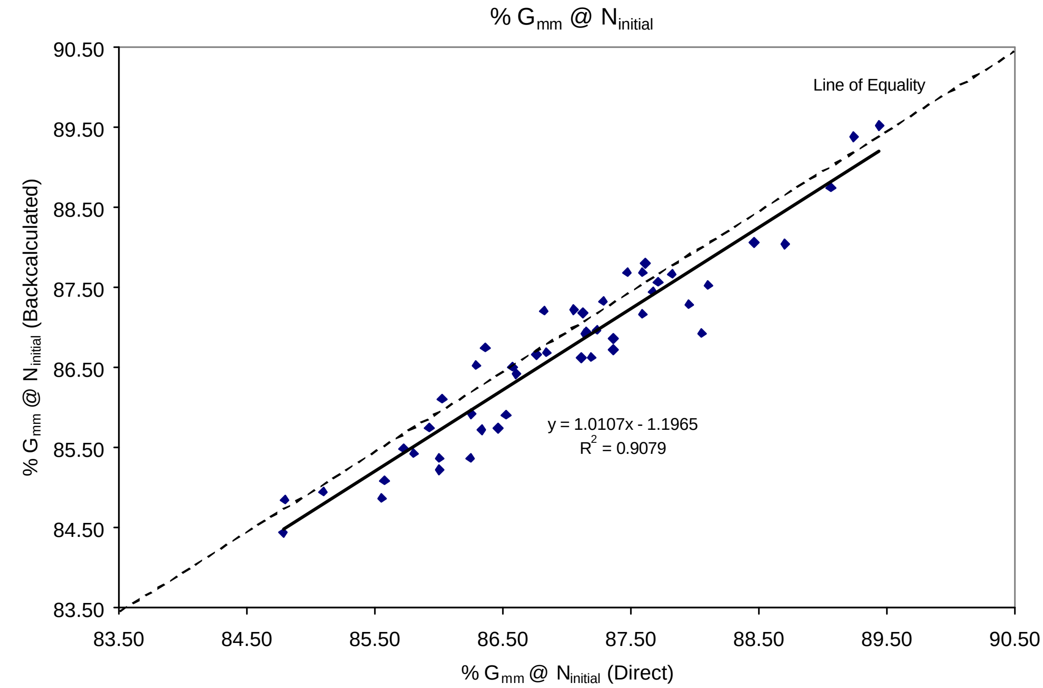

Figure 4.13 % G_{mm} at $N_{initial}$ (Back calculated versus Direct)

Table 4.8 ANOVA Results for $N_{initial}$ Density Difference

Source	Degrees of Freedom	Mean Squares	F-stat	Prob > F-stat	Statistically Significant (Yes/No?)[1]
Aggregate	2	0.447	2.100	0.1275	NO
PG	1	0.139	0.650	0.421	NO
Ndesign	1	0.153	0.730	0.395	NO
NMAS	1	0.094	0.440	0.509	NO
Gradation	1	0.544	0.280	0.758	NO
Agg*PG	2	0.078	0.370	0.693	NO
Agg*Ndesign	2	0.234	1.100	0.336	NO
Agg*NMAS	2	0.206	0.970	0.384	NO
Agg*Grad	2	0.483	2.270	0.108	NO
PG*Ndesign	1	0.863	4.070	0.047	YES
PG*NMAS	1	1.208	5.690	0.019	YES
PG*Grad	1	0.663	3.120	0.081	NO
Ndesign*NMAS	1	0.457	2.120	0.146	NO
Ndesign*Grad	1	0.081	0.380	0.539	NO
NMAS*Grad	1	0.129	0.610	0.438	NO
Agg*PG*Ndesign	2	0.188	0.890	0.415	NO
Agg*PG*NMAS	2	0.116	0.550	0.580	NO
Agg*PG*Grad	2	0.198	0.930	0.397	NO
Agg*Ndesign*NMAS	2	0.505	2.380	0.098	NO
Agg*Ndesign*Grad	2	0.017	0.080	0.921	NO
Agg*NMAS*Grad	2	0.036	0.170	0.844	NO
PG*Ndesign*NMAS	1	0.522	2.460	0.120	NO
PG*Ndesign*Grad	1	1.519	7.150	0.009	YES
PG*NMAS*Grad	1	0.061	0.290	0.593	NO
Ndesign*NMAS*Grad	1	1.066	5.020	0.027	YES
Agg*PG*Ndesign*NMAS	2	0.059	0.280	0.758	NO
Agg*PG*Ndesign*Grad	2	0.107	0.510	0.605	NO
Agg*Ndesign*NMAS*Grad	2	0.252	1.190	0.304	NO
Agg*PG*NMAS*Grad	2	0.515	2.430	0.094	NO
PG*Ndesign*NMAS*Grad	1	0.245	1.160	0.319	NO
Agg*PG*Ndesign*NMAS*Grad	2	0.037	0.170	0.677	NO
Model	47	0.32	1.49	0.0495	YES
Error	96	0.212			

Note: 1) Conducted at a level of significance of 5 percent.

4.4 MIX DESIGN EFFECTS

The effect of density differences at N_{design} is a possible change in design asphalt content (DAC) for the given mixes. Mixes with higher densities at N_{design}, as a result of compacting the mix design specimens directly to N_{design}, will have lower design asphalt content. Likewise, mixes with lower densities at N_{design} will likely yield slightly higher design asphalt contents. Magnitude of the design asphalt content change will obviously be a function of the magnitude of the density differences. The average change in the design asphalt content and VMA for the gravel, sandstone, and limestone/gravel mixes is illustrated in Figures 4.14, 4.15, and 4.16. Table 4.9 provides a summary of the average change in DAC.

Table 4.9 Summary Results for Design Asphalt Content Percent Change

Property	Average Percent Change in DAC and VMA (N_{design} Direct - N_{design} Back Calculated)											
	Overall	Aggregate			PG		N_{design}		NMAS, mm		Gradation	
		Gravel	Sandstone	Limestone	67	76	96	119	12.5	19	Fine	Coarse
DAC	-0.14	-0.18	-0.17	-0.05	-0.17	-0.10	-0.15	-0.12	-0.16	-0.11	-0.14	-0.13
VMA	-0.29	-0.38	-0.39	-0.09	-0.33	-0.24	-0.33	-0.25	-0.27	-0.31	-0.25	-0.33

As expected from the review of the N_{design} density data, the gravel and sandstone aggregate mixes have a greater decrease in design asphalt content than the limestone/gravel mixes. The average changes in design asphalt content for all study factors are negative and range from 0.10 to 0.17 percent. As expected, based on the N_{design} density data, the gravel and the sandstone aggregates show the largest design asphalt content change at 0.18 and 0.17 percent, respectively. The largest decrease in design asphalt content for any of the mixes in the study was 0.43 percent, for the 19.0 mm NMAS limestone/gravel blend with the PG 67-22 binder, with the overall study average in design asphalt content change is a decrease of 0.14 percent, as shown in Table 4.9. The corresponding overall VMA change was a decrease of 0.29 percent.

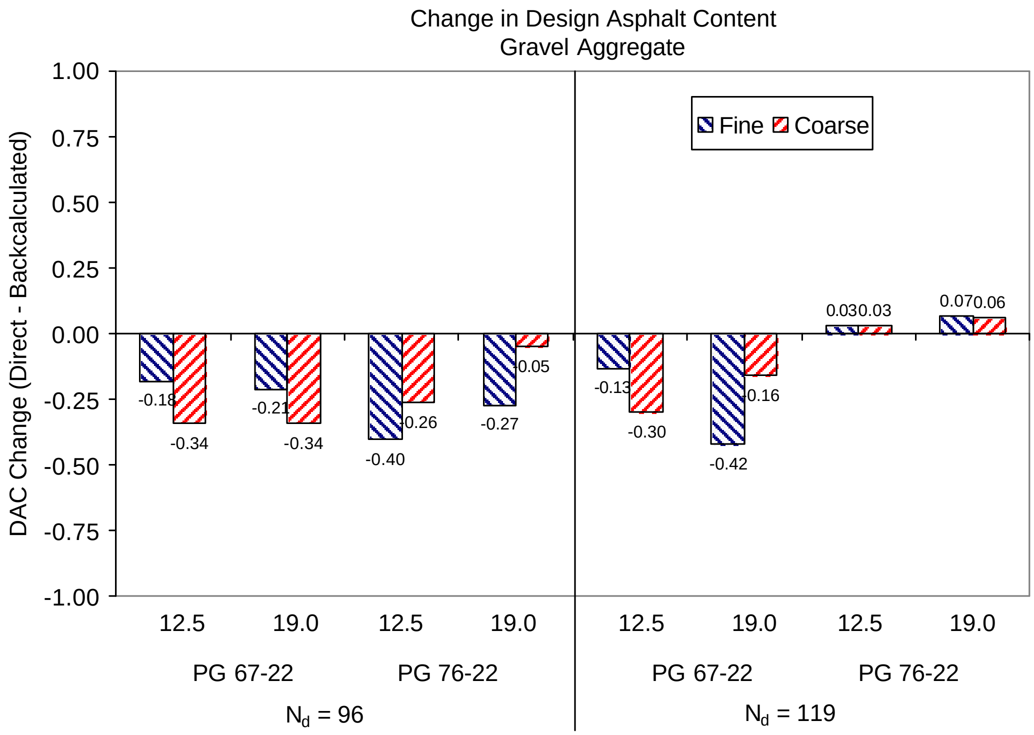

Figure 4.14 Change in Design Asphalt Content for Gravel Mixes

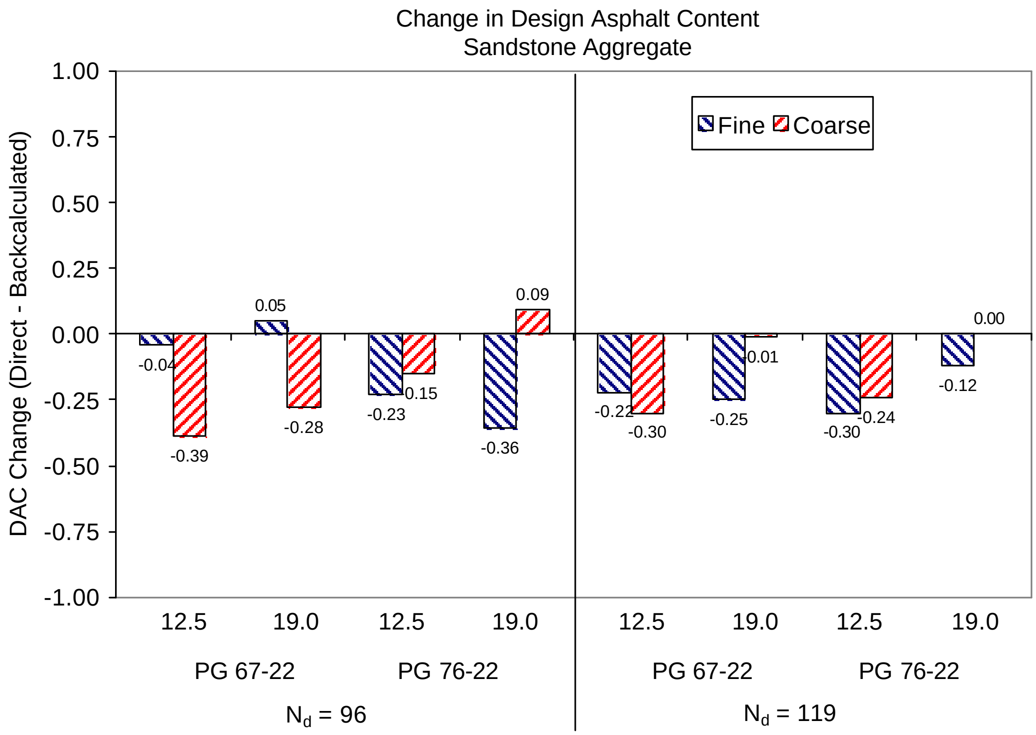

Figure 4.15 Change in Design Asphalt Content for Sandstone Mixes

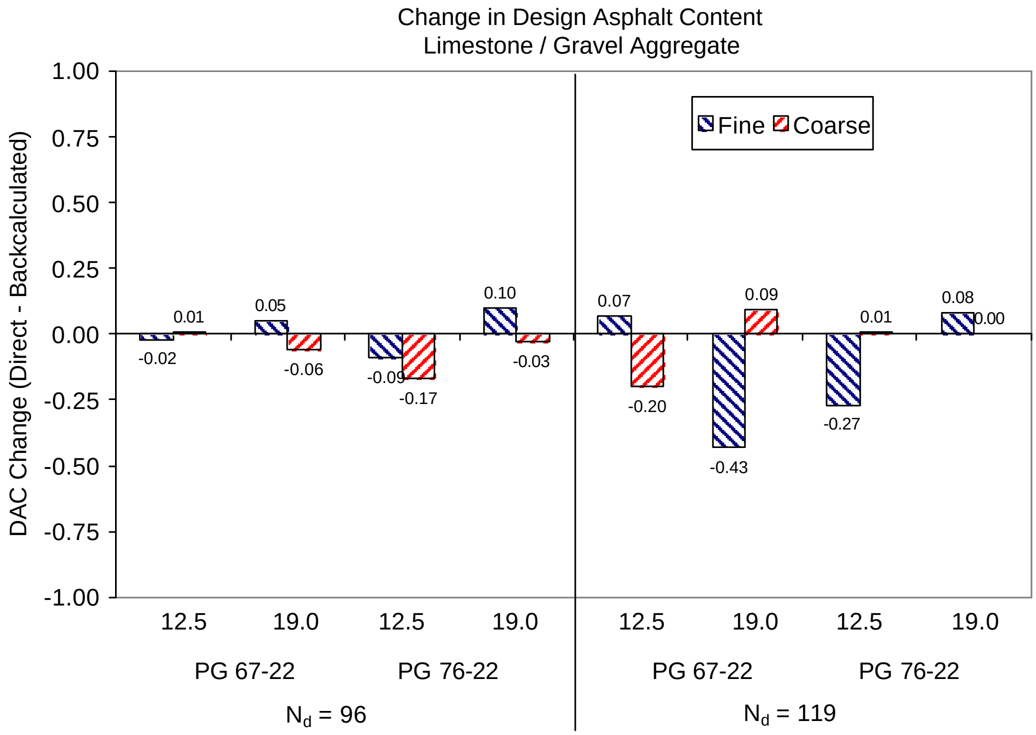

Figure 4.16 Change in Design Asphalt Content for Limestone/Gravel Mixes

4.5 COMPARISON OF WATER DISPLACEMENT AND CORELOK G_{MB} PROCEDURES

The Corelok vacuum sealing device was used to determine the G_{mb} of all compacted specimens (mix design and design asphalt content specimens). Corelok testing was conducted in response to observed variability in mix design results, especially for coarse-graded mixes. In the following sections of the report, background information on the Corelok procedure and discussions of G_{mb} differences between water displacement and Corelok vacuum sealing procedures and resulting changes in volumetric properties and optimum asphalt contents for the study mix designs will be presented.

4.5.1 Corelok Background

For many years, G_{mb} measurement has been accomplished by weighing compacted specimens in air and water, commonly referred to as water displacement. The test procedures for water displacement are provided in AASHTO T-166 (*10*) or ASTM D2726 (*11*). Both procedures consist of first weighing dry compacted specimens in air, then obtaining a submerged mass after the specimen has been placed in a water bath for 3 to 5 minutes, and finally weighing the specimen in a saturated surface-dry (SSD) condition. In these procedures, specimen volume is determined, through Archimedes principle, as the difference between SSD and submerged masses. The G_{mb} is obtained by dividing the specimen dry mass by the determined volume, multiplied by the density of water.

In water displacement test procedures, water absorption during testing is calculated and must be less than 2.0 percent. Water absorption is calculated by dividing the difference between SSD and dry specimen masses by the difference between SSD and submerged specimen masses. If water absorption exceeds 2.0 percent, an alternate method of G_{mb} evaluation (i.e., parafilm coated specimens) must be utilized. Water displacement procedures yield accurate G_{mb} for most conventional dense-graded mixes. However, with the advent of coarser, open-graded gradations, such as open-graded friction courses (OGFC), stone matrix asphalt (SMA), and coarse-graded Superpave mixes; research (*8*, *12*) has shown errors in G_{mb} measurement using water displacement methods, even when water absorption levels are less than 2.0 percent.

With compacted HMA mixes, the internal air voids occur between coated aggregate particles. However, with coarser, more open-graded mixes, these voids are larger and tend to be interconnected, leading to errors when using the water displacement method. Water readily permeates these interconnected larger voids during testing. Penetrating water reduces the calculated sample void volume, leading to a G_{mb} value that is too high, and therefore, calculated air voids that are too low.

In the past several years, vacuum sealing technology, using the Corelok device, as shown in Figure 4.17, has been used by a number of researchers and transportation agencies to determine HMA G_{mb}. ASTM D6752 "Standard Test Method for Bulk Specific Gravity and Density of Compacted Bituminous Mixtures Using Automatic Vacuum Sealing Method" (*13*) has recently been approved outlining the G_{mb} determination procedure with the Corelok device.

Buchanan (*12*) concluded the Corelok procedure can determine G_{mb} more accurately than conventional methods such as water displacement, parafilm, and dimensional analysis (i.e., mass / volume). There should be no instance where a Corelok G_{mb} is greater than a water displacement G_{mb}. As the specimen's air voids and surface texture decreases, results of Corelok and water displacement procedures should approach the same value.

Crouch et al (*14*) reported the Corelok procedure to be a widely applicable method of G_{mb} determination. Results from a recent round robin study (*8*) conducted by the National Center for Asphalt Technology (NCAT) showed the Corelok procedure to be a viable method for determining the G_{mb} of HMA mixes. It was further stated that the Corelok procedure provided a more accurate measure of G_{mb}, especially for mixes with high water absorption levels during water displacement procedures. The study (*8*) recommended determining G_{mb} with the Corelok procedure for coarse-graded mixes when water absorption levels exceed 0.4 percent. It was recommended that water displacement be used for fine graded specimens with water absorptions less than 2.0 percent, which is how current specifications (T166 and D2726) are written. The report goes on to recommend that since a significant portion of the coarse-graded mix design specimens will likely exceed the 0.4 percent water absorption level, the Corelok method

Figure 4.17 Corelok Vacuum Sealing Device

should be used for design and quality control testing of coarse-graded mixes. This recommendation was based on approximately 41 percent of coarse-graded mixes having water absorption levels exceeding 2 percent when evaluated at an N_{design} of 100 gyrations.

4.5.2 Corelok Operation

Determining G_{mb} using the Corelok procedure is described in the following steps (*15*).

1. Use the plastic specimen bag predetermined nominal density or determine the density using a standard aluminum reference cylinder provided.
2. Place the compacted HMA specimen (either core or laboratory compacted specimen) into the bag.
3. Place the bag and specimen inside the Corelok vacuum chamber.
4. Close the vacuum chamber door at which time the vacuum pump will start and evacuate the chamber to 760 mm (30 in) Hg.
5. In approximately two minutes, the chamber door will automatically open with the specimen completely sealed within the bag and ready for water displacement testing. User should insure that the bag seal is secure prior to going to step 6.
6. Perform water displacement method testing of the sealed specimen according to either AASHTO or ASTM standards. Correct the results for the bag density and the displaced bag volume as suggested by ASTM D1188 (*16*).

4.5.3 Comparison of Water Displacement and Corelok G_{mb} for Mix Design Specimens

Relationships between water displacement and Corelok determined G_{mb} values for fine and coarse-graded mix design specimens are illustrated in Figure 4.18. Both fine and coarse-graded specimens have excellent relationships between Corelok and water displacement G_{mb} (R^2 = 0.97 and 0.98, respectively). The Corelok procedure yields consistently lower G_{mb} values (higher air voids). Figure 4.18 shows coarse-graded mixes to have a slightly larger difference than fine-graded mixes. This agrees with

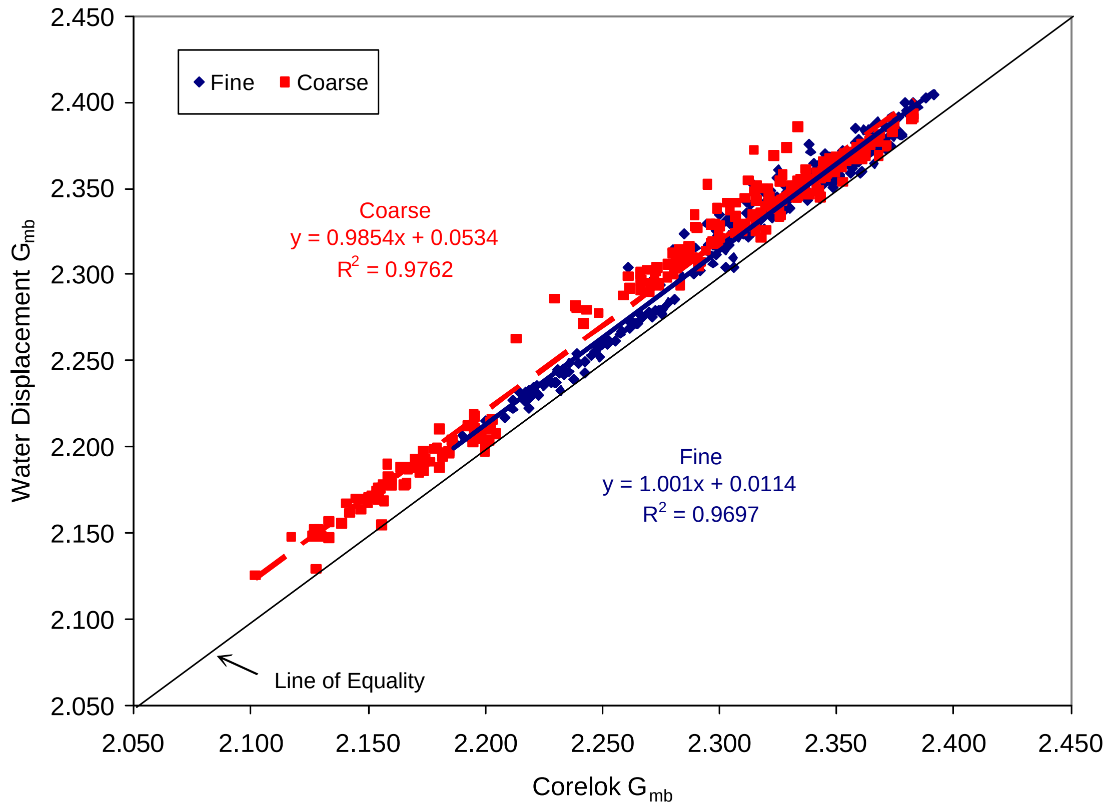

Figure 4.18 Water Displacement vs Corelok G_{mb}

past research (8,12) that showed coarse-graded mixes have larger differences than fine-graded mixes.

Only 6 of the 534 (1.1 percent) mix design specimens had a Corelok G_{mb} greater than the water displacement G_{mb}, with the differences, in each case, being very small and likely due to testing variability. The average G_{mb} difference for fine and coarse-graded mixes were 0.0133 and 0.0197, respectively. This corresponds to air void changes of 0.53 and 0.80 percent.

The relationship between water absorption and G_{mb} values for the two procedures is shown in Figure 4.19. Both relationships are marginal (R^2 = 0.39 for water displacement and R^2 = 0.43 for Corelok), but the difference between the two methods decreases slightly as G_{mb} increases and water absorption decreases. This is expected since water absorption is related to the specimen's internal air void structure. Higher water absorptions result in more water entering the specimen's during water displacement testing which reduces the specimen volume and yields a G_{mb} value that is too high. These results also agree closely with results from NCAT's study (8).

To evaluate NCAT's recommendation (8) on mix design (fine and coarse) specimens, relationships between air voids, as determined with the Corelok and water displacement procedures, and water absorption were developed and are provided in Figure 4.20. Separate relationships were established for fine and coarse-graded mixes. Results indicate fair correlation (R^2 from 0.64 to 0.71) between air voids and water absorption for each data set. The data also shows the expected larger air void difference between Corelok and water displacement procedures for coarse-graded mixes, relative to fine-graded mixes. The NCAT recommended using the Corelok procedure for coarse-graded mixes with water absorption levels greater than 0.4 percent. From Figure 4.20, it appears that the 0.4 percent absorption level is near where the air void differences increase. Using the recommended 0.4 percent water absorption criteria for coarse-graded mixes, approximately 48.5 percent of coarse-graded specimens had water absorption levels greater than 0.4 percent. This is in good agreement with the 41 percent value reported by the NCAT study (8). This emphasizes the need

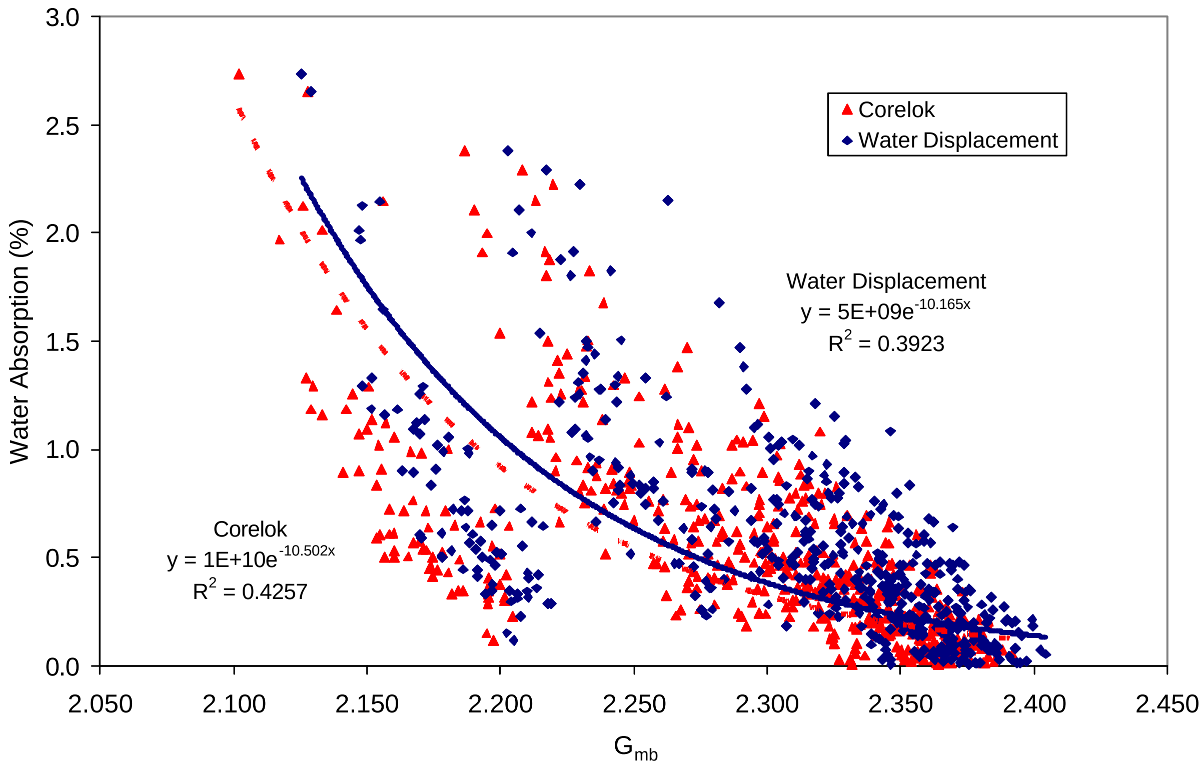

Figure 4.19 Water Absorption versus G_{mb}

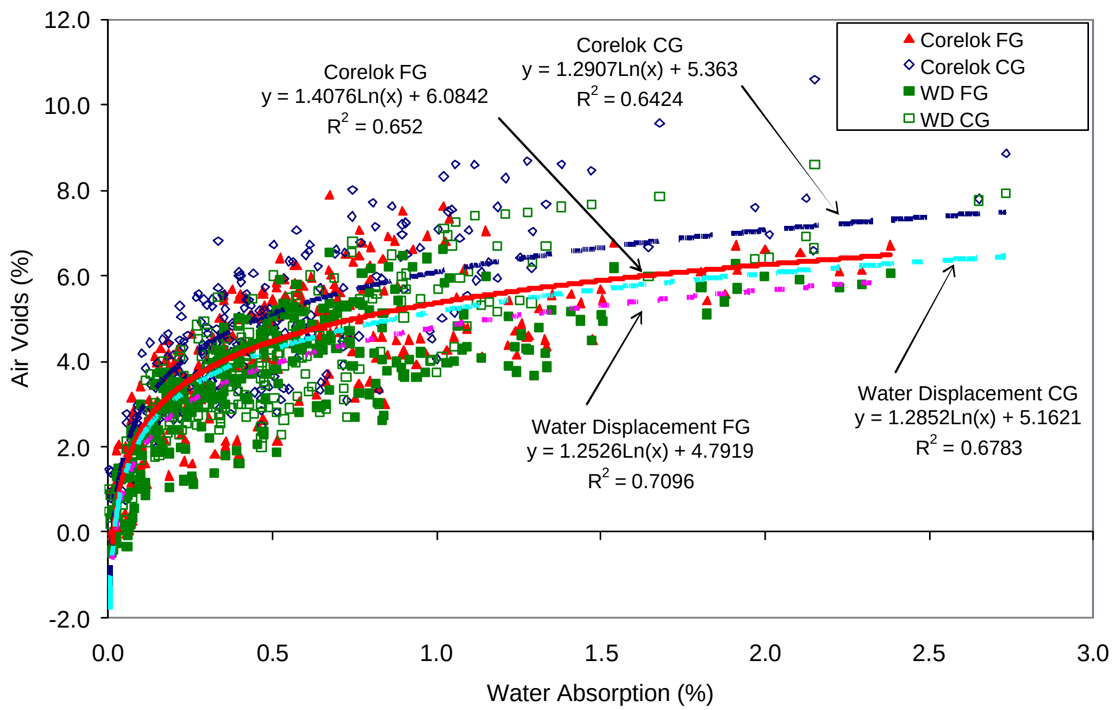

Figure 4.20 Air Voids versus Water Absorption

to use the Corelok procedure during mix design of coarse-graded mixes, as some design specimens may exceed 0.4 percent absorption, while others may not.

As expected, for fine-graded mixes, differences were less than coarse-graded mixes, with the average difference between Corelok and water displacement procedures for water absorptions less than 2 percent being approximately the same as those above 2 percent. For these mix design specimens, it does not appear that the 2 percent absorption level delineates larger air void differences from smaller air void differences. Only 1.5 percent of fine-graded mixes had water absorption levels greater than 2.0 percent, which agrees with NCAT's findings (*8*) where none of the fine-graded specimens had water absorptions greater than 2 percent.

4.5.4 Comparison of Water Displacement and Corelok G_{mb} at Design Asphalt Content

To further understand factors influencing differences between the two G_{mb} procedures, three specimens were compacted at the selected design asphalt content. This work simulates the QC/QA testing of specimens for laboratory density. Average G_{mb} of these specimens, determined using Corelok and water displacement procedures, are provided in Table 4.10. Also in Table 4.10, are paired t-test comparison results [t-calc, p-value, and statistical significance at a level of significance (LOS) of 5 percent] for each mix. From Table 4.10, differences between Corelok and water displacement G_{mb} were statistically significant for 40 of 48 mixes (83 percent). Of the eight mixes determined not to have a significant difference, five were fine-graded mixes, which was expected. The G_{mb} differences ranged from 0.002 to 0.047, corresponding to an air void difference of 0.08 to 3.0 percent, respectively. An ANOVA was conducted, at a LOS of 5 percent, to determine statistical significance of study factors with regards to G_{mb}, air voids, and VMA difference between Corelok and water displacement procedures. ANOVA results are provided in Table 4.11, 4.12, and 4.13 for the G_{mb}, air voids, and VMA difference, respectively.

The ANOVA results for G_{mb} differences indicate all main level factors, with the exception of NMAS, are significant, with gradation being the most significant followed by aggregate type. Several interactions were also deemed significant and in most cases

Table 4.10 Paired t-Tests Results for Corelok and Water Displacement G_{mb}

Aggregate	N_{design}	PG	NMAS	Gradation	G_{mb} Corelok	G_{mb} Water Displacement	G_{mb} Difference[1]	t-calc	p-value	Significant?[2]
Gravel	96	67	12.5	Fine	2.247	2.256	-0.009	22.72	0.00190	YES
Gravel	96	67	12.5	Coarse	2.183	2.194	-0.011	8.76	0.01270	NO
Gravel	96	67	19.0	Fine	2.232	2.244	-0.012	19.54	0.00260	YES
Gravel	96	67	19.0	Coarse	2.169	2.189	-0.020	71.06	0.00002	YES
Gravel	96	76	12.5	Fine	2.235	2.242	-0.007	2.14	0.16570	NO
Gravel	96	76	12.5	Coarse	2.154	2.170	-0.016	33.43	0.00089	YES
Gravel	96	76	19.0	Fine	2.215	2.230	-0.015	75.63	0.00017	YES
Gravel	96	76	19.0	Coarse	2.160	2.177	-0.017	5.91	0.02720	YES
Gravel	119	67	12.5	Fine	2.249	2.256	-0.007	54.17	0.00034	YES
Gravel	119	67	12.5	Coarse	2.196	2.207	-0.011	9.19	0.01160	YES
Gravel	119	67	19.0	Fine	2.235	2.246	-0.011	16.39	0.00369	YES
Gravel	119	67	19.0	Coarse	2.167	2.187	-0.020	22.49	0.00197	YES
Gravel	119	76	12.5	Fine	2.239	2.245	-0.006	1.63	0.24400	NO
Gravel	119	76	12.5	Coarse	2.164	2.182	-0.018	7.57	0.01698	YES
Gravel	119	76	19.0	Fine	2.221	2.234	-0.013	4.98	0.03800	YES
Gravel	119	76	19.0	Coarse	2.165	2.184	-0.019	27.36	0.00130	YES
Sandstone	96	67	12.5	Fine	2.314	2.325	-0.011	7.66	0.01670	YES
Sandstone	96	67	12.5	Coarse	2.336	2.347	-0.011	5.40	0.03250	YES
Sandstone	96	67	19.0	Fine	2.321	2.334	-0.013	4.58	0.04440	YES
Sandstone	96	67	19.0	Coarse	2.336	2.351	-0.015	13.34	0.00557	YES
Sandstone	96	76	12.5	Fine	2.318	2.337	-0.019	4.80	0.04070	YES
Sandstone	96	76	12.5	Coarse	2.280	2.314	-0.034	12.48	0.00635	YES
Sandstone	96	76	19.0	Fine	2.356	2.368	-0.012	5.19	0.03520	YES
Sandstone	96	76	19.0	Coarse	2.340	2.355	-0.015	4.62	0.04380	YES
Sandstone	119	67	12.5	Fine	2.325	2.334	-0.009	11.04	0.00809	YES
Sandstone	119	67	12.5	Coarse	2.280	2.314	-0.034	12.48	0.00636	YES
Sandstone	119	67	19.0	Fine	2.325	2.339	-0.014	5.99	0.02676	YES
Sandstone	119	67	19.0	Coarse	2.353	2.373	-0.020	2.99	0.09580	YES
Sandstone	119	76	12.5	Fine	2.327	2.341	-0.014	24.27	0.00169	YES
Sandstone	119	76	12.5	Coarse	2.342	2.356	-0.014	31.29	0.00100	YES
Sandstone	119	76	19.0	Fine	2.351	2.379	-0.028	4.92	0.03897	YES
Sandstone	119	76	19.0	Coarse	2.284	2.312	-0.028	4.68	0.04273	YES
Limestone	96	67	12.5	Fine	2.304	2.306	-0.002	1.94	0.19210	NO
Limestone	96	67	12.5	Coarse	2.279	2.306	-0.027	7.49	0.01730	YES
Limestone	96	67	19.0	Fine	2.342	2.357	-0.015	23.55	0.00179	YES
Limestone	96	67	19.0	Coarse	2.288	2.320	-0.032	28.50	0.00122	YES
Limestone	96	76	12.5	Fine	2.283	2.298	-0.015	5.53	0.03117	YES
Limestone	96	76	12.5	Coarse	2.259	2.288	-0.029	5.00	0.03770	YES
Limestone	96	76	19.0	Fine	2.339	2.355	-0.016	8.25	0.01437	YES
Limestone	96	76	19.0	Coarse	2.289	2.320	-0.031	28.50	0.00122	YES
Limestone	119	67	12.5	Fine	2.307	2.325	-0.018	3.66	0.06720	NO
Limestone	119	67	12.5	Coarse	2.273	2.296	-0.023	15.34	0.00422	YES
Limestone	119	67	19.0	Fine	2.343	2.360	-0.017	15.51	0.00413	YES
Limestone	119	67	19.0	Coarse	2.352	2.373	-0.021	2.99	0.09580	NO
Limestone	119	76	12.5	Fine	2.282	2.307	-0.025	3.14	0.08790	NO
Limestone	119	76	12.5	Coarse	2.309	2.356	-0.047	4.72	0.04200	YES
Limestone	119	76	19.0	Fine	2.343	2.359	-0.016	15.25	0.00427	YES
Limestone	119	76	19.0	Coarse	2.303	2.329	-0.026	4.01	0.05680	NO

Notes: 1) Corelok - Water Displacement; 2) Level of Significance = 5 percent

Table 4.11 ANOVA Results for G_{mb} (Corelok – Water Displacement)

Source	Degrees of Freedom	Mean Squares	F-stat	Prob > F-stat	Statistically Significant (Yes/No?)[1]
Aggregate	2	0.001165	34.29	<0.0001	YES
PG	1	0.000445	13.08	0.0005	YES
Ndesign	1	0.000298	8.76	0.0039	YES
NMAS	1	0.000098	2.89	0.0922	NO
Gradation	1	0.003335	98.13	<0.0001	YES
Agg*PG	2	0.000061	1.80	0.1700	NO
Agg*Ndesign	2	0.000088	2.60	0.0797	NO
Agg*NMAS	2	0.000117	3.43	0.0364	YES
Agg*Grad	2	0.000342	10.08	0.0001	YES
PG*Ndesign	1	0.000012	0.34	0.5592	NO
PG*NMAS	1	0.000228	6.69	0.0112	YES
PG*Grad	1	0.000011	0.31	0.5785	NO
Ndesign*NMAS	1	0.000000	0.00	0.9886	NO
Ndesign*Grad	1	0.000000	0.01	0.9205	NO
NMAS*Grad	1	0.000095	2.80	0.0977	NO
Agg*PG*Ndesign	2	0.000040	1.18	0.3126	NO
Agg*PG*NMAS	2	0.000201	5.90	0.0038	YES
Agg*PG*Grad	2	0.000031	0.90	0.4093	NO
Agg*Ndesign*NMAS	2	0.000250	7.36	0.0011	YES
Agg*Ndesign*Grad	2	0.000052	1.54	0.2194	NO
Agg*NMAS*Grad	2	0.000042	1.23	0.2968	NO
PG*Ndesign*NMAS	1	0.000089	2.61	0.1095	NO
PG*Ndesign*Grad	1	0.000029	0.86	0.3551	NO
PG*NMAS*Grad	1	0.000102	2.99	0.0869	NO
Ndesign*NMAS*Grad	1	0.000002	0.06	0.8085	NO
Agg*PG*Ndesign*NMAS	2	0.000456	13.42	<0.0001	YES
Agg*PG*Ndesign*Grad	2	0.000232	6.84	0.0017	YES
Agg*Ndesign*NMAS*Grad	2	0.000007	0.21	0.8101	NO
Agg*PG*NMAS*Grad	2	0.000043	1.27	0.2864	NO
PG*Ndesign*NMAS*Grad	1	0.000000	0.01	0.9105	NO
Agg*PG*Ndesign*NMAS*Grad	2	0.002069	6.09	0.0032	YES
Model	47	0.000242	7.14	<0.0001	YES
Error	96	0.000034			

Note: 1) Conducted at a level of significance of 5 percent.

Table 4.12 ANOVA Results for Air Voids (Corelok – Water Displacement)

Source	Degrees of Freedom	Mean Squares	F-stat	Prob > F-stat	Statistically Significant (Yes/No?)[1]
Aggregate	2	1.8850	35.26	<0.0001	YES
PG	1	0.7158	13.39	0.0004	YES
Ndesign	1	0.4851	9.07	0.0033	YES
NMAS	1	0.1692	3.16	0.0784	NO
Gradation	1	5.3400	100.00	<0.0001	YES
Agg*PG	2	0.0960	1.80	0.1715	NO
Agg*Ndesign	2	0.1420	2.66	0.0753	NO
Agg*NMAS	2	0.1894	3.54	0.0328	YES
Agg*Grad	2	0.5422	10.14	0.0001	YES
PG*Ndesign	1	0.0250	0.47	0.4949	NO
PG*NMAS	1	0.3610	6.75	0.0108	NO
PG*Grad	1	0.0165	0.31	0.5795	NO
Ndesign*NMAS	1	0.0000	0.00	0.9858	NO
Ndesign*Grad	1	0.0004	0.01	0.9360	NO
NMAS*Grad	1	0.1490	2.79	0.0983	NO
Agg*PG*Ndesign	2	0.0650	1.22	0.2998	NO
Agg*PG*NMAS	2	0.3160	5.91	0.0038	YES
Agg*PG*Grad	2	0.0465	0.87	0.4223	NO
Agg*Ndesign*NMAS	2	0.4230	7.92	0.0007	YES
Agg*Ndesign*Grad	2	0.0866	1.62	0.2032	NO
Agg*NMAS*Grad	2	0.0695	1.30	0.2773	NO
PG*Ndesign*NMAS	1	0.1490	5.91	0.0038	YES
PG*Ndesign*Grad	1	0.0480	0.91	0.3438	NO
PG*NMAS*Grad	1	0.1467	2.74	0.1009	NO
Ndesign*NMAS*Grad	1	0.0039	0.07	0.7873	NO
Agg*PG*Ndesign*NMAS	2	0.7350	13.74	<0.0001	YES
Agg*PG*Ndesign*Grad	2	0.3830	7.16	0.0013	YES
Agg*Ndesign*NMAS*Grad	2	0.0109	0.20	0.8154	NO
Agg*PG*NMAS*Grad	2	0.0714	1.34	0.2679	NO
PG*Ndesign*NMAS*Grad	1	0.0004	0.01	0.9340	NO
Agg*PG*Ndesign*NMAS*Grad	2	0.3339	6.24	0.0028	YES
Model	47	0.3917	7.33	<0.0001	YES
Error	96	0.0534			

Note: 1) Conducted at a level of significance of 5 percent.

Table 4.13 ANOVA Results for VMA (Corelok – Water Displacement)

Source	Degrees of Freedom	Mean Squares	F-stat	Prob > F-stat	Statistically Significant (Yes/No?)[1]
Aggregate	2	1.4580	35.26	<0.0001	YES
PG	1	0.5539	13.39	0.0004	YES
Ndesign	1	0.3750	9.07	0.0033	YES
NMAS	1	0.1309	3.16	0.0784	NO
Gradation	1	4.1374	100.00	<0.0001	YES
Agg*PG	2	0.0740	1.80	0.1715	NO
Agg*Ndesign	2	0.1099	2.66	0.0753	NO
Agg*NMAS	2	0.1465	3.54	0.0328	YES
Agg*Grad	2	0.4196	10.14	0.0001	YES
PG*Ndesign	1	0.0194	0.47	0.4949	NO
PG*NMAS	1	0.2794	6.75	0.0108	YES
PG*Grad	1	0.0128	0.31	0.5795	NO
Ndesign*NMAS	1	0.0000	0.00	0.9858	NO
Ndesign*Grad	1	0.0003	0.01	0.9360	NO
NMAS*Grad	1	0.1153	2.79	0.0013	YES
Agg*PG*Ndesign	2	0.0505	1.22	0.2998	NO
Agg*PG*NMAS	2	0.2443	5.91	0.0038	YES
Agg*PG*Grad	2	0.0360	0.87	0.4223	NO
Agg*Ndesign*NMAS	2	0.3277	7.92	0.0007	YES
Agg*Ndesign*Grad	2	0.0670	1.62	0.2032	NO
Agg*NMAS*Grad	2	0.0538	1.30	0.2773	NO
PG*Ndesign*NMAS	1	0.1155	2.79	0.0980	NO
PG*Ndesign*Grad	1	0.0374	0.91	0.3438	NO
PG*NMAS*Grad	1	0.1135	2.74	0.1009	NO
Ndesign*NMAS*Grad	1	0.0030	0.07	0.7873	NO
Agg*PG*Ndesign*NMAS	2	0.5686	13.74	<0.0001	YES
Agg*PG*Ndesign*Grad	2	0.2964	7.16	0.0013	YES
Agg*Ndesign*NMAS*Grad	2	0.0085	0.20	0.8154	NO
Agg*PG*NMAS*Grad	2	0.0553	1.34	0.2679	NO
PG*Ndesign*NMAS*Grad	1	0.0003	0.01	0.9340	NO
Agg*PG*Ndesign*NMAS*Grad	2	0.2580	6.24	0.0028	YES
Model	47	0.3030	7.33	<0.0001	YES
Error	96	0.0414			

Note: 1) Conducted at a level of significance of 5 percent.

included either gradation or aggregate type as one of the interacting factors. As expected, ANOVA results for air voids and VMA difference were similar and matched very closely with G_{mb} difference results.

Additionally, a Tukey's multiple comparison test was conducted on the study factors to determine their overall statistical significance with regards to G_{mb}, air voids, and VMA difference. Tukey's test results are provided in Table 4.14. Results agree with those from the various ANOVAs, with there being a statistical significant difference between each level of aggregate type, PG binder, N_{design} level, and gradation. There was no statistical difference between the NMAS levels.

Table 4.14 Tukey's Multiple Comparison Test Results (Corelok – Water Displacement)

Study Variable and Level		G_{mb} Difference	Tukey's Grouping[1]	Air Void Difference	Tukey's Grouping[1]	VMA Difference	Tukey's Grouping[1]
Aggregate	Gravel	0.013	A	0.534	A	0.470	A
	Sandstone	0.018	B	0.731	B	0.643	B
	Limestone/Gravel	0.023	C	0.930	C	0.818	C
PG	67	0.017	A	0.661	A	0.582	A
	76	0.020	B	0.802	B	0.706	B
N_{design}	96	0.017	A	0.674	A	0.593	A
	119	0.020	B	0.790	B	0.695	B
NMAS	12.5	0.017	A	0.697	A	0.614	A
	19	0.019	A	0.766	A	0.674	A
Gradation	Fine	0.013	A	0.539	A	0.474	A
	Coarse	0.023	B	0.924	B	0.813	B

Note: 1) Level of significance = 5 percent. Levels with the same letter are not statistically different

4.5.5 Effect of G_{mb} Differences on Design Asphalt Content and VMA

The most important aspect of using the Corelok procedure for G_{mb} determination during mix design is a change in design asphalt content. If the Corelok procedure provides slightly lower G_{mb} values than water displacement methods, design asphalt contents should be slightly higher. Design asphalt content changes for gravel, sandstone, and limestone/gravel mixes are provided in Figures 4.21, 4.22, and 4.23, respectively. For all mixes, design asphalt contents increased slightly when using the Corelok procedure, with the increase ranging from 0.01 to 0.51 percent.

A summary of the change in design asphalt contents for each overall study factor is provided in Table 4.15. Overall, there was a 0.29 percent change in design asphalt content. As expected from the ANOVA and Tukeys results, the largest differences in design asphalt content occurred within levels of aggregate type and gradation. Limestone/gravel and sandstone aggregate mixes had overall DAC differences of approximately 0.3 percent. Coarse-graded mixes had average DAC changes of 0.35 percent, compared to fine-graded mixes at 0.23 percent DAC change. Average DAC changes between levels of PG, N_{design}, and NMAS, in all cases, ranged from 0.28 to 0.30 percent. VMA changes are also shown in Table 4.15 and range from 0.47 to 0.82 percent, with an overall average of 0.64 percent.

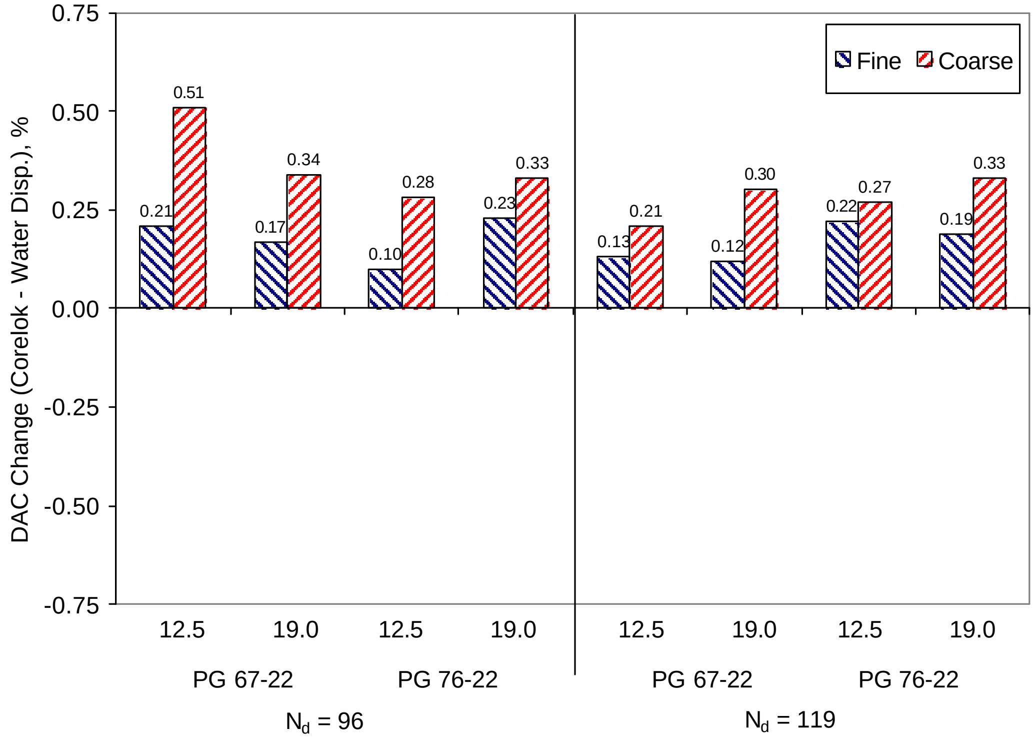

Figure 4.21 Design Asphalt Content Change (Corelok – Water Displacement) for Gravel Mixes

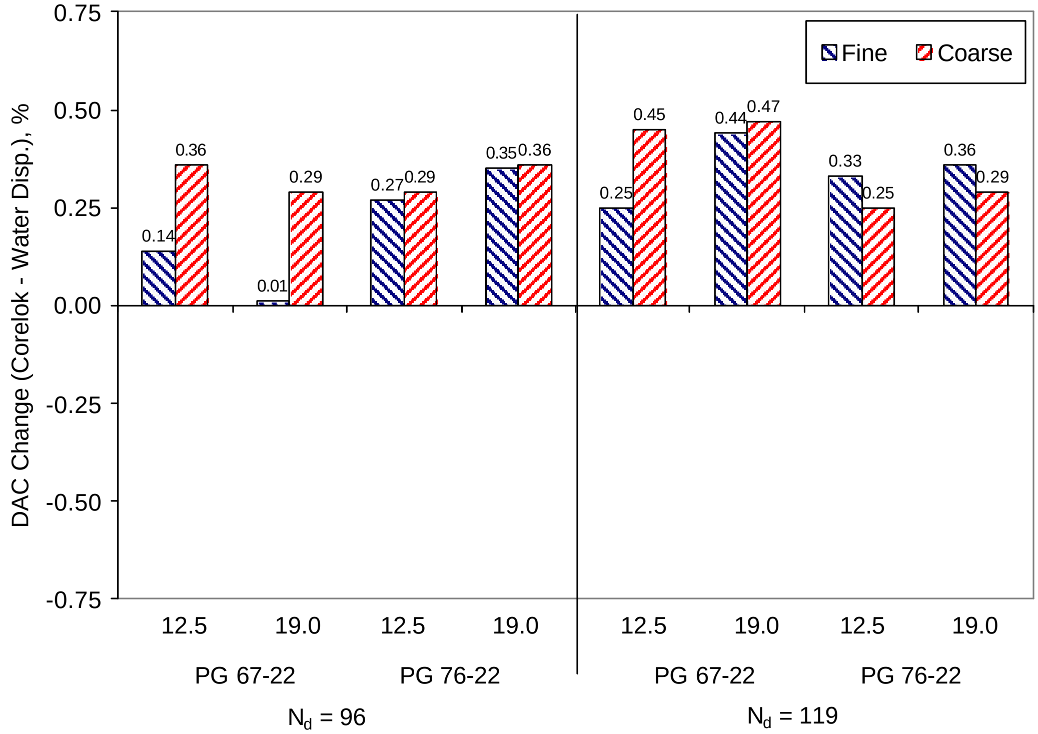

Figure 4.22 Design Asphalt Content Change (Corelok – Water Displacement) for Sandstone Mixes

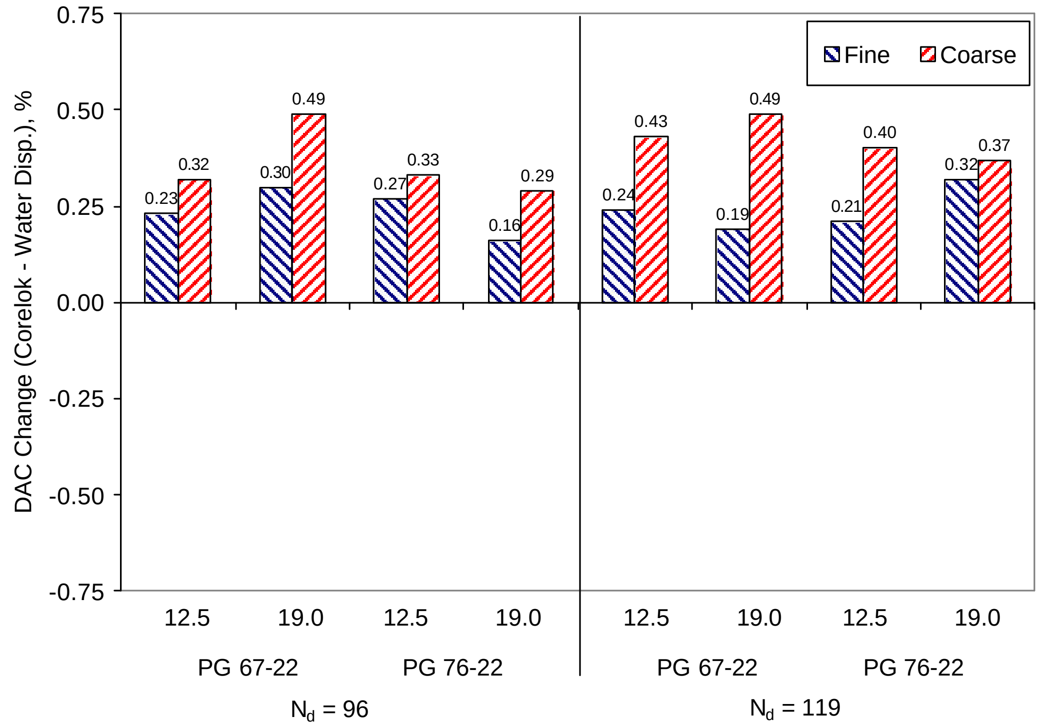

Figure 4.23 Design Asphalt Content Change (Corelok – Water Displacement) for Limestone/Gravel Mixes

Table 4.15 Design Asphalt Content and VMA Change (Corelok – Water Displacement)

Property	Average Percent Change in DAC and VMA (Corelok - Water Displacement)											
	Overall	Aggregate			PG		N_{design}		NMAS, mm		Gradation	
		Gravel	Sandstone	Limestone	67	76	96	119	12.5	19	Fine	Coarse
DAC	0.29	0.25	0.32	0.31	0.30	0.28	0.28	0.30	0.28	0.30	0.23	0.35
VMA	0.64	0.47	0.64	0.82	0.58	0.71	0.59	0.69	0.61	0.67	0.47	0.81

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The following conclusions can be drawn from the study regarding specimens compacted directly to N_{design} relative to specimens compacted to $N_{maximum}$ and their density back calculated to N_{design}.

- Approximately 80 percent of the study mixes had a density at N_{design}, determined by compacting specimens directly to N_{design}, which was greater than found through compacting specimens to $N_{maximum}$ and back calculating the density at N_{design}.
- Aggregate type was found to be the most significant factor influencing the change in density at N_{design} and VMA of the project mixes. Gravel and sandstone mixes had statistically larger differences in density at N_{design} and VMA than did the limestone/gravel mixes.
- Most of the study mixes had a density at $N_{initial}$ that was higher when back calculated from N_{design} relative to $N_{maximum}$. However, the differences between N_{design} and $N_{maximum}$ were not determined to be statistically significant.
- While differences in density at N_{design} and $N_{initial}$ and VMA did occur, the study factors of asphalt binder performance grade (PG), N_{design} level, nominal maximum aggregate size, or gradation were not statistically different when evaluated at a level of significance of 5 percent.

The following conclusions in regards to mix designs conducted by compacted specimens directly to N_{design} relative to specimens compacted to $N_{maximum}$ and their density back calculated at N_{design}.

- There will typically be a slight reduction in the design asphalt content and VMA of mixes. An overall reduction of 0.14 percent in design asphalt content was observed for the study mixes. The design asphalt content reduction was greater for the gravel and sandstone mixes when compared to the limestone/gravel mixes.
- The VMA at the design asphalt content can be expected to be reduced by an average of approximately 0.3 percent.

The following conclusions are made regarding the use of Corelok and water displacement procedures for G_{mb} determination.

- Significant G_{mb} difference existed between Corelok and water displacement procedures, with the Corelok procedure yielding slightly lower G_{mb} values.
- Water absorption decreased as G_{mb} values increased. Differences between Corelok and water displacement G_{mb} values increased as water absorption increased for coarse-graded mixes, but was generally constant for fine-graded mixes.
- HMA gradation most significantly affected G_{mb} difference between Corelok and water displacement procedures. Average G_{mb} difference of 0.013 and 0.019 existed for fine and coarse-graded specimens tested, respectively.
- An average increase in design asphalt content of 0.29 percent was observed by using the Corelok procedure, relative to the water displacement procedure. Coarse-graded mixes had a higher increase (0.35 percent) than fine-graded mixes (0.23 percent).
- An average increase in VMA of 0.64 percent was observed using the Corelok procedure. VMA increases were greater for coarse-graded mixes (0.81 percent) relative to fine-graded mixes (0.47 percent).

5.2 RECOMMENDATIONS

Based on results of the study, specimens should be compacted directly to N_{design} for mix design and quality control/assurance processes. Mix design and quality control/assurance specifications must be written so that "true" volumetric properties can be determined. Compacting specimens directly to N_{design} will insure the "true" volumetric properties of the specimens will be obtained. Back calculating specimen density from $N_{maximum}$ will likely result in something other than the "true" properties being obtained.

In compacting specimens directly to N_{design}, there will likely be a slight reduction in the design asphalt content (average of 0.14 percent) and VMA (average of 0.3 percent). Mixes narrowly meeting VMA criteria will be affected and adjustments in aggregate type of gradation may be needed to bring them into compliance. The slight reduction in asphalt content may have a minor effect on field compaction.

During mix design and quality control/assurance testing of HMA mixes, the Corelok device should be utilized to more accurately determine specimen G_{mb}. By using the Corelok device and compacting specimens directly to N_{design} overall average increases in the design asphalt content and VMA of 0.15 and 0.35 percent, respectively, were observed.

CHAPTER 6 REFERENCES

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APPENDIX A

INDIVIDUAL SPECIMEN DATA: GYRATORY COMPACTION HEIGHT, G_{MB} and G_{MM}

Table A.1 Gyratory Compaction Heights, G_{mb} and G_{mm} for Gravel, 12.5 mm NMAS Fine-Graded, PG 67-22, N_{design} = 96

Mixture:	Gravel 12.5 mm NMAS, Fine-Graded, PG 67-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	143.2	142.5	142.9	142.5	143.1	142.8
1	137.5	136.9	137.2	136.9	137.4	137.2
2	134.6	134.1	134.4	134.2	134.6	134.4
3	132.6	132.1	132.4	132.2	132.6	132.4
4	131.1	130.6	130.9	130.8	131.1	131.0
5	129.9	129.4	129.7	129.6	129.9	129.8
6	128.8	128.4	128.6	128.6	128.9	128.8
7	127.9	127.6	127.8	127.8	128.0	127.9
8	127.2	126.8	127.0	127.1	127.3	127.2
9	126.5	126.2	126.4	126.4	126.6	126.5
10	125.9	125.6	125.8	125.9	126.1	126.0
20	122.2	122.0	122.1	122.3	122.4	122.4
30	120.3	120.1	120.2	120.4	120.5	120.5
40	119.0	118.8	118.9	119.1	119.2	119.2
50	118.0	117.8	117.9	118.2	118.2	118.2
60	117.3	117.1	117.2	117.5	117.4	117.5
70	116.7	116.5	116.6	116.9	116.8	116.9
80	116.2	116.0	116.1	116.4	116.3	116.4
90	115.8	115.6	115.7	116.0	115.9	116.0
96	115.6	115.3	115.5	115.8	115.6	115.7
100				115.6	115.5	115.6
110				115.3	115.2	115.3
120				115.1	114.9	115.0
130				114.8	114.6	114.7
140				114.6	114.4	114.5
150				114.4	114.2	114.3
152				114.4	114.1	114.3
G_{mb}	2.257	2.255	2.256	2.276	2.279	2.278
G_{mm}	2.346					

Table A.2 Gyratory Compaction Heights, G_{mb} and G_{mm} for Gravel, 12.5 mm NMAS Fine-Graded, PG 76-22, N_{design} = 96

Mixture:	Gravel 12.5 mm NMAS, Fine-Graded, PG 76-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	144.9	144.8	144.9	143.5	143.7	143.6
1	139.1	139.0	139.1	137.6	137.8	137.7
2	136.1	136.1	136.1	134.8	135.0	134.9
3	134.0	134.1	134.1	132.7	133.0	132.9
4	132.5	132.5	132.5	131.2	131.4	131.3
5	131.3	131.3	131.3	130.0	130.2	130.1
6	130.2	130.3	130.3	129.0	129.2	129.1
7	129.4	129.4	129.4	128.1	128.3	128.2
8	128.6	128.7	128.7	127.4	127.5	127.5
9	128.0	128.0	128.0	126.7	126.9	126.8
10	127.4	127.4	127.4	126.2	126.3	126.3
20	123.7	123.7	123.7	122.5	122.5	122.5
30	121.7	121.7	121.7	120.6	120.5	120.6
40	120.4	120.4	120.4	119.3	119.2	119.3
50	119.4	119.5	119.5	118.4	118.3	118.4
60	118.6	118.7	118.7	117.7	117.5	117.6
70	118.0	118.1	118.1	117.1	116.9	117.0
80	117.5	117.6	117.6	116.6	116.4	116.5
90	117.1	117.2	117.2	116.2	116.0	116.1
96	116.9	117.0	117.0	116.0	115.8	115.9
100				115.8	115.6	115.7
110				115.5	115.3	115.4
120				115.3	115.0	115.2
130				115.0	114.8	114.9
140				114.8	114.6	114.7
150				114.6	114.4	114.5
152				114.6	114.4	114.5
G_{mb}	2.239	2.244	2.242	2.252	2.249	2.251
G_{mm}	2.335					

Table A.3 Gyratory Compaction Heights, G_{mb} and G_{mm} for Gravel, 19.0 mm NMAS Fine-Graded, PG 67-22, N_{design} = 96

Mixture:	Gravel 19.0 mm NMAS, Fine-Graded, PG 67-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	144.6	144.8	144.7	145.0	144.0	144.5
1	139.1	139.1	139.1	139.2	138.3	138.8
2	136.3	136.3	136.3	136.3	135.4	135.9
3	134.3	134.3	134.3	134.3	133.5	133.9
4	132.8	132.7	132.8	132.8	132.0	132.4
5	131.6	131.5	131.6	131.5	130.8	131.2
6	130.6	130.5	130.6	130.5	129.8	130.2
7	129.7	129.6	129.7	129.6	129.0	129.3
8	129.0	128.9	129.0	128.8	128.2	128.5
9	128.3	128.2	128.3	128.2	127.6	127.9
10	127.7	127.6	127.7	127.6	127.0	127.3
20	124.0	123.9	124.0	123.8	123.4	123.6
30	121.9	121.9	121.9	121.8	121.5	121.7
40	120.6	120.6	120.6	120.5	120.2	120.4
50	119.6	119.6	119.6	119.5	119.3	119.4
60	118.8	118.9	118.9	118.8	118.6	118.7
70	118.2	118.2	118.2	118.2	118.0	118.1
80	117.7	117.7	117.7	117.7	117.5	117.6
90	117.2	117.3	117.3	117.3	117.0	117.2
96	117.0	117.1	117.1	117.1	116.8	117.0
100				116.9	116.7	116.8
110				116.6	116.3	116.5
120				116.3	116.0	116.2
130				116.1	115.8	116.0
140				115.9	115.6	115.8
150				115.7	115.4	115.6
152				115.7	115.3	115.5
G_{mb}	2.244	2.245	2.244	2.259	2.264	2.262
G_{mm}	2.339					

Table A.4 Gyratory Compaction Heights, G_{mb} and G_{mm} for Gravel, 19.0 mm NMAS Fine-Graded, PG 76-22, N_{design} = 96

Mixture:	Gravel 19.0 mm NMAS, Fine-Graded, PG 76-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	144.3	145.9	145.1	145.8	147.4	146.6
1	138.4	140.2	139.3	139.9	141.4	140.7
2	135.6	137.3	136.5	137.0	138.6	137.8
3	133.7	135.3	134.5	135.0	136.5	135.8
4	132.2	133.8	133.0	133.4	135.0	134.2
5	131.0	132.6	131.8	132.1	133.7	132.9
6	130.0	131.6	130.8	131.1	132.7	131.9
7	129.2	130.7	130.0	130.3	131.8	131.1
8	128.4	130.0	129.2	129.6	131.0	130.3
9	127.8	129.3	128.6	128.9	130.3	129.6
10	127.2	128.7	128.0	128.3	129.7	129.0
20	123.7	125.0	124.4	124.7	126.0	125.4
30	121.7	123.0	122.4	122.7	124.0	123.4
40	120.4	121.7	121.1	121.5	122.7	122.1
50	119.5	120.8	120.2	120.5	121.8	121.2
60	118.8	120.1	119.5	119.8	121.0	120.4
70	118.2	119.5	118.9	119.2	120.4	119.8
80	117.7	119.0	118.4	118.6	119.9	119.3
90	117.3	118.6	118.0	118.2	119.5	118.9
96	117.1	118.4	117.8	118.0	119.3	118.7
100				117.8	119.2	118.5
110				117.5	118.8	118.2
120				117.2	118.6	117.9
130				117.0	118.3	117.7
140				116.7	118.1	117.4
150				116.5	117.9	117.2
152				116.5	117.9	117.2
G_{mb}	2.233	2.227	2.230	2.244	2.242	2.243
G_{mm}	2.326					

Table A.5 Gyratory Compaction Heights, G_{mb} and G_{mm} for Gravel, 12.5 mm NMAS Coarse-Graded, PG 67-22, N_{design} = 96

Mixture:	Gravel 12.5 mm NMAS, Coarse-Graded, PG 67-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	146.6	146.4	146.3	147.3	146.1	146.7
1	140.8	140.6	140.4	141.4	140.5	141.0
2	137.8	137.6	137.4	138.4	137.7	138.1
3	135.6	135.5	135.3	136.2	135.6	135.9
4	134.0	133.9	133.6	134.6	134.0	134.3
5	132.6	132.6	132.3	133.3	132.7	133.0
6	131.5	131.5	131.2	132.2	131.6	131.9
7	130.5	130.5	130.2	131.3	130.7	131.0
8	129.7	129.7	129.4	130.5	130.0	130.3
9	129.0	129.0	128.6	129.8	129.3	129.6
10	128.3	128.3	128.0	129.1	128.6	128.9
20	124.1	124.2	123.8	125.1	124.6	124.9
30	121.9	121.9	121.6	122.9	122.4	122.7
40	120.4	120.4	120.2	121.4	121.0	121.2
50	119.3	119.3	119.1	120.3	119.9	120.1
60	118.5	118.5	118.3	119.4	119.1	119.3
70	117.8	117.8	117.7	118.7	118.4	118.6
80	117.3	117.3	117.1	118.2	117.8	118.0
90	116.8	116.8	116.7	117.7	117.4	117.6
96	116.6	116.6	116.5	117.5	117.1	117.3
100				117.3	117.0	117.2
110				117.0	116.6	116.8
120				116.7	116.3	116.5
130				116.4	116.0	116.2
140				116.2	115.8	116.0
150				115.9	115.5	115.7
152				115.9	115.5	115.7
G_{mb}	2.194	2.197	2.196	2.218	2.219	2.218
G_{mm}	2.292					

Table A.6 Gyratory Compaction Heights, G_{mb} and G_{mm} for Gravel, 12.5 mm NMAS Coarse-Graded, PG 76-22, N_{design} = 96

Mixture:	Gravel 12.5 mm NMAS, Coarse-Graded, PG 76-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	147.8	147.0	147.4	144.6	144.7	144.7
1	141.8	141.1	141.5	138.8	139.0	138.9
2	138.9	138.1	138.5	136.0	136.1	136.1
3	136.8	135.9	136.4	133.9	134.1	134.0
4	135.1	134.3	134.7	132.4	132.5	132.5
5	133.8	132.9	133.4	131.1	131.2	131.2
6	132.7	131.8	132.3	130.0	130.1	130.1
7	131.8	130.8	131.3	129.2	129.2	129.2
8	130.9	130.0	130.5	128.4	128.5	128.5
9	130.2	129.3	129.8	127.7	127.8	127.8
10	129.6	128.6	129.1	127.1	127.1	127.1
20	125.5	124.4	125.0	123.2	123.2	123.2
30	123.3	122.3	122.8	121.0	121.0	121.0
40	121.8	120.8	121.3	119.5	119.6	119.6
50	120.8	119.8	120.3	118.4	118.6	118.5
60	120.0	119.0	119.5	117.6	117.7	117.7
70	119.3	118.4	118.9	117.0	117.1	117.1
80	118.8	117.8	118.3	116.4	116.6	116.5
90	118.3	117.4	117.9	115.9	116.1	116.0
96	118.1	117.2	117.7	115.7	115.9	115.8
100				115.5	115.7	115.6
110				115.2	115.4	115.3
120				114.9	115.1	115.0
130				114.6	114.9	114.8
140				114.4	114.6	114.5
150				114.2	114.4	114.3
152				114.2	114.4	114.3
G_{mb}	2.170	2.170	2.170	2.197	2.200	2.199
G_{mm}	2.263					

Table A.7 Gyratory Compaction Heights, G_{mb} and G_{mm} for Gravel, 19.0 mm NMAS Coarse-Graded, PG 67-22, N_{design} = 96

Mixture:	Gravel 19.0 mm NMAS, Coarse-Graded, PG 67-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	145.8	145.5	145.7	146.9	147.1	147.0
1	140.0	139.7	139.9	141.3	141.3	141.3
2	137.2	136.8	137.0	138.4	138.4	138.4
3	135.1	134.7	134.9	136.4	136.4	136.4
4	133.5	133.1	133.3	134.8	134.8	134.8
5	132.3	131.8	132.1	133.5	133.5	133.5
6	131.2	130.7	131.0	132.4	132.5	132.5
7	130.3	129.8	130.1	131.5	131.6	131.6
8	129.5	129.1	129.3	130.7	130.8	130.8
9	128.8	128.3	128.6	130.0	130.2	130.1
10	128.2	127.7	128.0	129.4	129.6	129.5
20	124.2	123.8	124.0	125.5	125.6	125.6
30	122.1	121.6	121.9	123.3	123.4	123.4
40	120.6	120.2	120.4	121.8	122.0	121.9
50	119.6	119.2	119.4	120.7	120.9	120.8
60	118.8	118.4	118.6	119.9	120.1	120.0
70	118.1	117.8	118.0	119.3	119.4	119.4
80	117.6	117.3	117.5	118.7	118.8	118.8
90	117.2	116.8	117.0	118.2	118.3	118.3
96	116.9	116.6	116.8	118.0	118.1	118.1
100				117.8	118.0	117.9
110				117.5	117.6	117.6
120				117.2	117.3	117.3
130				116.9	117.0	117.0
140				116.7	116.8	116.8
150				116.4	116.5	116.5
152				116.4	116.5	116.5
G_{mb}	2.188	2.191	2.189	2.198	2.210	2.204
G_{mm}	2.279					

Table A.8 Gyratory Compaction Heights, G_{mb} and G_{mm} for Gravel, 19.0 mm NMAS Coarse-Graded, PG 76-22, N_{design} = 96

Mixture:	Gravel 19.0 mm NMAS, Coarse-Graded, PG 76-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	145.9	146.4	146.2	146.4	145.0	145.7
1	140.0	140.6	140.3	140.5	139.3	139.9
2	137.0	137.6	137.3	137.5	136.5	137.0
3	135.0	135.5	135.3	135.4	134.6	135.0
4	133.4	134.0	133.7	133.7	133.1	133.4
5	132.2	132.7	132.5	132.4	131.8	132.1
6	131.1	131.6	131.4	131.3	130.8	131.1
7	130.2	130.7	130.5	130.4	129.9	130.2
8	129.4	129.9	129.7	129.6	129.2	129.4
9	128.7	129.2	129.0	128.9	128.5	128.7
10	128.1	128.6	128.4	128.3	127.9	128.1
20	124.2	124.4	124.3	124.3	124.0	124.2
30	122.0	122.2	122.1	122.1	121.8	122.0
40	120.6	120.7	120.7	120.6	120.4	120.5
50	119.6	119.7	119.7	119.6	119.4	119.5
60	118.8	118.9	118.9	118.8	118.5	118.7
70	118.2	118.2	118.2	118.1	117.9	118.0
80	117.6	117.7	117.7	117.6	117.3	117.5
90	117.2	117.3	117.3	117.1	116.9	117.0
96	117.0	117.1	117.1	116.9	116.6	116.8
100				116.7	116.5	116.6
110				116.4	116.1	116.3
120				116.1	115.8	116.0
130				115.8	115.6	115.7
140				115.6	115.3	115.5
150				115.3	115.1	115.2
152				115.3	115.1	115.2
G_{mb}	2.179	2.176	2.178	2.200	2.208	2.204
G_{mm}	2.270					

Table A.9 Gyratory Compaction Heights, G_{mb} and G_{mm} for Gravel, 12.5 mm NMAS Fine-Graded, PG 67-22, N_{design} = 119

Mixture:	Gravel 12.5 mm NMAS, Fine-Graded, PG 67-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	143.2	142.9	143.1	142.9	142.1	142.5
1	137.4	137.3	137.4	137.2	136.6	136.9
2	134.6	134.4	134.5	134.4	133.7	134.1
3	132.6	132.4	132.5	132.4	131.8	132.1
4	131.1	130.9	131.0	130.9	130.3	130.6
5	129.9	129.8	129.9	129.7	129.1	129.4
6	128.9	128.7	128.8	128.8	128.2	128.5
7	128.1	127.9	128.0	127.9	127.4	127.7
8	127.3	127.2	127.3	127.2	126.6	126.9
9	126.7	126.5	126.6	126.5	126.0	126.3
10	126.1	126.0	126.1	126.0	125.5	125.8
20	122.5	122.4	122.5	122.4	121.9	122.2
30	120.5	120.5	120.5	120.4	120.0	120.2
40	119.2	119.2	119.2	119.1	118.7	118.9
50	118.3	118.3	118.3	118.2	117.8	118.0
60	117.5	117.6	117.6	117.4	117.1	117.3
70	116.9	117.0	117.0	116.8	116.5	116.7
80	116.5	116.5	116.5	116.3	116.0	116.2
90	116.0	116.1	116.1	115.9	115.6	115.8
100	115.7	115.8	115.8	115.5	115.2	115.4
110	115.4	115.4	115.4	115.2	114.9	115.1
119	115.1	115.2	115.2	115.0	114.7	114.9
120				114.9	114.6	114.8
130				114.7	114.4	114.6
140				114.5	114.2	114.4
150				114.3	114.0	114.2
160				114.1	113.8	114.0
170				113.9	113.6	113.8
180				113.8	113.5	113.7
190				113.6	113.3	113.5
192				113.6	113.3	113.5
G_{mb}	2.260	2.254	2.257	2.281	2.285	2.283
G_{mm}	2.353					

Table A.10 Gyratory Compaction Heights, G_{mb} and G_{mm} for Gravel, 12.5 mm NMAS Fine-Graded, PG 76-22, N_{design} = 119

Mixture:	Gravel 12.5 mm NMAS, Fine-Graded, PG 76-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	144.7	145.0	144.9	144.5	145.5	145.0
1	138.8	139.1	139.0	138.7	139.6	139.2
2	136.0	136.3	136.2	135.9	136.7	136.3
3	134.0	134.2	134.1	133.9	134.7	134.3
4	132.4	132.7	132.6	132.4	133.1	132.8
5	131.2	131.4	131.3	131.2	131.8	131.5
6	130.2	130.4	130.3	130.1	130.8	130.5
7	129.3	129.5	129.4	129.3	129.9	129.6
8	128.5	128.8	128.7	128.5	129.2	128.9
9	127.9	128.1	128.0	127.9	128.5	128.2
10	127.3	127.5	127.4	127.3	127.9	127.6
20	123.6	123.8	123.7	123.6	124.2	123.9
30	121.6	121.7	121.7	121.6	122.2	121.9
40	120.3	120.4	120.4	120.3	120.8	120.6
50	119.3	119.4	119.4	119.3	119.9	119.6
60	118.5	118.7	118.6	118.6	119.1	118.9
70	117.9	118.1	118.0	118.0	118.5	118.3
80	117.4	117.6	117.5	117.4	118.0	117.7
90	117.0	117.1	117.1	117.0	117.6	117.3
100	116.6	116.8	116.7	116.6	117.2	116.9
110	116.3	116.4	116.4	116.3	116.9	116.6
119	116.1	116.2	116.2	116.1	116.6	116.4
120				116.0	116.6	116.3
130				115.8	116.3	116.1
140				115.6	116.1	115.9
150				115.4	115.9	115.7
160				115.2	115.7	115.5
170				115.0	115.5	115.3
180				114.9	115.4	115.2
190				114.7	115.2	115.0
192				114.7	115.2	115.0
G_{mb}	2.244	2.247	2.245	2.277	2.272	2.274
G_{mm}	2.334					

Table A.11 Gyratory Compaction Heights, G_{mb} and G_{mm} for Gravel, 19.0 mm NMAS Fine-Graded, PG 67-22, N_{design} = 119

Mixture:	Gravel 19.0 mm NMAS, Fine-Graded, PG 67-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	145.3	145.3	145.3	145.0	146.2	145.6
1	139.6	139.4	139.5	139.3	140.4	139.9
2	136.7	136.5	136.6	136.5	137.5	137.0
3	134.7	134.4	134.6	134.5	135.5	135.0
4	133.1	132.9	133.0	132.9	134.0	133.5
5	131.8	131.6	131.7	131.7	132.8	132.3
6	130.8	130.5	130.7	130.7	131.7	131.2
7	129.9	129.7	129.8	129.8	130.8	130.3
8	129.2	128.9	129.1	129.0	130.1	129.6
9	128.5	128.2	128.4	128.4	129.4	128.9
10	127.9	127.7	127.8	127.8	128.8	128.3
20	124.1	123.9	124.0	124.1	125.0	124.6
30	122.1	121.9	122.0	122.1	123.0	122.6
40	120.8	120.6	120.7	120.8	121.7	121.3
50	119.8	119.6	119.7	119.8	120.7	120.3
60	119.0	118.9	119.0	119.1	119.9	119.5
70	118.4	118.3	118.4	118.5	119.3	118.9
80	117.9	117.8	117.9	118.0	118.8	118.4
90	117.4	117.3	117.4	117.5	118.4	118.0
100	117.1	117.0	117.1	117.2	118.0	117.6
110	116.7	116.6	116.7	116.8	117.7	117.3
119	116.5	116.4	116.5	116.6	117.4	117.0
120				116.6	117.4	117.0
130				116.3	117.1	116.7
140				116.1	116.9	116.5
150				115.9	116.7	116.3
160				115.7	116.5	116.1
170				115.5	116.3	115.9
180				115.3	116.2	115.8
190				115.2	116.0	115.6
192				115.2	116.0	115.6
G_{mb}	2.244	2.249	2.246	2.256	2.255	2.256
G_{mm}	2.342					

Table A.12 Gyratory Compaction Heights, G_{mb} and G_{mm} for Gravel, 19.0 mm NMAS Fine-Graded, PG 76-22, N_{design} = 119

Mixture:	Gravel 19.0 mm NMAS, Fine-Graded, PG 76-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	146.6	145.8	146.2	144.6	145.4	145.0
1	140.9	140.0	140.5	138.8	139.5	139.2
2	138.0	137.1	137.6	136.0	136.6	136.3
3	136.0	135.1	135.6	134.0	134.5	134.3
4	134.4	133.5	134.0	132.4	133.0	132.7
5	133.1	132.3	132.7	131.2	131.8	131.5
6	132.1	131.3	131.7	130.2	130.8	130.5
7	131.2	130.4	130.8	129.3	130.0	129.7
8	130.5	129.6	130.1	128.6	129.2	128.9
9	129.8	129.0	129.4	127.9	128.6	128.3
10	129.2	128.4	128.8	127.4	128.0	127.7
20	125.5	124.6	125.1	123.7	124.4	124.1
30	123.5	122.6	123.1	121.8	122.4	122.1
40	122.2	121.2	121.7	120.5	121.2	120.9
50	121.2	120.3	120.8	119.6	120.2	119.9
60	120.5	119.5	120.0	118.8	119.5	119.2
70	119.9	118.9	119.4	118.3	118.9	118.6
80	119.4	118.4	118.9	117.8	118.4	118.1
90	119.0	118.0	118.5	117.4	118.0	117.7
100	118.6	117.6	118.1	117.0	117.7	117.4
110	118.3	117.3	117.8	116.7	117.3	117.0
119	118.0	117.1	117.6	116.5	117.1	116.8
120				116.5	117.1	116.8
130				116.2	116.8	116.5
140				116.0	116.6	116.3
150				115.8	116.4	116.1
160				115.7	116.2	116.0
170				115.5	116.1	115.8
180				115.4	115.9	115.7
190				115.3	115.8	115.6
192				115.3	115.8	115.6
G_{mb}	2.232	2.237	2.234	2.265	2.261	2.263
G_{mm}	2.326					

Table A.13 Gyratory Compaction Heights, G_{mb} and G_{mm} for Gravel, 12.5 mm NMAS Coarse-Graded, PG 67-22, N_{design} = 119

Mixture:	Gravel 12.5 mm NMAS, Coarse-Graded, PG 67-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	145.3	147.1	144.9	145.9	145.6	146.0
1	139.5	141.2	139.2	140.2	139.8	140.2
2	136.6	138.3	136.2	137.3	136.9	137.1
3	134.4	136.0	134.1	135.2	134.8	134.9
4	132.8	134.3	132.5	133.6	133.2	133.3
5	131.4	133.0	131.2	132.3	131.9	131.9
6	130.3	131.8	130.1	131.2	130.8	130.8
7	129.3	130.9	129.2	130.2	129.9	129.9
8	128.5	130.0	128.3	129.4	129.0	129.0
9	127.8	129.3	127.6	128.7	128.3	128.3
10	127.1	128.6	127.0	128.1	127.7	127.6
20	122.9	124.4	122.9	123.9	123.6	123.5
30	120.7	122.1	120.7	121.6	121.4	121.3
40	119.2	120.6	119.2	120.1	120.0	119.8
50	118.1	119.5	118.2	119.0	119.0	118.8
60	117.3	118.7	117.4	118.2	118.2	117.9
70	116.6	118.0	116.7	117.5	117.5	117.3
80	116.1	117.5	116.1	116.9	117.0	116.7
90	115.6	117.0	115.7	116.4	116.5	116.3
100	115.2	116.6	115.3	116.0	116.1	115.9
110	114.9	116.3	115.0	115.7	115.8	115.5
119	114.6	116.0	114.7	115.4	115.5	115.2
120				115.4	115.5	115.2
130				115.1	115.2	114.9
140				114.9	115.0	114.7
150				114.6	114.7	114.5
160				114.4	114.5	114.3
170				114.3	114.3	114.1
180				114.1	114.2	114.0
190				113.9	114.0	113.8
192				113.9	114.0	113.8
G_{mb}	2.210	2.207	2.209	2.225	2.227	2.226
G_{mm}	2.299					

Table A.14 Gyratory Compaction Heights, G_{mb} and G_{mm} for Gravel, 12.5 mm NMAS Coarse-Graded, PG 76-22, N_{design} = 119

Mixture:	Gravel 12.5 mm NMAS, Coarse-Graded, PG 76-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	148.1	146.6	147.4	146.9	145.6	146.3
1	142.3	140.8	141.6	140.9	139.9	140.4
2	139.3	137.8	138.6	137.8	137.0	137.4
3	137.1	135.6	136.4	135.7	135.0	135.4
4	135.5	134.1	134.8	134.0	133.4	133.7
5	134.2	132.8	133.5	132.7	132.1	132.4
6	133.0	131.7	132.4	131.6	131.1	131.4
7	132.0	130.7	131.4	130.7	130.2	130.5
8	131.2	129.9	130.6	129.9	129.4	129.7
9	130.5	129.2	129.9	129.2	128.7	129.0
10	129.9	128.6	129.3	128.5	128.1	128.3
20	125.7	124.5	125.1	124.5	124.0	124.3
30	123.5	122.4	123.0	122.3	121.8	122.1
40	122.1	120.9	121.5	120.9	120.3	120.6
50	121.0	119.8	120.4	119.8	119.3	119.6
60	120.2	119.0	119.6	119.0	118.5	118.8
70	119.6	118.4	119.0	118.4	117.8	118.1
80	119.1	117.8	118.5	117.8	117.3	117.6
90	118.6	117.4	118.0	117.4	116.8	117.1
100	118.2	117.0	117.6	117.0	116.4	116.7
110	117.9	116.7	117.3	116.7	116.1	116.4
119	117.6	116.4	117.0	116.4	115.8	116.1
120				116.4	115.8	116.1
130				116.1	115.5	115.8
140				115.9	115.3	115.6
150				115.6	115.1	115.4
160				115.4	114.9	115.2
170				115.3	114.7	115.0
180				115.1	114.6	114.9
190				114.9	114.4	114.7
192				114.9	114.4	114.7
G_{mb}	2.178	2.186	2.182	2.214	2.208	2.211
G_{mm}	2.275					

Table A.15 Gyratory Compaction Heights, G_{mb} and G_{mm} for Gravel, 19.0 mm NMAS Coarse-Graded, PG 67-22, N_{design} = 119

Mixture:	Gravel 19.0 mm NMAS, Coarse-Graded, PG 67-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	146.8	146.0	146.4	147.1	146.7	146.9
1	141.0	140.3	140.7	141.1	140.9	141.0
2	138.1	137.5	137.8	138.2	138.0	138.1
3	136.0	135.4	135.7	136.0	135.9	136.0
4	134.4	133.8	134.1	134.3	134.2	134.3
5	133.1	132.6	132.9	132.9	132.9	132.9
6	132.0	131.5	131.8	131.8	131.8	131.8
7	131.1	130.6	130.9	130.9	130.9	130.9
8	130.3	129.9	130.1	130.0	130.0	130.0
9	129.6	129.2	129.4	129.4	129.3	129.4
10	129.0	128.6	128.8	128.7	128.7	128.7
20	124.9	124.6	124.8	124.7	124.7	124.7
30	122.7	122.5	122.6	122.5	122.5	122.5
40	121.3	121.1	121.2	121.0	121.1	121.1
50	120.3	120.0	120.2	119.9	120.0	120.0
60	119.5	119.2	119.4	119.1	119.2	119.2
70	118.8	118.6	118.7	118.4	118.5	118.5
80	118.3	118.1	118.2	117.9	118.0	118.0
90	117.8	117.6	117.7	117.4	117.5	117.5
100	117.4	117.2	117.3	117.0	117.1	117.1
110	117.1	116.9	117.0	116.7	116.8	116.8
119	116.9	116.6	116.8	116.4	116.5	116.5
120				116.4	116.5	116.5
130				116.1	116.2	116.2
140				115.9	116.0	116.0
150				115.7	115.8	115.8
160				115.5	115.6	115.6
170				115.3	115.4	115.4
180				115.1	115.2	115.2
190				114.9	115.0	115.0
192				114.9	115.0	115.0
G_{mb}	2.182	2.193	2.187	2.213	2.212	2.213
G_{mm}	2.283					

Table A.16 Gyratory Compaction Heights, G_{mb} and G_{mm} for Gravel, 19.0 mm NMAS Coarse-Graded, PG 76-22, N_{design} = 119

Mixture:	Gravel 19.0 mm NMAS, Coarse-Graded, PG 76-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	146.8	144.8	145.8	145.4	146.8	146.1
1	140.7	139.1	139.9	139.7	140.8	140.3
2	137.8	136.2	137.0	136.6	137.9	137.3
3	135.6	134.2	134.9	134.5	135.8	135.2
4	134.0	132.6	133.3	133.0	134.2	133.6
5	132.8	131.4	132.1	131.6	132.9	132.3
6	131.7	130.3	131.0	130.6	131.8	131.2
7	130.8	129.4	130.1	129.7	130.8	130.3
8	130.0	128.6	129.3	128.9	130.0	129.5
9	129.3	127.9	128.6	128.2	129.3	128.8
10	128.7	127.3	128.0	127.6	128.7	128.2
20	124.7	123.4	124.1	123.6	124.7	124.2
30	122.5	121.3	121.9	121.5	122.6	122.1
40	121.1	119.9	120.5	120.1	121.1	120.6
50	120.0	118.9	119.5	119.1	120.1	119.6
60	119.2	118.1	118.7	118.3	119.3	118.8
70	118.6	117.4	118.0	117.7	118.7	118.2
80	118.1	116.9	117.5	117.2	118.1	117.7
90	117.6	116.5	117.1	116.7	117.6	117.2
100	117.2	116.1	116.7	116.3	117.2	116.8
110	116.9	115.8	116.4	116.0	116.9	116.5
119	116.6	115.5	116.1	115.7	116.6	116.2
120				115.7	116.6	116.2
130				115.5	116.3	115.9
140				115.2	116.1	115.7
150				115.0	115.9	115.5
160				114.8	115.7	115.3
170				114.7	115.5	115.1
180				114.5	115.4	115.0
190				114.4	115.2	114.8
192				114.3	115.2	114.8
G_{mb}	2.180	2.188	2.184	2.216	2.212	2.214
G_{mm}	2.279					

Table A.17 Gyratory Compaction Heights, G_{mb} and G_{mm} for Sandstone, 12.5 mm NMAS Fine-Graded, PG 67-22, N_{design} = 96

Mixture:	Sandstone 12.5 mm NMAS, Fine-Graded, PG 67-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	135.5	135.6	136.2	135.8	135.8	137.1
1	130.2	130.2	131.0	130.5	130.6	131.8
2	127.7	127.6	128.5	128.1	128.2	129.2
3	126.1	125.9	126.8	126.3	126.5	127.4
4	124.8	124.6	125.4	125.1	125.2	126.1
5	123.8	123.5	124.4	124.1	124.1	125.0
6	122.9	122.6	123.5	123.2	123.2	124.2
7	122.2	121.9	122.8	122.5	122.5	123.4
8	121.5	121.3	122.1	121.9	121.9	122.8
9	121.0	120.7	121.5	121.3	121.3	122.2
10	120.5	120.2	121.1	120.9	120.8	121.7
20	117.3	117.1	117.9	117.8	117.7	118.5
30	115.6	115.4	116.1	116.1	115.9	116.7
40	114.5	114.2	114.9	115.0	114.7	115.5
50	113.6	113.3	114.0	114.1	113.9	114.7
60	113.0	112.6	113.3	113.5	113.2	114.0
70	112.4	112.1	112.8	112.9	112.6	113.4
80	112.0	111.6	112.3	112.5	112.2	112.9
90	111.6	111.3	111.9	112.1	111.7	112.6
96	111.4	111.1	111.7	111.9	111.5	112.3
100				111.8	111.4	112.2
110				111.5	111.1	111.9
120				111.2	110.8	111.6
130				111.0	110.5	111.4
140				110.8	110.3	111.2
150				110.6	110.1	111.0
152				110.6	110.1	111.0
G_{mb}	2.324	2.321	2.329	2.347	2.356	2.349
G_{mm}	2.454					

Table A.18 Gyratory Compaction Heights, G_{mb} and G_{mm} for Sandstone, 12.5 mm NMAS Fine-Graded, PG 76-22, N_{design} = 96

Mixture:	Sandstone12.5 mm NMAS, Fine-Graded, PG 76-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	133.8	134.3	138.7	134.1	135.2	136.5
1	128.4	129.0	133.3	128.9	129.9	131.1
2	126.0	126.5	130.8	126.5	127.6	128.5
3	124.3	124.7	129.0	124.8	125.8	126.8
4	123.1	123.4	127.7	123.5	124.6	125.4
5	122.0	122.3	126.6	122.4	123.5	124.4
6	121.2	121.4	125.7	121.6	122.7	123.5
7	120.5	120.7	124.9	120.8	122.0	122.7
8	119.8	120.1	124.3	120.2	121.3	122.1
9	119.3	119.5	123.7	119.7	120.8	121.5
10	118.8	119.0	123.2	119.2	120.3	121.0
20	115.7	115.8	119.9	116.0	117.2	117.7
30	114.0	114.1	118.2	114.3	115.4	116.0
40	112.8	112.9	117.0	113.2	114.3	114.8
50	112.0	112.0	116.2	112.4	113.5	113.9
60	111.4	111.4	115.6	111.8	112.9	113.2
70	111.0	110.9	115.1	111.3	112.3	112.7
80	110.6	110.5	114.7	110.8	111.9	112.3
90	110.2	110.1	114.4	110.5	111.6	111.9
96	110.0	110.0	114.2	110.3	111.4	111.7
100				110.2	111.3	111.6
110				109.9	111.0	111.3
120				109.7	110.8	111.1
130				109.4	110.5	110.9
140				109.3	110.4	110.7
150				109.1	110.2	110.5
152				109.1	110.1	110.5
G_{mb}	2.347	2.338	2.346	2.349	2.365	2.352
G_{mm}	2.440					

Table A.19 Gyratory Compaction Heights, G_{mb} and G_{mm} for Sandstone, 19.0 mm NMAS Fine-Graded, PG 67-22, N_{design} = 96

Mixture:	Sandstone 19.0 mm NMAS, Fine-Graded, PG 67-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	136.1	136.2	136.0	135.6	136.0	136.8
1	130.7	130.9	130.7	130.3	130.7	131.5
2	128.1	128.2	128.2	127.8	128.2	128.9
3	126.4	126.4	126.4	126.1	126.4	127.0
4	125.1	125.0	125.0	124.8	125.1	125.7
5	124.0	123.9	123.9	123.7	124.0	124.6
6	123.0	123.0	123.0	122.8	123.1	123.7
7	122.3	122.3	122.2	122.1	122.3	122.9
8	121.6	121.6	121.6	121.5	121.7	122.2
9	121.0	121.1	121.0	120.9	121.1	121.7
10	120.5	120.6	120.5	120.4	120.5	121.2
20	117.2	117.3	117.2	117.3	117.2	117.9
30	115.4	115.6	115.4	115.6	115.5	116.2
40	114.3	114.4	114.2	114.4	114.3	115.0
50	113.4	113.5	113.4	113.6	113.4	114.1
60	112.7	112.8	112.7	112.9	112.7	113.5
70	112.2	112.3	112.1	112.4	112.2	112.9
80	111.7	111.8	111.7	111.9	111.8	112.5
90	111.3	111.5	111.3	111.6	111.4	112.1
96	111.1	111.3	111.1	111.4	111.2	111.9
100				111.2	111.1	111.8
110				110.9	110.8	111.5
120				110.7	110.6	111.2
130				110.5	110.3	111.0
140				110.2	110.1	110.8
150				110.1	109.9	110.6
152				110.0	109.9	110.5
G_{mb}	2.349	2.325	2.329	2.370	2.368	2.362
G_{mm}	2.473					

Table A.20 Gyratory Compaction Heights, G_{mb} and G_{mm} for Sandstone, 19.0 mm NMAS Fine-Graded, PG 76-22, N_{design} = 96

Mixture:	Sandstone 19.0 mm NMAS, Fine-Graded, PG 76-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	136.1	136.2	136.0	135.6	136.0	136.8
1	130.7	130.9	130.7	130.3	130.7	131.5
2	128.1	128.2	128.2	127.8	128.2	128.9
3	126.4	126.4	126.4	126.1	126.4	127.0
4	125.1	125.0	125.0	124.8	125.1	125.7
5	124.0	123.9	123.9	123.7	124.0	124.6
6	123.0	123.0	123.0	122.8	123.1	123.7
7	122.3	122.3	122.2	122.1	122.3	122.9
8	121.6	121.6	121.6	121.5	121.7	122.2
9	121.0	121.1	121.0	120.9	121.1	121.7
10	120.5	120.6	120.5	120.4	120.5	121.2
20	117.2	117.3	117.2	117.3	117.2	117.9
30	115.4	115.6	115.4	115.6	115.5	116.2
40	114.3	114.4	114.2	114.4	114.3	115.0
50	113.4	113.5	113.4	113.6	113.4	114.1
60	112.7	112.8	112.7	112.9	112.7	113.5
70	112.2	112.3	112.1	112.4	112.2	112.9
80	111.7	111.8	111.7	111.9	111.8	112.5
90	111.3	111.5	111.3	111.6	111.4	112.1
96	111.1	111.3	111.1	111.4	111.2	111.9
100				111.2	111.1	111.8
110				110.9	110.8	111.5
120				110.7	110.6	111.2
130				110.5	110.3	111.0
140				110.2	110.1	110.8
150				110.1	109.9	110.6
152				110.0	109.9	110.5
G_{mb}	2.371	2.377	2.356	2.390	2.392	2.384
G_{mm}	2.470					

Table A.21 Gyratory Compaction Heights, G_{mb} and G_{mm} for Sandstone, 12.5 mm NMAS Coarse-Graded, PG 67-22, N_{design} = 96

Mixture:	Sandstone 12.5 mm NMAS, Coarse-Graded, PG 67-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	141.3	141.6	135.6	142.4	142.6	141.4
1	135.6	135.7	133.1	136.8	137.0	135.8
2	132.6	132.8	131.2	133.9	133.9	132.8
3	130.5	130.7	129.7	132.0	131.8	130.7
4	128.9	129.0	128.5	130.4	130.3	129.1
5	127.5	127.7	127.5	129.1	129.0	127.8
6	126.4	126.6	126.6	128.0	127.9	126.7
7	125.4	125.6	125.9	127.1	126.9	125.8
8	124.6	124.8	125.1	126.3	126.1	125.0
9	123.9	124.0	124.5	125.6	125.3	124.2
10	123.2	123.4	124.0	124.9	124.7	123.6
20	118.8	119.1	120.1	120.8	120.3	119.4
30	116.4	116.6	117.8	118.4	117.9	117.1
40	114.8	115.0	116.2	116.8	116.2	115.5
50	113.6	113.8	115.0	115.6	115.0	114.3
60	112.6	112.9	114.1	114.6	114.0	113.3
70	111.8	112.2	113.4	113.9	113.2	112.5
80	111.2	111.6	112.8	113.2	112.5	111.9
90	110.6	111.0	112.2	112.7	111.9	111.3
96	110.4	110.8	112.0	112.4	111.6	111.0
100				112.2	111.4	110.8
110				111.8	111.0	110.4
120				111.4	110.6	110.0
130				111.1	110.3	109.7
140				110.8	110.0	109.4
150				110.5	109.7	109.1
152				110.5	109.7	109.1
G_{mb}	2.357	2.347	2.341	2.368	2.377	2.375
G_{mm}	2.430					

Table A.22 Gyratory Compaction Heights, G_{mb} and G_{mm} for Sandstone, 12.5 mm NMAS Coarse-Graded, PG 76-22, N_{design} = 96

Mixture:	Sandstone 12.5 mm NMAS, Coarse-Graded, PG 76-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	140.1	140.4	137.8	144.3	141.1	140.8
1	134.4	134.8	132.2	138.7	135.6	135.1
2	131.6	132.1	129.5	135.9	132.9	132.3
3	129.7	130.1	127.6	133.9	131.0	130.3
4	128.2	128.7	126.1	132.4	129.5	128.8
5	127.0	127.4	124.9	131.2	128.3	127.6
6	126.0	126.4	123.9	130.2	127.4	126.6
7	125.2	125.5	123.0	129.3	126.5	125.7
8	124.4	124.8	122.3	128.5	125.8	124.9
9	123.8	124.1	121.6	127.8	125.1	124.2
10	123.2	123.5	121.0	127.2	124.5	123.6
20	119.3	119.5	117.1	123.1	120.6	119.6
30	117.1	117.3	114.9	120.8	118.4	117.4
40	115.6	115.7	113.4	119.2	117.0	115.9
50	114.5	114.6	112.3	118.0	115.9	114.8
60	113.7	113.7	111.4	117.1	115.0	113.9
70	113.0	113.0	110.7	116.4	114.3	113.3
80	112.4	112.4	110.1	115.8	113.7	112.7
90	111.9	111.9	109.6	115.2	113.2	112.2
96	111.7	111.6	109.3	114.9	113.0	112.0
100				114.7	112.8	111.8
110				114.3	112.4	111.5
120				114.0	112.1	111.2
130				113.6	111.8	110.9
140				113.3	111.5	110.6
150				113.1	111.3	110.4
152				113.0	111.2	110.4
G_{mb}	2.302	2.303	2.338	2.346	2.328	2.360
G_{mm}	2.435					

Table A.23 Gyratory Compaction Heights, G_{mb} and G_{mm} for Sandstone, 19.0 mm NMAS Coarse-Graded, PG 67-22, N_{design} = 96

Mixture:	Sandstone 19.0 mm NMAS, Coarse-Graded, PG 67-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	140.7	140.1	140.8	141.3	141.0	140.3
1	135.1	134.5	135.2	135.6	135.4	134.8
2	132.3	131.7	132.4	132.8	132.6	132.0
3	130.3	129.8	130.5	130.8	130.6	130.1
4	128.8	128.3	128.9	129.2	129.0	128.5
5	127.6	127.0	127.7	127.9	127.8	127.3
6	126.5	125.9	126.7	126.8	126.7	126.3
7	125.6	125.1	125.8	125.9	125.8	125.4
8	124.8	124.3	125.0	125.1	125.1	124.6
9	124.1	123.6	124.3	124.4	124.4	123.9
10	123.5	122.9	123.6	123.8	123.8	123.3
20	119.5	118.9	119.6	119.6	119.8	119.3
30	117.2	116.6	117.3	117.2	117.5	117.0
40	115.7	115.1	115.7	115.7	115.9	115.5
50	114.5	113.9	114.6	114.5	114.8	114.4
60	113.6	113.0	113.6	113.6	113.9	113.4
70	112.9	112.3	112.9	112.8	113.1	112.7
80	112.3	111.7	112.2	112.2	112.5	112.1
90	111.8	111.2	111.7	111.7	111.9	111.6
96	111.5	111.0	111.4	111.4	111.7	111.3
100				111.2	111.5	111.1
110				110.8	111.1	110.7
120				110.4	110.7	110.4
130				110.1	110.4	110.1
140				109.8	110.1	109.8
150				109.5	109.8	109.6
152				109.5	109.8	109.5
G_{mb}	2.346	2.356	2.350	2.383	2.373	2.367
G_{mm}	2.440					

Table A.24 Gyratory Compaction Heights, G_{mb} and G_{mm} for Sandstone, 19.0 mm NMAS Coarse-Graded, PG 76-22, N_{design} = 96

Mixture:	Sandstone 19.0 mm NMAS, Coarse-Graded, PG 76-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	134.8	139.2	141.1	136.8	137.3	139.3
1	129.5	133.5	135.3	131.3	131.8	133.9
2	126.9	130.8	132.6	128.7	129.1	131.3
3	125.1	128.9	130.6	126.9	127.3	129.4
4	123.6	127.4	129.1	125.5	125.8	127.9
5	122.5	126.2	127.9	124.3	124.6	126.8
6	121.6	125.2	126.9	123.4	123.6	125.7
7	120.8	124.3	126.0	122.6	122.8	124.9
8	120.0	123.6	125.2	121.8	122.0	124.1
9	119.4	122.9	124.5	121.2	121.4	123.5
10	118.8	122.3	123.9	120.6	120.8	122.9
20	115.0	118.4	119.9	116.9	117.0	119.0
30	112.9	116.3	117.6	114.8	114.8	116.8
40	111.4	114.8	116.1	113.4	113.4	115.4
50	110.3	113.7	115.0	112.4	112.3	114.3
60	109.5	112.8	114.2	111.6	111.5	113.4
70	108.8	112.1	113.5	111.0	110.8	112.8
80	108.3	111.5	112.9	110.4	110.3	112.2
90	107.8	111.0	112.5	110.0	109.8	111.8
96	107.6	110.7	112.2	109.7	109.6	111.5
100				109.6	109.4	111.4
110				109.2	109.1	111.0
120				108.9	108.7	110.7
130				108.6	108.5	110.4
140				108.4	108.2	110.2
150				108.1	108.0	109.9
152				108.1	107.9	109.9
G_{mb}	2.351	2.350	2.363	2.363	2.374	2.370
G_{mm}	2.422					

Table A.25 Gyratory Compaction Heights, G_{mb} and G_{mm} for Sandstone, 12.5 mm NMAS Fine-Graded, PG 67-22, N_{design} = 119

Mixture:	Sandstone 12.5 mm NMAS, Fine-Graded, PG 67-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	136.1	136.4	136.2	136.6	135.3	136.3
1	130.6	131.0	130.8	131.2	130.0	130.9
2	128.1	128.4	128.2	128.6	127.4	128.3
3	126.2	126.6	126.4	126.8	125.6	126.5
4	124.8	125.2	125.0	125.5	124.3	125.1
5	123.7	124.2	124.0	124.4	123.2	124.0
6	122.9	123.2	123.1	123.5	122.3	123.1
7	122.1	122.5	122.3	122.8	121.6	122.3
8	121.4	121.8	121.7	122.1	121.0	121.6
9	120.8	121.2	121.1	121.5	120.4	121.0
10	120.3	120.7	120.6	121.0	119.9	120.5
20	117.0	117.4	117.4	117.8	116.7	117.3
30	115.2	115.6	115.6	116.1	115.0	115.5
40	114.0	114.3	114.4	114.9	113.8	114.3
50	113.2	113.4	113.5	114.0	113.0	113.5
60	112.5	112.7	112.8	113.3	112.3	112.8
70	111.9	112.2	112.3	112.8	111.8	112.3
80	111.5	111.7	111.8	112.3	111.4	111.8
90	111.1	111.3	111.4	111.9	111.0	111.4
100	110.8	111.0	111.1	111.6	110.6	111.1
110	110.5	110.7	110.7	111.3	110.4	110.8
119	110.3	110.4	110.5	111.0	110.1	110.6
120				111.0	110.1	110.6
130				110.8	109.9	110.3
140				110.6	109.7	110.1
150				110.4	109.5	109.9
160				110.2	109.3	109.8
170				110.0	109.1	109.6
180				109.9	109.0	109.4
190				109.7	108.9	109.3
192				109.7	108.8	109.3
G_{mb}	2.339	2.336	2.327	2.359	2.374	2.369
G_{mm}	2.465					

Table A.26 Gyratory Compaction Heights, G_{mb} and G_{mm} for Sandstone, 12.5 mm NMAS Fine-Graded, PG 76-22, N_{design} = 119

Mixture:	Sandstone 12.5 mm NMAS, Fine-Graded, PG 76-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	135.1	135.6	137.1	135.6	135.5	135.5
1	129.9	130.3	131.8	130.5	130.4	130.3
2	127.5	127.8	129.4	128.1	127.9	127.8
3	125.7	126.1	127.7	126.4	126.2	126.1
4	124.4	124.7	126.4	125.2	124.9	124.8
5	123.4	123.7	125.4	124.2	123.9	123.8
6	122.6	122.8	124.5	123.3	123.0	123.0
7	121.8	122.1	123.8	122.6	122.3	122.2
8	121.2	121.5	123.1	122.0	121.7	121.6
9	120.7	120.9	122.6	121.5	121.2	121.1
10	120.2	120.4	122.1	121.0	120.7	120.6
20	117.1	117.2	118.9	118.0	117.6	117.5
30	115.3	115.5	117.2	116.3	115.9	115.7
40	114.2	114.3	116.0	115.2	114.8	114.6
50	113.4	113.5	115.2	114.4	114.0	113.8
60	112.7	112.8	114.5	113.8	113.4	113.1
70	112.2	112.3	114.0	113.2	113.0	112.6
80	111.8	111.9	113.5	112.8	112.6	112.2
90	111.4	111.6	113.2	112.5	112.2	111.8
100	111.1	111.3	112.8	112.2	111.9	111.5
110	110.8	111.0	112.6	111.9	111.7	111.2
119	110.6	110.8	112.4	111.7	111.5	111.0
120				111.7	111.5	111.0
130				111.5	111.3	110.8
140				111.3	111.1	110.6
150				111.1	110.9	110.4
160				110.9	110.8	110.2
170				110.8	110.7	110.1
180				110.7	110.5	110.0
190				110.5	110.4	109.8
192				110.5	110.4	109.8
G_{mb}	2.348	2.334	2.343	2.360	2.374	2.362
G_{mm}	2.465					

Table A.27 Gyratory Compaction Heights, G_{mb} and G_{mm} for Sandstone, 19.0 mm NMAS Fine-Graded, PG 67-22, N_{design} = 119

Mixture:	Sandstone 19.0 mm NMAS, Fine-Graded, PG 67-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	135.1	136.2	138.2	137.1	137.5	139.2
1	129.8	130.9	132.9	131.9	132.1	133.8
2	127.2	128.4	130.3	129.4	129.6	131.3
3	125.5	126.7	128.6	127.6	127.8	129.5
4	124.2	125.4	127.3	126.3	126.5	128.1
5	123.2	124.4	126.2	125.3	125.4	127.1
6	122.3	123.6	125.4	124.4	124.5	126.2
7	121.6	122.9	124.6	123.6	123.8	125.4
8	121.0	122.3	124.0	123.0	123.1	124.7
9	120.4	121.7	123.4	122.4	122.5	124.2
10	119.9	121.2	122.9	121.9	122.0	123.7
20	116.8	118.1	119.6	118.7	118.7	120.4
30	115.1	116.4	117.8	116.9	116.9	118.6
40	114.0	115.3	116.6	115.8	115.7	117.4
50	113.1	114.4	115.7	114.9	114.8	116.4
60	112.5	113.7	115.0	114.2	114.1	115.7
70	111.9	113.2	114.4	113.6	113.5	115.1
80	111.4	112.7	114.0	113.1	113.0	114.6
90	111.0	112.3	113.6	112.7	112.6	114.2
100	110.7	111.9	113.2	112.4	112.3	113.9
110	110.4	111.6	112.9	112.1	111.9	113.5
119	110.1	111.4	112.7	111.8	111.7	113.3
120				111.8	111.7	113.3
130				111.6	111.4	113.0
140				111.3	111.2	112.8
150				111.1	111.0	112.6
160				111.0	110.8	112.4
170				110.8	110.6	112.2
180				110.6	110.4	112.1
190				110.5	110.3	111.9
192				110.4	110.3	111.9
G_{mb}	2.342	2.340	2.333	2.360	2.353	2.346
G_{mm}	2.473					

Table A.28 Gyratory Compaction Heights, G_{mb} and G_{mm} for Sandstone, 19.0 mm NMAS Fine-Graded, PG 76-22, N_{design} = 119

Mixture:	Sandstone 19.0 mm NMAS, Fine-Graded, PG 76-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	135.1	136.2	138.2	137.1	137.5	139.2
1	129.8	130.9	132.9	131.9	132.1	133.8
2	127.2	128.4	130.3	129.4	129.6	131.3
3	125.5	126.7	128.6	127.6	127.8	129.5
4	124.2	125.4	127.3	126.3	126.5	128.1
5	123.2	124.4	126.2	125.3	125.4	127.1
6	122.3	123.6	125.4	124.4	124.5	126.2
7	121.6	122.9	124.6	123.6	123.8	125.4
8	121.0	122.3	124.0	123.0	123.1	124.7
9	120.4	121.7	123.4	122.4	122.5	124.2
10	119.9	121.2	122.9	121.9	122.0	123.7
20	116.8	118.1	119.6	118.7	118.7	120.4
30	115.1	116.4	117.8	116.9	116.9	118.6
40	114.0	115.3	116.6	115.8	115.7	117.4
50	113.1	114.4	115.7	114.9	114.8	116.4
60	112.5	113.7	115.0	114.2	114.1	115.7
70	111.9	113.2	114.4	113.6	113.5	115.1
80	111.4	112.7	114.0	113.1	113.0	114.6
90	111.0	112.3	113.6	112.7	112.6	114.2
100	110.7	111.9	113.2	112.4	112.3	113.9
110	110.4	111.6	112.9	112.1	111.9	113.5
119	110.1	111.4	112.7	111.8	111.7	113.3
120				111.8	111.7	113.3
130				111.6	111.4	113.0
140				111.3	111.2	112.8
150				111.1	111.0	112.6
160				111.0	110.8	112.4
170				110.8	110.6	112.2
180				110.6	110.4	112.1
190				110.5	110.3	111.9
192				110.4	110.3	111.9
G_{mb}	2.376	2.385	2.376	2.400	2.389	2.399
G_{mm}	2.473					

Table A.29 Gyratory Compaction Heights, G_{mb} and G_{mm} for Sandstone, 12.5 mm NMAS Coarse-Graded, PG 67-22, N_{design} = 119

Mixture:	Sandstone 12.5 mm NMAS, Coarse-Graded, PG 67-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	142.1	142.5	141.9	140.4	142.4	143.5
1	136.5	136.8	136.3	135.0	136.7	137.8
2	133.6	134.0	133.4	132.2	133.8	134.8
3	131.5	131.9	131.4	130.2	131.7	132.7
4	130.0	130.3	129.8	128.7	130.1	131.0
5	128.7	129.0	128.5	127.4	128.8	129.7
6	127.6	127.9	127.4	126.4	127.7	128.6
7	126.7	127.0	126.5	125.5	126.7	127.6
8	125.8	126.2	125.7	124.7	125.9	126.8
9	125.1	125.5	125.0	124.0	125.2	126.0
10	124.5	124.8	124.4	123.4	124.6	125.4
20	120.2	120.5	120.1	119.3	120.4	121.0
30	117.8	118.1	117.7	116.9	118.0	118.5
40	116.2	116.5	116.1	115.3	116.4	116.8
50	115.0	115.2	114.8	114.1	115.3	115.6
60	114.0	114.3	113.9	113.2	114.3	114.6
70	113.2	113.5	113.1	112.4	113.6	113.8
80	112.6	112.8	112.4	111.8	112.9	113.2
90	112.0	112.2	111.9	111.2	112.4	112.6
100	111.5	111.8	111.4	110.8	111.9	112.2
110	111.1	111.3	110.9	110.3	111.5	111.8
119	110.8	111.0	110.6	110.0	111.1	111.4
120				109.9	111.1	111.4
130				109.6	110.8	111.1
140				109.3	110.5	110.8
150				109.0	110.2	110.5
160				108.8	109.9	110.3
170				108.5	109.7	110.0
180				108.3	109.5	109.8
190				108.1	109.3	109.6
192				108.1	109.2	109.6
G_{mb}	2.360	2.352	2.365	2.382	2.375	2.401
G_{mm}	2.433					

Table A.30 Gyratory Compaction Heights, G_{mb} and G_{mm} for Sandstone, 12.5 mm NMAS Coarse-Graded, PG 76-22, N_{design} = 119

Mixture:	Sandstone 12.5 mm NMAS, Coarse-Graded, PG 76-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	128.1	141.3	142.7	141.4	141.9	143.1
1	127.0	135.7	137.0	135.8	136.2	137.4
2	126.1	133.1	134.1	133.0	133.4	134.6
3	125.3	131.1	132.0	131.1	131.4	132.6
4	124.6	129.6	130.5	129.6	129.9	131.1
5	124.0	128.3	129.2	128.3	128.6	129.8
6	123.5	127.3	128.2	127.3	127.6	128.8
7	123.0	126.4	127.3	126.4	126.8	127.9
8	122.5	125.6	126.5	125.6	126.0	127.1
9	122.0	125.0	125.8	124.9	125.3	126.5
10	121.6	124.4	125.2	124.3	124.7	125.8
20	118.7	120.4	121.1	120.2	120.8	121.8
30	116.9	118.1	118.8	118.0	118.5	119.6
40	115.6	116.6	117.2	116.4	117.0	118.1
50	114.7	115.5	116.1	115.3	115.9	116.9
60	114.0	114.6	115.1	114.4	115.0	116.0
70	113.4	113.9	114.4	113.7	114.3	115.3
80	112.9	113.3	113.8	113.1	113.7	114.7
90	112.5	112.8	113.2	112.7	113.2	114.2
100	112.1	112.4	112.8	112.2	112.7	113.7
110	111.8	112.0	112.4	111.9	112.3	113.4
119	111.7	111.8	112.1	111.6	112.0	113.1
120				109.9	111.1	111.4
130				109.6	110.8	111.1
140				109.3	110.5	110.8
150				109.0	110.2	110.5
160				108.8	109.9	110.3
170				108.5	109.7	110.0
180				108.3	109.5	109.8
190				108.1	109.3	109.6
192				108.1	109.2	109.6
G_{mb}	2.369	2.354	2.345	2.367	2.385	2.369
G_{mm}	2.437					

Table A.31 Gyratory Compaction Heights, G_{mb} and G_{mm} for Sandstone, 19.0 mm NMAS Coarse-Graded, PG 67-22, N_{design} = 119

Mixture:	Sandstone 19.0 mm NMAS, Coarse-Graded, PG 67-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	139.7	141.5	140.4	140.7	141.2	141.1
1	134.1	135.9	134.8	135.2	135.7	135.7
2	131.4	133.2	131.9	132.5	132.8	132.9
3	129.5	131.1	129.9	130.5	130.9	130.9
4	128.0	129.6	128.4	129.0	129.4	129.3
5	126.7	128.4	127.2	127.8	128.1	128.1
6	125.7	127.3	126.1	126.7	127.1	127.0
7	124.8	126.4	125.2	125.9	126.2	126.1
8	124.0	125.6	124.4	125.1	125.4	125.3
9	123.3	124.9	123.7	124.4	124.7	124.6
10	122.7	124.2	123.1	123.8	124.1	123.9
20	118.6	120.1	119.0	119.7	120.0	119.9
30	116.4	117.8	116.8	117.5	117.7	117.6
40	114.9	116.2	115.3	115.9	116.2	116.1
50	113.7	115.1	114.2	114.8	115.1	114.9
60	112.9	114.2	113.3	113.9	114.2	114.0
70	112.1	113.4	112.5	113.2	113.4	113.3
80	111.5	112.8	111.9	112.6	112.8	112.6
90	111.0	112.3	111.4	112.1	112.3	112.1
100	110.6	111.9	110.9	111.6	111.9	111.6
110	110.2	111.5	110.5	111.2	111.5	111.2
119	109.9	111.2	110.2	110.9	111.2	110.9
120				110.9	111.1	110.9
130				110.5	110.8	110.6
140				110.2	110.5	110.3
150				110.0	110.2	110.0
160				109.7	110.0	109.8
170				109.5	109.8	109.5
180				109.3	109.6	109.3
190				109.1	109.4	109.1
192				109.1	109.3	109.1
G_{mb}	2.375	2.368	2.378	2.393	2.390	2.381
G_{mm}	2.452					

Table A.32 Gyratory Compaction Heights, G_{mb} and G_{mm} for Sandstone, 19.0 mm NMAS Coarse-Graded, PG 76-22, N_{design} = 119

Mixture:	Sandstone 19.0 mm NMAS, Coarse-Graded, PG 76-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	137.2	141.1	140.6	138.3	142.3	139.7
1	131.7	135.6	135.0	132.9	136.7	134.2
2	129.1	132.8	132.2	130.2	133.9	131.5
3	127.2	130.9	130.3	128.3	131.9	129.6
4	125.8	129.4	128.8	126.9	130.4	128.1
5	124.6	128.3	127.6	125.7	129.1	126.9
6	123.6	127.2	126.6	124.7	128.1	125.9
7	122.7	126.4	125.7	123.9	127.2	125.1
8	122.0	125.6	124.9	123.2	126.4	124.3
9	121.3	125.0	124.3	122.5	125.7	123.6
10	120.7	124.4	123.7	121.9	125.1	123.0
20	116.8	120.4	119.7	118.0	121.0	119.1
30	114.6	118.2	117.5	115.8	118.7	116.8
40	113.1	116.7	116.0	114.3	117.2	115.2
50	112.0	115.5	114.8	113.2	116.0	114.0
60	111.1	114.7	113.9	112.4	115.1	113.1
70	110.4	114.0	113.1	111.7	114.4	112.4
80	109.8	113.4	112.5	111.1	113.8	111.7
90	109.2	112.9	112.0	110.6	113.3	111.2
100	108.8	112.4	111.5	110.1	112.8	110.8
110	108.4	112.1	111.1	109.7	112.5	110.4
119	108.1	111.8	110.8	109.4	112.1	110.0
120				109.4	112.1	110.0
130				109.1	111.8	109.7
140				108.8	111.5	109.4
150				108.6	111.3	109.2
160				108.3	111.0	108.9
170				108.1	110.8	108.7
180				107.9	110.6	108.5
190				107.7	110.4	108.3
192				107.7	110.4	108.3
G_{mb}	2.299	2.324	2.314	2.339	2.359	2.325
G_{mm}	2.434					

Table A.33 Gyratory Compaction Heights, G_{mb} and G_{mm} for Limestone/Gravel, 12.5 mm NMAS Fine-Graded, PG 67-22, N_{design} = 96

Mixture:	Limestone/Gravel 12.5 mm NMAS, Fine-Graded, PG 67-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	136.3	136.2	137.2	137.2	136.0	139.4
1	131.0	130.8	132.0	131.8	130.7	134.0
2	128.4	128.3	129.5	129.4	128.2	131.4
3	126.7	126.6	127.8	127.6	126.6	129.6
4	125.4	125.3	126.4	126.3	125.3	128.2
5	124.3	124.2	125.4	125.2	124.2	127.1
6	123.4	123.4	124.5	124.3	123.4	126.2
7	122.7	122.6	123.8	123.6	122.6	125.4
8	122.1	122.0	123.1	122.9	122.0	124.7
9	121.5	121.4	122.6	122.4	121.5	124.1
10	121.0	120.9	122.1	121.9	121.0	123.6
20	117.8	117.8	118.9	118.7	117.9	120.2
30	116.1	116.1	117.2	117.0	116.2	118.3
40	114.9	115.0	116.0	115.8	115.1	117.1
50	114.1	114.1	115.2	115.0	114.2	116.2
60	113.4	113.5	114.5	114.3	113.6	115.5
70	112.9	113.0	114.0	113.8	113.1	114.9
80	112.4	112.5	113.6	113.4	112.7	114.4
90	112.1	112.2	113.2	113.0	112.3	114.0
96	111.9	112.0	113.0	112.8	112.1	113.8
100				112.7	112.0	113.7
110				112.4	111.7	113.4
120				112.2	111.5	113.1
130				112.0	111.3	112.9
140				111.8	111.1	112.7
150				111.6	110.9	112.5
152				111.6	110.9	112.5
G_{mb}	2.304	2.304	2.309	2.338	2.339	2.317
G_{mm}	2.424					

Table A.34 Gyratory Compaction Heights, G_{mb} and G_{mm} for Limestone/Gravel, 12.5 mm NMAS Fine-Graded, PG 76-22, N_{design} = 96

Mixture:	Limestone/Gravel 12.5 mm NMAS, Fine-Graded, PG 76-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	134.1	135.1	136.6	137.5	137.8	136.8
1	128.8	129.9	131.3	132.2	132.5	131.5
2	126.5	127.5	128.8	129.7	130.0	129.1
3	124.9	125.8	127.1	127.9	128.3	127.5
4	123.6	124.6	125.8	126.6	127.0	126.2
5	122.7	123.6	124.8	125.6	126.0	125.2
6	121.9	122.8	123.9	124.7	125.1	124.4
7	121.2	122.1	123.2	124.0	124.4	123.7
8	120.6	121.5	122.6	123.3	123.8	123.1
9	120.1	121.0	122.1	122.8	123.2	122.5
10	119.6	120.5	121.6	122.3	122.7	122.0
20	116.7	117.6	118.5	119.1	119.6	119.0
30	115.1	116.0	116.9	117.4	117.9	117.3
40	114.0	114.9	115.8	116.3	116.8	116.2
50	113.2	114.1	114.9	115.4	116.0	115.4
60	112.6	113.5	114.3	114.8	115.3	114.8
70	112.1	113.0	113.8	114.2	114.8	114.3
80	111.7	112.6	113.4	113.8	114.4	113.8
90	111.3	112.2	113.0	113.4	114.0	113.5
96	111.1	112.1	112.8	113.2	113.8	113.3
100				113.0	113.7	113.1
110				112.8	113.4	112.8
120				112.5	113.1	112.6
130				112.3	112.9	112.4
140				112.1	112.7	112.2
150				111.9	112.5	112.0
152				111.8	112.5	112.0
G_{mb}	2.299	2.302	2.294	2.319	2.317	2.317
G_{mm}	2.424					

Table A.35 Gyratory Compaction Heights, G_{mb} and G_{mm} for Limestone/Gravel, 19.0 mm NMAS Fine-Graded, PG 67-22, N_{design} = 96

Mixture:	Limestone/Gravel 19.0 mm NMAS, Fine-Graded, PG 67-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	133.6	132.1	132.0	132.1	132.1	132.6
1	128.4	127.1	126.9	127.1	127.1	127.5
2	126.0	124.8	124.5	124.8	124.7	125.2
3	124.4	123.2	122.9	123.2	123.1	123.7
4	123.2	122.0	121.6	122.1	121.9	122.5
5	122.2	121.1	120.7	121.1	120.9	121.6
6	121.4	120.3	119.9	120.3	120.1	120.8
7	120.7	119.6	119.2	119.7	119.5	120.1
8	120.1	119.0	118.7	119.2	118.9	119.6
9	119.6	118.6	118.2	118.7	118.4	119.1
10	119.1	118.1	117.7	118.2	117.9	118.7
20	116.2	115.4	114.8	115.4	115.1	115.8
30	114.6	113.8	113.2	113.9	113.5	114.3
40	113.5	112.8	112.2	112.9	112.5	113.3
50	112.7	112.1	111.4	112.1	111.7	112.5
60	112.1	111.5	110.9	111.5	111.1	111.9
70	111.6	111.1	110.4	111.0	110.7	111.4
80	111.1	110.7	110.0	110.6	110.3	111.0
90	110.8	110.4	109.7	110.3	110.0	110.7
96	110.6	110.2	109.5	110.1	109.8	110.5
100				110.0	109.7	110.4
110				109.8	109.4	110.1
120				109.5	109.2	109.9
130				109.3	109.0	109.7
140				109.1	108.8	109.5
150				109.0	108.6	109.3
152				109.0	108.6	109.3
G_{mb}	2.349	2.325	2.329	2.370	2.368	2.362
G_{mm}	2.433					

Table A.36 Gyratory Compaction Heights, G_{mb} and G_{mm} for Limestone/Gravel, 19.0 mm NMAS Fine-Graded, PG 76-22, N_{design} = 96

Mixture:	Limestone/Gravel 19.0 mm NMAS, Fine-Graded, PG 76-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	131.6	131.1	133.8	132.9	133.3	133.3
1	126.5	126.1	128.8	128.0	128.3	128.4
2	124.1	123.9	126.5	125.7	126.1	126.1
3	122.5	122.4	124.9	124.2	124.5	124.5
4	121.3	121.2	123.6	123.0	123.3	123.3
5	120.4	120.2	122.7	122.0	122.4	122.4
6	119.6	119.5	121.9	121.3	121.6	121.6
7	118.9	118.8	121.2	120.6	120.9	120.9
8	118.3	118.3	120.6	120.0	120.3	120.4
9	117.9	117.8	120.1	119.5	119.8	119.8
10	117.4	117.3	119.6	119.1	119.3	119.4
20	114.5	114.5	116.7	116.2	116.5	116.5
30	112.9	113.0	115.0	114.6	114.9	114.9
40	111.9	112.0	113.9	113.5	113.9	113.8
50	111.1	111.2	113.1	112.7	113.1	113.1
60	110.6	110.7	112.5	112.2	112.5	112.5
70	110.1	110.2	112.0	111.7	112.1	112.0
80	109.8	109.8	111.6	111.3	111.7	111.7
90	109.5	109.5	111.3	111.0	111.4	111.4
96	109.3	109.4	111.1	110.8	111.2	111.2
100				110.7	111.1	111.1
110				110.5	110.8	110.9
120				110.3	110.6	110.7
130				110.1	110.4	110.5
140				110.0	110.2	110.4
150				109.8	110.1	110.2
152				109.8	110.1	110.2
G_{mb}	2.358	2.357	2.351	2.372	2.370	2.364
G_{mm}	2.442					

Table A.37 Gyratory Compaction Heights, G_{mb} and G_{mm} for Limestone/Gravel, 12.5 mm NMAS Coarse-Graded, PG 67-22, N_{design} = 96

Mixture:	Limestone/Gravel 12.5 mm NMAS, Coarse-Graded, PG 67-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	133.6	132.1	132.0	132.1	132.1	132.6
1	128.4	127.1	126.9	127.1	127.1	127.5
2	126.0	124.8	124.5	124.8	124.7	125.2
3	124.4	123.2	122.9	123.2	123.1	123.7
4	123.2	122.0	121.6	122.1	121.9	122.5
5	122.2	121.1	120.7	121.1	120.9	121.6
6	121.4	120.3	119.9	120.3	120.1	120.8
7	120.7	119.6	119.2	119.7	119.5	120.1
8	120.1	119.0	118.7	119.2	118.9	119.6
9	119.6	118.6	118.2	118.7	118.4	119.1
10	119.1	118.1	117.7	118.2	117.9	118.7
20	116.2	115.4	114.8	115.4	115.1	115.8
30	114.6	113.8	113.2	113.9	113.5	114.3
40	113.5	112.8	112.2	112.9	112.5	113.3
50	112.7	112.1	111.4	112.1	111.7	112.5
60	112.1	111.5	110.9	111.5	111.1	111.9
70	111.6	111.1	110.4	111.0	110.7	111.4
80	111.1	110.7	110.0	110.6	110.3	111.0
90	110.8	110.4	109.7	110.3	110.0	110.7
96	110.6	110.2	109.5	110.1	109.8	110.5
100				110.0	109.7	110.4
110				109.8	109.4	110.1
120				109.5	109.2	109.9
130				109.3	109.0	109.7
140				109.1	108.8	109.5
150				109.0	108.6	109.3
152				109.0	108.6	109.3
G_{mb}	2.306	2.312	2.300	2.335	2.329	2.342
G_{mm}	2.401					

Table A.38 Gyratory Compaction Heights, G_{mb} and G_{mm} for Limestone/Gravel, 12.5 mm NMAS Coarse-Graded, PG 76-22, N_{design} = 96

Mixture:	Limestone/Gravel 12.5 mm NMAS, Coarse-Graded, PG 76-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	139.3	138.4	138.4	139.1	139.2	141.5
1	134.0	133.1	133.1	133.6	133.8	136.1
2	131.4	130.6	130.6	131.1	131.2	133.5
3	129.6	128.9	128.8	129.3	129.4	131.7
4	128.3	127.5	127.5	128.0	128.1	130.4
5	127.2	126.5	126.4	126.9	127.0	129.3
6	126.3	125.6	125.5	125.9	126.1	128.3
7	125.5	124.9	124.8	125.2	125.3	127.6
8	124.8	124.2	124.2	124.5	124.7	126.9
9	124.2	123.6	123.6	123.9	124.1	126.3
10	123.7	123.1	123.1	123.4	123.6	125.7
20	120.3	119.8	119.8	120.1	120.3	122.3
30	118.4	118.1	118.1	118.3	118.4	120.5
40	117.2	116.8	116.9	117.1	117.2	119.3
50	116.2	115.9	115.9	116.2	116.3	118.3
60	115.5	115.2	115.3	115.5	115.6	117.6
70	114.9	114.7	114.7	114.9	115.0	117.1
80	114.4	114.2	114.2	114.5	114.5	116.6
90	114.0	113.8	113.8	114.1	114.1	116.2
96	113.8	113.6	113.6	113.8	113.8	116.0
100				113.7	113.7	115.9
110				113.4	113.4	115.6
120				113.1	113.1	115.3
130				112.9	112.8	115.1
140				112.7	112.6	114.9
150				112.5	112.4	114.7
152				112.5	112.4	114.7
G_{mb}	2.280	2.288	2.298	2.314	2.304	2.309
G_{mm}	2.397					

Table A.39 Gyratory Compaction Heights, G_{mb} and G_{mm} for Limestone/Gravel, 19.0 mm NMAS Coarse-Graded, PG 67-22, N_{design} = 96

Mixture:	Limestone/Gravel 19.0 mm NMAS, Coarse-Graded, PG 67-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	124.7	136.8	137.6	138.0	137.5	138.0
1	124.0	131.5	132.3	132.7	132.1	132.9
2	123.4	129.1	129.8	130.3	129.7	130.4
3	122.9	127.4	128.1	128.5	128.0	128.7
4	122.5	126.2	126.8	127.2	126.7	127.5
5	122.1	125.1	125.8	126.2	125.7	126.4
6	121.7	124.2	124.9	125.3	124.8	125.5
7	121.3	123.5	124.2	124.5	124.1	124.8
8	121.0	122.9	123.5	123.9	123.5	124.1
9	120.7	122.3	123.0	123.3	122.9	123.6
10	120.4	121.8	122.4	122.8	122.4	123.0
20	118.3	118.5	119.1	119.5	119.1	119.8
30	116.9	116.7	117.3	117.7	117.4	118.0
40	116.0	115.5	116.1	116.5	116.2	116.8
50	115.2	114.6	115.1	115.6	115.4	115.9
60	114.7	113.9	114.4	114.9	114.7	115.2
70	114.2	113.3	113.9	114.4	114.2	114.6
80	113.8	112.8	113.4	113.9	113.7	114.2
90	113.5	112.4	113.0	113.5	113.3	113.8
96	113.3	112.2	112.7	113.3	113.1	113.6
100				113.2	112.9	113.4
110				112.9	112.6	113.1
120				112.6	112.3	112.9
130				112.4	112.1	112.6
140				112.1	111.8	112.4
150				111.9	111.6	112.2
152				111.9	111.6	112.2
G_{mb}	2.314	2.329	2.316	2.355	2.351	2.350
G_{mm}	2.438					

Table A.40 Gyratory Compaction Heights, G_{mb} and G_{mm} for Limestone/Gravel, 19.0 mm NMAS Coarse-Graded, PG 76-22, N_{design} = 96

Mixture:	Limestone/Gravel 19.0 mm NMAS, Coarse-Graded, PG 76-22, Ndesign = 96					
	Height Data, mm					
	N_{design} = 96			$N_{maximum}$ = 152		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	133.5	134.6	135.9	133.9	135.8	136.6
1	128.2	129.4	130.7	128.7	130.6	131.3
2	125.8	127.1	128.2	126.4	128.2	128.8
3	124.1	125.4	126.6	124.8	126.6	127.1
4	122.9	124.2	125.3	123.5	125.3	125.8
5	121.8	123.2	124.4	122.5	124.4	124.8
6	121.0	122.4	123.5	121.7	123.5	123.9
7	120.3	121.7	122.8	121.0	122.8	123.2
8	119.7	121.1	122.2	120.4	122.2	122.6
9	119.1	120.5	121.7	119.9	121.7	122.1
10	118.7	120.0	121.2	119.4	121.2	121.6
20	115.6	117.0	118.2	116.4	118.1	118.5
30	113.9	115.3	116.5	114.7	116.4	116.8
40	112.8	114.2	115.4	113.6	115.3	115.7
50	112.0	113.4	114.6	112.7	114.4	114.9
60	111.4	112.8	113.9	112.1	113.8	114.2
70	110.9	112.3	113.4	111.6	113.3	113.7
80	110.5	111.8	113.0	111.2	112.8	113.3
90	110.1	111.5	112.7	110.8	112.5	112.9
96	110.0	111.3	112.5	110.7	112.3	112.7
100				110.5	112.2	112.6
110				110.3	111.9	112.3
120				110.0	111.7	112.1
130				109.8	111.5	111.8
140				109.6	111.3	111.6
150				109.4	111.1	111.4
152				109.4	111.1	111.4
G_{mb}	2.314	2.329	2.316	2.355	2.351	2.350
G_{mm}	2.435					

Table A.41 Gyratory Compaction Heights, G_{mb} and G_{mm} for Limestone/Gravel, 12.5 mm NMAS Fine-Graded, PG 67-22, N_{design} = 119

Mixture:	Limestone/Gravel 12.5 mm NMAS, Fine-Graded, PG 67-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	136.4	135.1	137.3	134.3	137.3	136.4
1	130.9	129.8	131.9	129.1	131.9	131.0
2	128.4	127.4	129.4	126.7	129.4	128.6
3	126.7	125.7	127.6	125.1	127.7	126.9
4	125.4	124.5	126.3	123.8	126.4	125.5
5	124.3	123.5	125.3	122.9	125.3	124.5
6	123.5	122.6	124.4	122.0	124.5	123.7
7	122.7	121.9	123.7	121.3	123.7	123.0
8	122.1	121.3	123.0	120.7	123.1	122.4
9	121.5	120.8	122.5	120.2	122.5	121.8
10	121.1	120.3	122.0	119.8	122.0	121.3
20	117.9	117.4	118.9	116.8	118.9	118.3
30	116.2	115.8	117.2	115.2	117.2	116.6
40	115.1	114.7	116.0	114.1	116.0	115.5
50	114.2	113.9	115.2	113.3	115.1	114.6
60	113.6	113.3	114.6	112.7	114.5	114.0
70	113.0	112.8	114.0	112.2	113.9	113.4
80	112.6	112.4	113.6	111.7	113.5	113.0
90	112.2	112.0	113.2	111.4	113.1	112.6
100	111.9	111.7	112.9	111.0	112.8	112.2
110	111.6	111.4	112.6	110.8	112.5	112.0
119	111.4	111.2	112.4	110.5	112.2	111.7
120				110.5	112.2	111.7
130				110.3	112.0	111.5
140				110.1	111.8	111.2
150				109.9	111.6	111.1
160				109.7	111.4	110.9
170				109.5	111.2	110.7
180				109.4	111.1	110.6
190				109.3	110.9	110.4
192				109.2	110.9	110.4
G_{mb}	2.331	2.323	2.321	2.360	2.349	2.343
G_{mm}	2.434					

Table A.42 Gyratory Compaction Heights, G_{mb} and G_{mm} for Limestone/Gravel, 12.5 mm NMAS Fine-Graded, PG 76-22, N_{design} = 119

Mixture:	Limestone/Gravel 12.5 mm NMAS, Fine-Graded, PG 76-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	137.1	137.1	136.2	136.6	136.8	136.6
1	131.6	131.6	131.1	131.3	131.6	131.4
2	129.1	129.1	128.7	128.8	129.1	129.0
3	127.4	127.4	127.1	127.2	127.5	127.3
4	126.1	126.1	125.9	125.9	126.2	126.1
5	125.1	125.1	124.9	124.9	125.2	125.1
6	124.3	124.3	124.1	124.0	124.4	124.3
7	123.6	123.6	123.4	123.3	123.7	123.6
8	122.9	122.9	122.8	122.7	123.1	123.0
9	122.4	122.4	122.3	122.2	122.5	122.5
10	121.9	121.9	121.8	121.7	122.0	122.0
20	118.8	118.8	118.8	118.6	118.9	119.0
30	117.2	117.2	117.2	117.0	117.3	117.4
40	116.0	116.0	116.1	115.9	116.2	116.4
50	115.2	115.2	115.3	115.1	115.3	115.6
60	114.6	114.6	114.7	114.4	114.7	115.0
70	114.0	114.0	114.2	113.9	114.2	114.4
80	113.6	113.6	113.8	113.5	113.7	114.0
90	113.2	113.2	113.4	113.1	113.3	113.7
100	112.9	112.9	113.1	112.8	113.0	113.3
110	112.6	112.6	112.8	112.5	112.7	113.1
119	112.4	112.4	112.6	112.3	112.5	112.8
120				112.2	112.5	112.8
130				112.0	112.3	112.6
140				111.8	112.1	112.4
150				111.6	111.9	112.2
160				111.5	111.7	112.0
170				111.3	111.5	111.9
180				111.2	111.4	111.7
190				111.0	111.3	111.6
192				111.0	111.2	111.6
G_{mb}	2.297	2.300	2.323	2.335	2.334	2.344
G_{mm}	2.424					

Table A.43 Gyratory Compaction Heights, G_{mb} and G_{mm} for Limestone/Gravel, 19.0 mm NMAS Fine-Graded, PG 67-22, N_{design} = 119

Mixture:	Limestone/Gravel 19.0 mm NMAS, Fine-Graded, PG 67-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	135.1	136.2	138.2	137.1	137.5	139.2
1	129.8	130.9	132.9	131.9	132.1	133.8
2	127.2	128.4	130.3	129.4	129.6	131.3
3	125.5	126.7	128.6	127.6	127.8	129.5
4	124.2	125.4	127.3	126.3	126.5	128.1
5	123.2	124.4	126.2	125.3	125.4	127.1
6	122.3	123.6	125.4	124.4	124.5	126.2
7	121.6	122.9	124.6	123.6	123.8	125.4
8	121.0	122.3	124.0	123.0	123.1	124.7
9	120.4	121.7	123.4	122.4	122.5	124.2
10	119.9	121.2	122.9	121.9	122.0	123.7
20	116.8	118.1	119.6	118.7	118.7	120.4
30	115.1	116.4	117.8	116.9	116.9	118.6
40	114.0	115.3	116.6	115.8	115.7	117.4
50	113.1	114.4	115.7	114.9	114.8	116.4
60	112.5	113.7	115.0	114.2	114.1	115.7
70	111.9	113.2	114.4	113.6	113.5	115.1
80	111.4	112.7	114.0	113.1	113.0	114.6
90	111.0	112.3	113.6	112.7	112.6	114.2
100	110.7	111.9	113.2	112.4	112.3	113.9
110	110.4	111.6	112.9	112.1	111.9	113.5
119	110.1	111.4	112.7	111.8	111.7	113.3
120				111.8	111.7	113.3
130				111.6	111.4	113.0
140				111.3	111.2	112.8
150				111.1	111.0	112.6
160				111.0	110.8	112.4
170				110.8	110.6	112.2
180				110.6	110.4	112.1
190				110.5	110.3	111.9
192				110.4	110.3	111.9
G_{mb}	2.359	2.364	2.357	2.378	2.382	2.380
G_{mm}	2.426					

Table A.44 Gyratory Compaction Heights, G_{mb} and G_{mm} for Limestone/Gravel, 19.0 mm NMAS Fine-Graded, PG 76-22, N_{design} = 119

Mixture:	Limestone/Gravel 19.0 mm NMAS, Fine-Graded, PG 76-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	134.3	132.9	134.6	130.0	134.8	131.3
1	129.2	127.9	129.6	125.0	129.8	126.5
2	126.9	125.5	127.3	122.7	127.4	124.3
3	125.4	124.0	125.7	121.2	125.8	122.8
4	124.2	122.8	124.5	120.0	124.6	121.7
5	123.2	121.9	123.6	119.1	123.6	120.7
6	122.5	121.1	122.8	118.3	122.8	120.0
7	121.8	120.4	122.1	117.7	122.1	119.3
8	121.2	119.9	121.5	117.2	121.6	118.8
9	120.7	119.4	121.0	116.7	121.0	118.3
10	120.3	118.9	120.5	116.2	120.6	117.8
20	117.3	116.1	117.6	113.4	117.7	115.0
30	115.7	114.5	116.0	111.9	116.1	113.5
40	114.7	113.4	114.9	110.9	115.1	112.5
50	113.9	112.7	114.2	110.2	114.3	111.8
60	113.4	112.1	113.6	109.6	113.7	111.3
70	112.9	111.6	113.1	109.2	113.3	110.8
80	112.5	111.3	112.7	108.8	112.9	110.5
90	112.2	111.0	112.4	108.5	112.6	110.2
100	111.9	110.7	112.1	108.3	112.3	109.9
110	111.7	110.5	111.9	108.1	112.1	109.7
119	111.5	110.3	111.7	107.9	111.9	109.5
120				107.9	111.9	109.5
130				107.7	111.7	109.3
140				107.5	111.6	109.2
150				107.4	111.4	109.0
160				107.3	111.3	108.9
170				107.2	111.2	108.8
180				107.0	111.1	108.7
190				106.9	111.0	108.6
192				106.9	111.0	108.5
G_{mb}	2.365	2.358	2.356	2.383	2.380	2.379
G_{mm}	2.442					

Table A.45 Gyratory Compaction Heights, G_{mb} and G_{mm} for Limestone/Gravel, 12.5 mm NMAS Coarse-Graded, PG 67-22, N_{design} = 119

Mixture:	Limestone/Gravel 12.5 mm NMAS, Coarse-Graded, PG 67-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	139.1	140.3	140.7	139.5	139.7	140.6
1	133.6	134.7	135.3	134.1	134.2	135.3
2	131.1	132.2	132.7	131.6	131.6	132.8
3	129.3	130.5	130.9	129.8	129.9	131.0
4	128.0	129.2	129.5	128.4	128.5	129.7
5	126.9	128.1	128.4	127.3	127.4	128.6
6	126.0	127.3	127.5	126.4	126.5	127.7
7	125.3	126.5	126.7	125.6	125.8	126.9
8	124.6	125.9	126.0	125.0	125.1	126.2
9	124.0	125.3	125.4	124.4	124.5	125.7
10	123.5	124.8	124.9	123.9	124.0	125.1
20	120.2	121.5	121.6	120.5	120.7	121.8
30	118.4	119.7	119.8	118.6	118.9	120.0
40	117.2	118.5	118.6	117.3	117.6	118.7
50	116.3	117.5	117.7	116.4	116.7	117.8
60	115.6	116.8	116.9	115.7	116.0	117.1
70	115.0	116.2	116.4	115.1	115.4	116.5
80	114.5	115.7	115.9	114.5	114.9	116.1
90	114.1	115.3	115.5	114.1	114.5	115.6
100	113.7	114.9	115.1	113.7	114.1	115.3
110	113.4	114.6	114.8	113.4	113.8	115.0
119	113.2	114.3	114.5	113.2	113.6	114.7
120				113.1	113.5	114.7
130				112.9	113.3	114.4
140				112.6	113.1	114.2
150				112.4	112.8	114.0
160				112.2	112.7	113.8
170				112.1	112.5	113.6
180				111.9	112.3	113.4
190				111.7	112.2	113.3
192				111.7	112.2	113.3
G_{mb}	2.295	2.294	2.297	2.327	2.335	2.326
G_{mm}	2.401					

Table A.46 Gyratory Compaction Heights, G_{mb} and G_{mm} for Limestone/Gravel, 12.5 mm NMAS Coarse-Graded, PG 76-22, N_{design} = 119

Mixture:	Limestone/Gravel 12.5 mm NMAS, Coarse-Graded, PG 76-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	140.1	138.4	140.9	140.0	136.4	139.9
1	134.4	132.7	135.2	134.5	131.0	134.1
2	131.7	130.0	132.5	131.9	128.6	131.2
3	129.9	128.2	130.7	130.1	126.9	129.2
4	128.5	126.9	129.3	128.8	125.6	127.7
5	127.3	125.8	128.2	127.7	124.6	126.5
6	126.4	124.9	127.3	126.8	123.7	125.5
7	125.6	124.1	126.5	126.0	123.0	124.7
8	125.0	123.4	125.8	125.4	122.4	124.0
9	124.4	122.9	125.2	124.8	121.8	123.3
10	123.8	122.3	124.7	124.3	121.3	122.8
20	120.5	119.1	121.3	121.0	118.2	119.1
30	118.8	117.4	119.5	119.2	116.5	117.0
40	117.5	116.2	118.2	118.0	115.3	115.7
50	116.6	115.4	117.3	117.1	114.4	114.7
60	115.9	114.7	116.7	116.4	113.7	113.9
70	115.4	114.1	116.1	115.8	113.2	113.3
80	114.9	113.7	115.6	115.4	112.7	112.8
90	114.5	113.3	115.2	114.9	112.3	112.3
100	114.2	113.0	114.9	114.6	112.0	111.9
110	113.9	112.7	114.6	114.3	111.7	111.6
119	113.7	112.5	114.4	114.0	111.5	111.3
120				114.0	111.4	111.3
130				113.8	111.2	111.0
140				113.5	111.0	110.8
150				113.3	110.8	110.5
160				113.1	110.6	110.3
170				113.0	110.4	110.1
180				112.8	110.3	110.0
190				112.7	110.1	109.8
192				112.6	110.1	109.8
G_{mb}	2.315	2.295	2.316	2.312	2.326	2.326
G_{mm}	2.437					

Table A.47 Gyratory Compaction Heights, G_{mb} and G_{mm} for Limestone/Gravel, 19.0 mm NMAS Coarse-Graded, PG 67-22, N_{design} = 119

Mixture:	Limestone/Gravel 19.0 mm NMAS, Coarse-Graded, PG 67-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	134.8	136.7	136.5	134.6	136.6	136.8
1	129.8	131.3	131.4	129.6	131.3	131.4
2	127.5	128.9	129.0	127.3	128.9	129.1
3	125.9	127.3	127.4	125.7	127.3	127.5
4	124.6	126.0	126.2	124.5	126.1	126.2
5	123.6	125.0	125.3	123.6	125.1	125.2
6	122.8	124.2	124.5	122.8	124.3	124.4
7	122.1	123.5	123.8	122.1	123.6	123.7
8	121.5	122.9	123.2	121.5	123.0	123.2
9	121.0	122.4	122.7	121.0	122.4	122.6
10	120.5	122.0	122.2	120.5	122.0	122.1
20	117.5	119.0	119.3	117.6	118.9	119.1
30	115.8	117.3	117.7	116.0	117.2	117.4
40	114.7	116.1	116.5	114.9	116.0	116.3
50	113.9	115.3	115.7	114.1	115.1	115.5
60	113.2	114.6	115.1	113.5	114.4	114.9
70	112.7	114.1	114.6	113.0	113.8	114.3
80	112.3	113.7	114.1	112.6	113.4	113.9
90	111.9	113.3	113.8	112.2	112.9	113.5
100	111.6	113.0	113.4	111.9	112.6	113.2
110	111.3	112.7	113.1	111.6	112.3	112.9
119	111.1	112.5	112.9	111.3	112.0	112.7
120				111.3	112.0	112.7
130				111.1	111.7	112.5
140				110.9	111.5	112.3
150				110.7	111.3	112.1
160				110.5	111.1	111.9
170				110.3	110.9	111.7
180				110.2	110.7	111.6
190				110.0	110.6	111.4
192				110.0	110.6	111.4
G_{mb}	2.342	2.341	2.337	2.371	2.359	2.351
G_{mm}	2.431					

Table A.48 Gyratory Compaction Heights, G_{mb} and G_{mm} for Limestone/Gravel, 19.0 mm NMAS Coarse-Graded, PG 76-22, N_{design} = 119

Mixture:	Limestone/Gravel 19.0 mm NMAS, Coarse-Graded, PG 76-22, Ndesign = 119					
	Height Data, mm					
	N_{design} = 119			$N_{maximum}$ = 192		
Gyrations	Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3
0	135.5	135.8	137.3	136.8	137.2	137.2
1	130.4	130.7	132.1	131.6	132.0	132.3
2	128.0	128.3	129.7	129.3	129.5	130.1
3	126.4	126.7	128.0	127.6	127.8	128.4
4	125.1	125.4	126.8	126.4	126.6	127.2
5	124.1	124.4	125.7	125.4	125.6	126.2
6	123.3	123.6	124.9	124.6	124.7	125.4
7	122.6	122.8	124.1	123.9	124.0	124.7
8	121.9	122.2	123.5	123.3	123.4	124.1
9	121.4	121.7	122.9	122.8	122.9	123.5
10	120.9	121.2	122.4	122.3	122.4	123.1
20	117.9	118.3	119.3	119.3	119.2	120.0
30	116.3	116.7	117.6	117.6	117.5	118.4
40	115.2	115.7	116.4	116.5	116.4	117.3
50	114.4	114.9	115.6	115.7	115.6	116.4
60	113.8	114.3	114.9	115.1	115.0	115.8
70	113.2	113.8	114.4	114.6	114.4	115.3
80	112.8	113.3	113.9	114.2	114.0	114.8
90	112.5	113.0	113.6	113.8	113.6	114.4
100	112.1	112.7	113.3	113.5	113.3	114.1
110	111.9	112.4	113.0	113.2	113.1	113.8
119	111.6	112.2	112.8	113.0	112.8	113.6
120				113.0	112.8	113.5
130				112.8	112.6	113.3
140				112.6	112.4	113.1
150				112.4	112.2	112.9
160				112.2	112.1	112.7
170				112.1	111.9	112.6
180				111.9	111.8	112.4
190				111.8	111.6	112.3
192				111.8	111.6	112.3
G_{mb}	2.318	2.342	2.327	2.358	2.374	2.344
G_{mm}	2.445					