IMPACT OF VARIOUS COMPACTION EQUIPMENT ON HOT-MIX ASPHALT (HMA) DESIGN IN OHIO.

PB99-110280

Prepared in Cooperation with

The Ohio Department of Transportation

and

The U.S. Department of Transportation
Federal Highway Administration

FINAL REPORT

by

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September, 1998

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EXECUTIVE SUMMARY

1. INTRODUCTION

Completed in March 1994, the Strategic Highway Research Program (SHRP) presented a new Hot Mix Asphalt (HMA) design method called Superpave, and recommended use of the SHRP gyratory compactor in lieu of the traditional compactors for preparation of laboratory test specimens. The SHRP gyratory compactor is claimed to produce laboratory HMA specimens similar in aggregate orientation and compaction level to those cored from actual pavement as it is placed in the field. Superpave research predetermined, based on the design high air temperature of the paving location and the predicted traffic level, the required number of gyrations to be used in test specimen preparation.

This study was initiated to examine the effect of different laboratory compaction devices on density, air voids, and optimum asphalt binder content for mixes designed for heavy volume traffic that are currently used in Ohio. A total of six and twelve asphalt concrete mixes were compacted using the SHRP gyratory and Marshall compactors, respectively. Three types of Marshall compactors; namely, mechanical, manual, and rotating base – slanted foot were used. The variables included: maximum nominal size aggregate, and aggregate type. Properties of the produced asphalt concrete mixes were evaluated based on the results of applicable tests that were performed.

2. FINDINGS

The principal findings of this research study are:

- The optimum asphalt cement content determined for an aged mix with 12.5 mm nominal maximum size aggregate by using laboratory specimens prepared by the SHRP gyratory compactor was approximately 1% lower than the average asphalt cement content determined for the same mix using laboratory specimens prepared by mechanical, manual, and rotating base Marshall compactors.

- The optimum asphalt cement content determined for an aged mix with 19.0mm nominal maximum size aggregate using laboratory specimens prepared by the SHRP gyratory compactor was approximately 0.4% lower than the average asphalt cement content determined for the same mix using laboratory specimens prepared by mechanical, manual, and rotating base Marshall compactors.

- The aggregate specific gravity test was found to be the most critical test for void analysis. A small variation in the test results can greatly influence the VMA and VFA calculations.

3. CONCLUSIONS

The principal conclusions of this study are:

- The number of gyrations as recommended by the Superpave gyratory compaction process may not be appropriate for Ohio heavy traffic volume mixes.

- The complete elimination of natural sand may result in construction problems with respect to compaction especially at higher gyration levels.

4. RECOMMENDATIONS

- The number of gyrations currently recommended under the Superpave gyratory compaction process should be reduced for Ohio mixes designed for heavy traffic volumes. It is the authors' opinion that the currently used number of gyrations should be multiplied by a factor of 0.67 for mixes with 12.5mm nominal maximum size aggregate, and 0.75 for mixes with 19.0mm nominal maximum size aggregate. The reduction of the number of gyrations will result in a higher optimum asphalt cement content that is more consistent with current Ohio experience.

- Natural sand plays an important role in mix densification during compaction, particularly at mid-range compaction temperatures (93-115°C). On the other hand, too much natural sand in the mix will produce unstable and tender mixes. It is the authors' opinion that up to 10% natural sand should be allowed in Ohio mixes.

- The current VMA and VFA requirements were established for mixes designed using laboratory specimens prepared by Marshall type compactor. Since the SHRP gyratory compactor uses larger molds and produces much higher density specimens, a change of the VMA and VFA requirements should be considered for Ohio heavy traffic volume mixes. If the number of gyrations is lowered by the proposed factor, as described in the first recommendation, the current VMA and VFA requirements need not be changed.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/OH-98/013	PB99-110280	

4. Title and Subtitle	5. Report Date
IMPACT OF VARIOUS COMPACTION EQUIPMENT ON HOT-MIX ASPHALT (HMA) DESIGN IN OHIO	September 1998
	6. Performing Organization Code
	8. Performing Organization Report No.
7. Author(s) Osama Abdulshafi /Bozena Kedzierski	10. Work Unit No. (TRAIS)
9. Performing Organization Name and Address Civil & Environmental Engineering & Geodetic Science The Ohio State University 470 Hitchcock Hall 2070 Neil Avenue Columbus, Ohio 43210	11. Contract or Grant No. State Job No. 14644(0)
	13. Type of Report and Period Covered Final Report
12. Sponsoring Agency Name and Address Ohio Department of Transportation 25 S. Front St. Columbus, OH 43215	14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration

16. Abstract

The strategic Highway Research Program (SHRP) recommended us e of the SHRP gyratory compactor in lieu of the traditional Marshall or Hveem compactors in Hot Mix Asphalt (HMA) design process. The SHRP gyratory compactor is claimed to produce laboratory HMA specimens similar in aggregate orientation and compaction level to those cored from actual pavement as it is placed in the field. This study addresses the evaluation of different compaction methods for asphalt concrete mixes with 12.5 and 19.0mm nominal maximum size aggregate used in Ohio for pavements with heavy traffic volume. This evaluation of mixes was based on testing of laboratory prepared asphalt concrete specimens. Six asphalt concrete mixes were compacted using SHRP gyratory compactor and twelve using Marshall compactors. Three types of Marshall compactors were used, namely, mechanical, manual, and rotating base-slant foot. Project variables included maximum nominal size aggregate and aggregate type. Properties of the produced asphalt concrete mixes were evaluated based on the results of applicable tests that were performed.

It was concluded that current Ohio heavy traffic volume mixes, when prepared using the SHRP gyratory compactor, will have lower design optimum asphalt cement contents as compared to those determined by using the traditional type of compaction. The percentage of reduction is depended on the maximum nominal size of the aggregate and is lower for mixes with 19.0mm nominal maximum size aggregate than for mixes with 12.5mm nominal maximum size aggregate.

Due to the fact that certain types of distress prevalent in Ohio are sensitive to asphalt cement content, it was recommended that the current optimum asphalt cement content be retained in order to maintain Ohio pavement durability and long-term performance.

17. Key Words	18. Distribution Statement
superpave, SHRP gyratory compactor, Marshall compactor	No Restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

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This report does not constitute a standard, specification, or regulation.

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CHAPTER 1

INTRODUCTION

1.1. DESCRIPTION OF THE PROBLEM

The compaction of an asphalt concrete pavement layer is an important factor in providing a durable pavement structure. A properly designed and compacted asphalt concrete layer provides high resistance against rutting and fatigue cracking. A relatively low air void content (3-5%) also enhances the mixture's resistance to aging and moisture damage.

The goal of any laboratory compaction process is to simulate, as closely as possible, the actual compaction effort produced in the field by the rolling equipment. In the laboratory, the compactive effort is applied in the form of a vertical load to a confined sample of the asphalt mix. In the field, the roller compactive effort is applied as a combination of shear (applied at an angle to the mat layer) and vertical loading. This difference in loading conditions results in differences in aggregate orientation and compaction level for the laboratory and field samples.

The Strategic Highway Research Program (SHRP) was completed in March, 1994. In the area of hot mix asphalt (HMA) design, one of the major changes recommended by SHRP, is the use of the SHRP Gyratory Compactor in lieu of the traditional Marshall or Hveem Compactors. It is claimed that this compactor will produce laboratory HMA specimens similar in aggregate orientation and compaction level to those cored from actual pavement as it is placed in the field.

The current SHRP mixture design and analysis processes for HMA are rather complex and costly, and consequently are impractical for use on a daily basis at all HMA facilities for either mixture design or quality control. To overcome this problem, the National Cooperative Highway Research Program (NCHRP) of the Transportation Research Board (TRB) in 1993 initiated NCHRP Project 9-7, entitled "Field Procedures and Equipment to Implement SHRP Asphalt Specification."

Currently, a large number of Ohio HMA laboratories do not have access to a gyratory compactor. Therefore, it was considered desirable to evaluate various available laboratory compactors and identify any that could produce laboratory specimens having similar volumetric properties, and compaction levels to those produced by the SHRP gyratory compactor.

1.2. OBJECTIVES OF THE STUDY

The objectives of this study were to:

1. Determine if any of the various Marshall compactors (mechanical, manual, or rotating base and slanted foot) can produce laboratory specimens similar to specimens produced by the SHRP gyratory compactor when used for Ohio materials and mixes.

2. Compare and rank the various Marshall compactors to the SHRP gyratory compactor based on specimen volumetric properties and compaction levels.

1.3. SCOPE OF WORK

This study addressed the evaluation of different compaction methods for asphalt concrete mixes having 12.5 and 19.0mm nominal maximum size aggregate. This evaluation was based on testing of laboratory-prepared asphalt concrete specimens and comparison of test results.

1.4. RESEARCH APPROACH

The following research approach was used to satisfy objectives of this study.

- Asphalt concrete mixes having the following variables were examined:

  1. Two aggregate gradations (as specified for surface and leveling courses).
  2. Two sources of coarse aggregate.
  3. Three sources of fine aggregate.

  The combination of the above variables resulted in twelve mix designs.

- Test specimens were prepared using the following types of compaction equipment:

  1. Mechanical Marshall Compactor.
  2. Manual Marshall Compactor.
  3. Rotating Base and Slanted Foot Marshall Compactor.
  4. SHRP Gyratory Compactor.

- Prior to specimen compaction, all asphalt concrete mixes were heated for two hours in an oven at 135°C to simulate the aging of hot mix asphalt paving mixes during field plant mixing operations. Additionally, twelve mix designs were prepared using the mechanical Marshall compactor without temperature aging to determine the effects of short-term asphalt aging.

- All Marshall specimens were compacted using 75 blows per face which corresponds to a traffic level $>10^6$ ESALs.

- The optimum asphalt cement contents for the mixes compacted by Marshall compactors was determined at 4% air voids.

- The optimum asphalt cement contents for the mixes compacted using the Gyratory Compactor were selected where the densification curve passes through 96% of theoretical maximum specific gravity at the design number of gyrations (N_{design}). The N_{design} value was selected for a traffic level of $>10^6$ ESALs which is consistent with the use of 75 blows for Marshall compaction.

- The evaluation of the asphalt concrete mixes was based on volumetric analyses of asphalt concrete test specimens. These analyses were conducted in accordance with criteria stated in SHRP-A-408.

For each mix design based on the specimens made by Marshall compactors the optimum asphalt cement content was selected by investigating five asphalt cement contents. The general laboratory testing approach for these mixes was to test three replicate specimens for each experimental cell.

For each mix design based on the specimens made by SHRP gyratory compactor the optimum asphalt cement content was selected by investigating four asphalt cement contents. Two replicate specimens were tested for each experimental cell.

CHAPTER 2

LITERATURE REVIEW

Two primary processes affect asphalt pavement performance: mix design and compaction. The mix design process is one of the first steps in hot mix asphalt (HMA) pavement construction, reconstruction, or resurfacing. The primary objective of this process is to achieve an asphalt mix that, when properly constructed, will perform as intended over the service life of the pavement. The mix design process involves determination of an aggregate blend to satisfy gradation requirements, and selection of the type and amount of asphalt cement to be used.

Traditionally, two procedures have been used to design asphalt concrete mixes. These procedures are known as the Marshall and Hveem methods of asphalt mix design, the former is being most commonly used. Both of these mix design methods are empirical and not correlated with actual pavement performance.

The Marshall mix design method utilizes an impact-type of compactive effort (Marshall hammer blows) to prepare test specimens. The Marshall hammer has a flat circular tamping face 98mm in diameter, and weighs 4500 grams. This hammer is let to fall free from a distance of 457mm to the specimen surface. The typical Marshall specimen measures 102mm in diameter and has a nominal height of 64mm. Specimens are prepared over a range of different asphalt cement contents, usually at 0.5% increments. Typically, five asphalt cement contents (AC) are examined for each mix design, with three specimens prepared at each AC content. The specimens are tested for density, stability, and flow. On the basis of the density test results, volumetric analyses for the design mix are performed and the air voids (AV), voids in mineral aggregate (VMA), and voids filled with asphalt (VFA) contents are calculated. An estimation of mix strength is determined based on an empirical stability test, while flow measurements indicate the susceptibility of the mix to deformation. Traditionally, the optimum asphalt cement content has been calculated as the average value of the optimum determined on the basis of maximum stability, optimum determined on the basis of maximum density, and AC content at 4.0% air voids. Alternatively, the optimum AC selection has been based exclusively on the 4.0% air voids criteria. In both cases, the determined optimum asphalt cement content is checked against VMA, VFA, and flow requirements.

An asphalt pavement has to achieve a sufficient level of compaction to meet the requirements of the expected traffic. The Marshall mix design method recognizes three levels of traffic: low, medium, and high. To simulate the traffic variable in the laboratory mix design process, the Marshall method uses a different number of blows applied to each face of the laboratory specimens: 35, 50, and 75 for low, medium, and high traffic levels, respectively. Use of Marshall mix design method over the years has resulted in development of three Marshall hammer types: hand, mechanical and rotating base slanted foot. For several decades, asphalt concrete mixes designed by the Marshall method supplied the pavement industry with pavements that were satisfactory for the needs of existing traffic, but it was observed that different mix densities could be achieved at the same blow numbers when different hammers were used. As a result, laboratory specimens of the same mix could have different volumetric properties depending on the type of hammer used for compaction. Additionally, these properties could be different than the properties of the same mix compacted in the field, where the pavement is compacted initially during construction and later under traffic. Hot-mix asphalt placed in the field is initially compacted to an air void content of 6 to 8%. Traffic loads further compact the pavement to its ultimate density, which is usually achieved after the third summer of traffic. With increases in traffic levels and tire pressures over time, more and more pavements were observed to be stabilizing at densities exceeding the original laboratory design density. It became apparent that the 75-blow Marshall compactive effort did not sufficiently duplicate the compaction level that pavements with high traffic had experienced [1].

Consequently, use of the empirical Marshall mix design method was brought into question, and the need to develop a mix design method that would consider pavement performance was realized. This need resulted in major research studies that proposed a new performance-oriented method of asphalt concrete mix design. This method, to be based on performance-related criteria, was to account for a wide range of distress mechanisms, such as fatigue and thermal cracking, permanent deformation, moisture damage, and age-hardening. Compaction is considered to be "the single most important factor affecting the performance of asphalt pavements"[2]. For this reason, one of the major objectives of the undertaken studies was to ensure that laboratory-prepared test specimens would be fabricated in a manner that would adequately simulate field conditions, and by doing so would yield reliable information on mix engineering properties.

The National Cooperative Highway Research Program (NCHRP) sponsored a study, entitled "Asphalt-Aggregate Mixture Analysis System" (AAMAS) to achieve the following [3].

- Develop a mix design system based on performance-related criteria that would account for distress mechanisms such as fatigue cracking, thermal cracking, permanent deformation, moisture damage, and age-hardening.
- Evaluate the elements of laboratory sample preparation necessary to duplicate field conditions closely enough to yield realistic engineering properties of the asphalt concrete mixes.
- Select the compaction technique best able to produce asphalt concrete specimens that would demonstrate material and engineering properties (such as percent air voids, aggregate orientation, strength, and stiffness) similar to those of the asphalt concrete placed in the field using standard compaction methods.

Several compaction devices were examined in the AAMAS study, each representing a unique compaction technique. The Marshall compactor simulated an impact type of compaction, the California kneading compactor a kneading type of compaction, the mobile steel wheel simulator a rolling type of compaction, and the Texas gyratory compactor a gyratory action. After completion of this evaluation compactors were reported in descending order in terms of their success in simulating field conditions, as follows:

1. Texas Gyratory Shear Compactor

2. California Kneading Compactor
3. Mobile Steel Wheel Simulator
4. Arizona Vibratory/Kneading Compactor
5. Marshall Mechanical Hammer.

The limitation of this study is the fact that short-term aging was not considered prior to specimen compaction.

Gyratory compaction was developed in the 1930s in the state of Texas [4]. During the gyratory compaction process a static load is applied to the specimen while the mold gyrates in a back-and-forth motion. The angle of gyration for the Texas 6-inch gyratory compactor is 6°. Although gyratory compaction did not gain wide acceptance at the time, the concept was further developed by the Corps of Engineers, and the Central Laboratory for Bridges and Roads in France. The U.S. Army Corps of Engineers started to develop its gyratory compactor in the 1940s and demonstrated its use in the 1960s [5]. The Central Laboratory for Bridges and Roads (LCPC) in France started to experiment with gyratory compaction in late the1950s and finalized their protocol in 1972. The angle of gyration, speed of rotation, and scope of vertical pressure were the three major variables studied. In the French application, the gyratory compactor was used to simulate density at the end of the construction process rather than during service. Presently, gyratory compaction is widely used in France as a part of the mix design process [1].

The search for new methods of asphalt mix design resulted in development of the SHRP gyratory compactor and Superpave mix design system. As stated in AASHTO Designation TP4-93 procedure [6], the SHRP gyratory compactor is an eletrohydraulic or electromechanical machine with a ram and ram heads that are restrained from revolving during compaction. The axis of the ram is required to be perpendicular to the platen of the compactor. During specimen compaction, the ram applies and maintains a pressure of 600±18 kPa that is perpendicular to the specimen cylindrical axis. The compactor tilts specimen mold at an angle of 1.25±0.02°, and gyrates it at a rate of 30.0 ± 0.5 gyrations per minute throughout the compaction process. During gyration the specimen mold is free to revolve on its tilted axis.

The Superpave mix design system recognizes three steps of mix design and analysis [7]. The first step is a volumetric mixture design and is recommended to be used to design low traffic pavements (less than 10^6 80kN ESALs). The second step is mix analysis which is recommended to design medium traffic pavements (less than 10^7 80kN ESALs). The third step is enhanced mix analysis which is to be used to design high traffic pavements (greater than for 10^7 80kN ESALs).

Step 1 is a volumetric mix design process with no direct measurements of mixture mechanical properties or performance predictions (with the exception of moisture susceptibility) made. Step 2, mix analysis, introduces performance tests into the mix design process and starts with mixes that satisfy Step 1 requirements. During Step 2, performance evaluation specimens are tested for permanent deformation, fatigue and low-temperature cracking. Tests and analysis of Step 2 are performed on small number of specimens and at limited environmental conditions. Step 3, enhanced mix analysis, requires testing of more specimens over a wider temperature range.

Gyratory compaction is essential to Step 1 mix design success. The process starts with selection of asphalt cement, and aggregates that meet SHRP specifications. Selection of asphalt cement type is based on geographic location of the paving project, and pavement and air temperatures at this location. Selection of the optimum asphalt cement content is based on achieving desired levels of air voids, voids in mineral aggregate, and voids filled in asphalt at the initial, design, and maximum levels of compaction. These compaction levels are achieved at different numbers of gyrations, referred to as $N_{initial}$, N_{design}, and N_{max}. The $N_{initial}$ represents the number of gyrations needed to achieve a compaction level less than 89% of Maximum Theoretical Specific Gravity (MSG), or 11% air voids, in the laboratory specimens. The N_{design} represents number of gyrations needed to achieve a traffic compaction level of 96% MSG, or 4% air voids, in the laboratory specimens. The N_{max} represents the number of gyrations at which the laboratory specimens achieve no more than 98% MSG or an air voids content of more than 2%. Overall the gyration limits for an acceptable mix are set at 89 and 98% MSG [8,9].

The current Superpave manual, publication SHRP-A-407 [9], recognizes twenty eight different gyration groups relating number of $N_{initial}$, N_{design}, and N_{max} gyrations to various levels of traffic and maximum seven-day air temperatures. With information regarding predicted traffic and climate conditions, the mix designer selects the appropriate number of gyrations to produce laboratory specimens that will have similar densities as field specimens after pavement construction and traffic consolidation. For the Step 1 mix design laboratory specimens are prepared at several asphalt cement contents and volumetric analyses performed at the design number of gyrations for each asphalt cement content. Graphs of AV, VMA, and VFA versus asphalt cement content are generated. Since years of research and observations of asphalt pavement performance have led to the conclusion that volumetric properties of asphalt concrete have a greater impact on its final performance than stability [2], the 4% air voids content became a primary factor in the determination of an optimum asphalt cement content. The VMA requirement is related to the aggregate nominal size, and VFA depends on expected traffic level.

In the future the use of the SHRP gyratory compactors will be wide spread. At the present time, however, the state of technology transfer is such that many of asphalt concrete producers have long experience with traditional compactors and little if any experience with SHRP gyratory compactor. For this reason, identification of ways to compare engineering properties of mixes prepared with traditional compactors with those prepared using the SHRP gyratory compactor, is of importance.

CHAPTER 3

RESEARCH METHODS

3.1 EXPERIMENTAL DESIGN

All asphalt concrete mixes investigated in this study were produced with one type of virgin asphalt (AC-20). The experiment variables consisted of:

- Two types of coarse aggregate (gravel and limestone),
- Three types of fine aggregate (manufactured sand, natural sand, and a 50/50% blend of manufactured and natural sand),
- Two types of gradation (surface and leveling courses having 12.5 and 19.0 nominal maximum size aggregate, respectively).

Table 3.1 presents a test matrix for the combination of these mix variables.

Table 3.1. Test matrix for the combination of mix variables.

Type of Fine Aggregate	Surface Course		Leveling Course	
	Limestone	Gravel	Limestone	Gravel
Manufactured Sand	1	2	3	4
Natural Sand	5	6	7	8
50/50 Sand Blend	9	10	11	12

Laboratory specimens for these 12 mixes were prepared by using Marshall (mechanical, manual, and rotating base slanted foot) compactors. Laboratory samples of six mixes (# 1, 3, 9, 10, 11, and 12) were additionally prepared using the SHRP gyratory compactor.

All asphalt concrete mixes were aged for 2 hours at 135° C before compaction.

Additionally, all twelve mixes were prepared using mechanical Marshal compactor without the aging procedure.

3.2. PROGRAM OF TESTING

Samples of aggregate and compacted asphalt concrete were tested in accordance with established ASTM and AASHTO test procedures.

Aggregate samples were subjected to the following tests:

- "Sieve Analysis of Fine and Coarse Aggregates", ASTM C136.
- "Specific Gravity and Absorption of Fine Aggregate", ASTM C 128.
- "Specific Gravity and Absorption of Coarse Aggregate", ASTM 127.

Samples of the compacted asphalt concrete mixtures were subjected to the following tests:

- "Bulk Specific Gravity and Density of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens", ASTM D 2726.
- "Theoretical Maximum Specific Gravity of Bituminous Paving Mixtures", ASTM D 2041.
- "Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus", ASTM D 1559.
- "Preparing and Determining the Density of Hot Mix Asphalt (HMA) Specimens by Means of the SHRP Gyratory Compactor", AASHTO Designation: TP4-93, Edition 1C.

CHAPTER 4

TEST RESULTS AND ANALYSIS

The data collected in this study is summarized in Tables 4.1 through 4.62 and Figures 4.1 through 4.46.

4.1. LABORATORY TESTING OF AGGREGATE AS DELIVERED.

Tables 4.1 through 4.4 present results of gradation tests that were performed on aggregate as delivered. Tables 4.1 and 4.2 present aggregate gradation for the limestone and gravel surface mixes, and Tables 4.3 and 4.4 present aggregate gradation for the limestone and gravel leveling mixes.

Table 4.1. Limestone surface mix - gradation of aggregate as delivered, (% passing).

Sieve Size (mm)	#7 Limestone	#8 Limestone	Manufactured Sand	Natural Sand
12.500	96	100	100	100
9.500	66	91	100	100
4.750	7	24	100	100
2.360	3	5	95	96
1.180	3	3	73	75
0.600	3	2	41	41
0.300	3	1	13	15
0.150	3	1	3	3
0.075	2.3	0	1	1

Table 4.2. Gravel surface mix - gradation of aggregate as delivered, (% passing).

Sieve Size (mm)	#7 Gravel	#8 Gravel	Manufactured Sand	Natural Sand
12.500	40	100	100	100
9.500	7	90	100	100
4.750	0.7	16	98	99
2.360	0.5	2.4	89	81
1.180	0.3	1.7	66	54
0.600	0.3	1.4	35	25
0.300	0.3	1.1	13	10
0.150	0.3	0.9	3	1.7
0.075	0.2	0.7	1.5	0.8

Table 4.3. Limestone leveling mix - gradation of aggregate as delivered, (% passing).

Sieve Size (mm)	#57 Limestone	#8 Limestone	Manufactured Sand	Natural Sand
25.000	100	100	100	100
19.000	97.7	100	100	100
12.500	43.9	100	100	100
9.500	7.8	82.6	100	100
4.750	0.4	10.7	100	100
2.360	0.4	1.8	92.7	83
1.180	0.4	1.5	54.9	57
0.600	0.4	1.4	33.2	31
0.300	0.4	1.4	24.2	12
0.150	0.4	1.3	19.3	4.9
0.075	0.4	1.1	16.5	2.9

Table 4.4. Gravel leveling mix - gradation of aggregate as delivered, (% passing).

Sieve Size (mm)	#57 Gravel	#8 Gravel	Manufactured Sand	Natural Sand
37.500	100	100	100	100
25.000	97.6	100	100	100
19.000	73.3	100	100	100
12.500	19.6	100	100	100
9.500	2.4	83.8	100	100
4.750	0	21.2	93.4	99.5
2.360	0	4.3	73.9	90
1.180	0	1.7	54.9	75.6
0.600	0	1.5	37.6	55.8
0.300	0	1.2	35	31.4
0.150	0	0.9	14.9	5.1
0.075	0	0.5	9.7	2.1

The aggregates were sieved into individual sizes and later blended to meet ODOT specifications for mix 446-1H (surface mix), and 441-T2 (leveling mix). Aggregate gradations for the four mixes that used a 50/50% blend of manufactured and natural sand as fine aggregate were provided in job mix formulas (JMF's) supplied by Ohio Department of Transportation (ODOT). Aggregates for mixes made with manufactured or natural sand were blended to satisfy the same gradation curve as mixes made with 50/50% manufactured and natural sand.

4.2. LABORATORY TESTING OF AGGREGATE BLENDS.

Tables 4.5 and Figure 4.1, and Table 4.6 and Figure 4.2 present, respectively, gradation for aggregate blends used in surface and leveling course mixes.

Table 4.5. Surface mixes - aggregate gradation and ODOT specification requirements, (% passing).

Sieve Size (mm)	Limestone Mix	Gravel Mix	ODOT Specification Requirements
19.000	100	100	100
12.500	98	95	95 – 100
9.500	83	85	70 – 85
4.750	45	50	38 – 50
2.360	34	36	20 – 37
1.180	23	23	14 – 30
0.600	13	14	10 – 22
0.300	7	7	6 – 15
0.150	4	4	4 – 10
0.075	2.7	2.8	2 – 6

Figure 4.1 presents a comparison of the gradation of aggregates used in this study for surface course mixes with gradation requirements established by Superpave for mixes with 12.5mm nominal maximum size aggregate. The Superpave gradation requirements are represented by set of control points and a restricted zone on the 0.45 power gradation graph. The surface course mixes examined in this study have gradations that lie within control point requirements, and avoid the restricted zone. Consequently, these mixes meet the requirements of Superpave with respect to aggregate gradation.

Table 4.6. Leveling mixes - aggregate gradation and ODOT specification requirements (% passing).

Sieve Size (mm)	Limestone Mix	Gravel Mix	ODOT Specification Requirements
25.000	100	100	95 – 100
19.000	99	94	85 – 100
12.500	75	69	65 – 85
9.500	63	57	
4.750	52	47	35 – 60
2.360	40	38	25 – 48
1.180	24	30	16 – 36
0.600	15	20	12 – 30
0.300	7	9	5 – 18
0.150	5	4	2 – 10
0.075	3.5	2.6	

Figure 4.2 presents a comparison of the gradation of aggregates used in this study for leveling course mixes with gradation requirements established by Superpave for mixes with 19.0mm nominal maximum size aggregate. The leveling course mixes examined in this study have gradations that lie within control point requirements but pass through the restricted zone. Consequently, these mixes do not meet the requirements of Superpave with respect to aggregate gradation.

Figure 4.1. Comparison of Surface Course Gradation Used in this Study With SuperPave Gradation Requirements

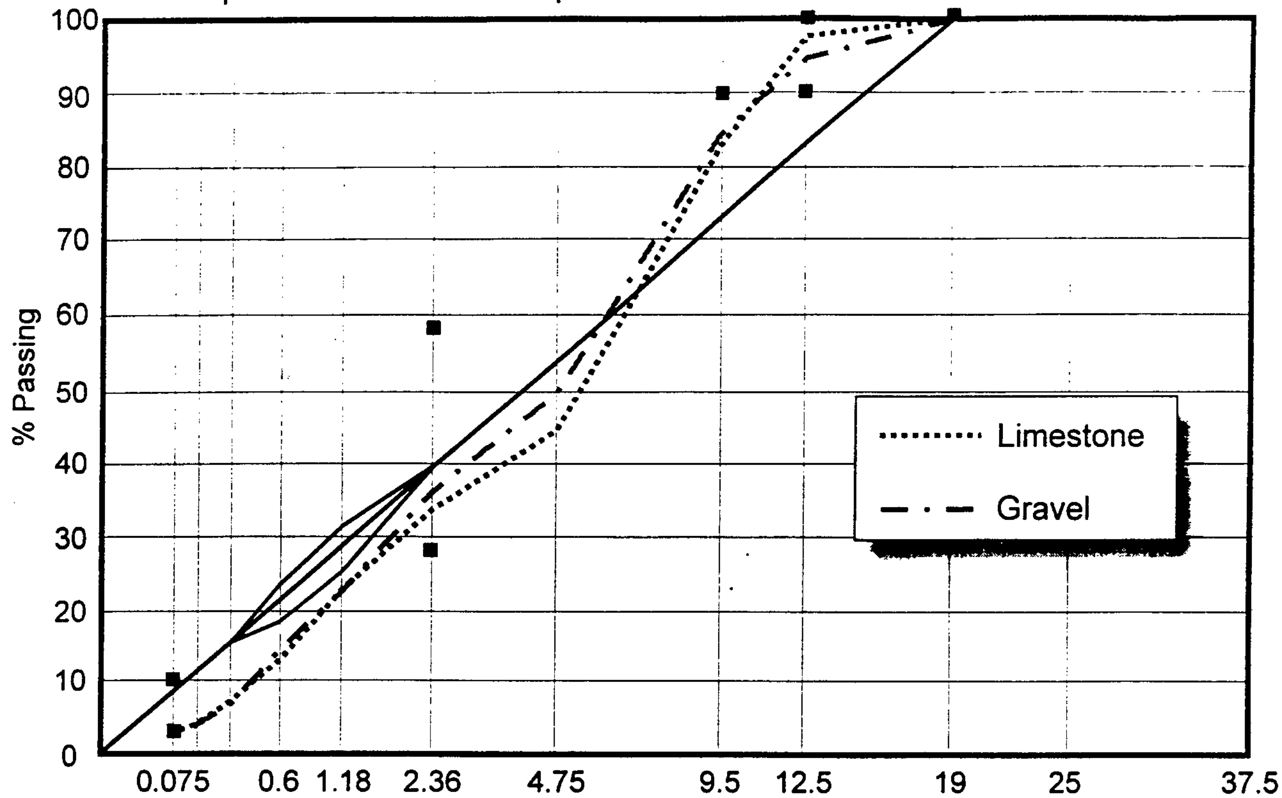
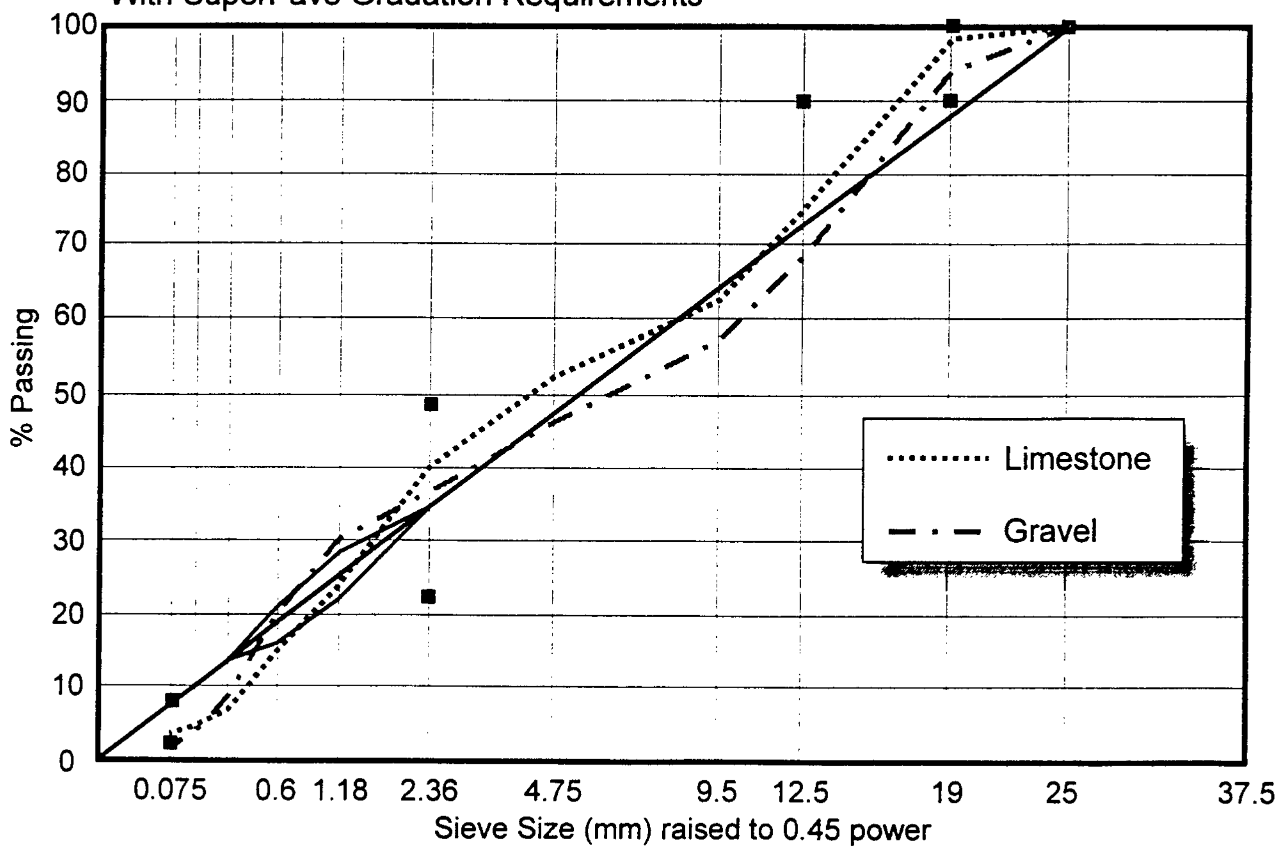


Figure 4.2. Comparison of Leveling Course Gradation Used in this Study With SuperPave Gradation Requirements



Tables 4.7 and 4.8 present, respectively, specific gravity test results for aggregate blends used for surface and leveling mixes.

Table 4.7. Surface mixes - specific gravity of aggregate blends.

Mix Type	Specific Gravity (Dry)	Specific Gravity (Saturated Surface Dry)	Absorption, (Percent)
Limestone, Manufactured Sand	2.557	2.626	2.7
Limestone, Natural Sand	2.532	2.583	2.6
Limestone, 50/50 Sand Blend	2.541	2.606	2.6
Gravel, Manufactured Sand	2.565	2.633	2.6
Gravel, Natural Sand	2.564	2.633	2.6
Gravel, 50/50 Sand Blend	2.564	2.633	2.6

Table 4.8. Leveling mixes - specific gravity of aggregate blends.

Mix Type	Specific Gravity (Dry)	Specific Gravity (Saturated Surface Dry)	Absorption, (Percent)
Limestone, Manufactured Sand	2.631	2.659	1.6
Limestone, Natural Sand	2.597	2.634	1.9
Limestone, 50/50 Sand Mixture	2.613	2.648	1.8
Gravel, Manufactured Sand	2.493	2.580	3.3
Gravel, Natural Sand	2.556	2.596	1.6
Gravel, 50/50 Sand Blend	2.532	2.591	2.3

Tests for a dry specific gravity of aggregates was conducted using 4,800g aggregate specimens prepared to satisfy exact gradation requirements. The 4,800g specimen was divided to two parts on 4.75mm sieve. The portion retained on this sieve was tested in accordance with the requirements of ASTM C127. The portion passing 4.75mm sieve was tested in accordance with ASTM C128 test procedure. Results of these tests, in conjunction with the percentages of aggregate retained and passing the 4.75mm sieve, were then used to calculate the dry specific gravity of the aggregate blend.

Paving industry contractors use a different procedure to establish the value of dry specific gravity of aggregate. This procedure involves determination of a dry specific gravity for a particular type of aggregate, for example #57, #8, and natural sand, and then combining the separate test results theoretically in conjunction with percentage of a particular type of aggregate used in the aggregate blend.

The following approach was used to compare test results using these different test procedures. Acceptable ranges of multilaboratory test results from ASTM C127 (0.038) and ASTM C 128 (0.066) were multiplied by the percentages of coarse and fine aggregate used in a mix and then added together. The result of this calculation constituted a new acceptable range of test results for an aggregate mix and was used to compare specific gravity test result values as determined by both a contractor and study personnel.

Table 4.9 presents values of aggregate dry specific gravity for surface mixes as determined by study personnel and by a contractor. This table also includes actual and calculated acceptable ranges for test results and the results of a comparison between these two ranges. Table 4.10 presents values of the same data for leveling course mix made with gravel coarse aggregate. The contractor's mix design data for limestone leveling mix did not include aggregate specific gravity data; therefore, it was not available for comparison.

Table 4.9. Comparison of aggregate dry specific gravity test results for surface mixes.

Mix Type	Dry Specific Gravity of Aggregate Blends as Determine by		Range of Two Results		
	This Study	Contractor	Actual	Acceptable	Difference
Limestone Aggregate Manufactured Sand	2.557	2.593	0.036	0.048	Within the range
Limestone Aggregate Natural Sand	2.532	2.592	0.060	0.048	Exceeds by 0.012
Limestone Aggregate 50/50 Sand Blend	2.541	2.592	0.051	0.048	Exceeds by 0.003
Gravel Aggregate Manufactured Sand	2.565	2.551	0.014	0.050	Within the range
Gravel Aggregate Natural Sand	2.564	2.558	0.006	0.050	Within the range
Gravel Aggregate 50/50 Sand Blend	2.564	2.554	0.010	0.050	Within the Range

Table 4.10. Comparison of aggregate dry specific gravity test results for leveling mixes.

Mix Type	Dry Specific Gravity of Aggregate Blends as Determine by		Range of Two Results		
	This Study	Contractor	Actual	Acceptable	Difference
Gravel Aggregate Manufactured Sand	2.493	2.573	0.080	0.052	Exceeds by 0.028
Gravel Aggregate Natural Sand	2.556	2.564	0.008	0.052	Within the range
Gravel Aggregate 50/50 Sand Blend	2.532	2.568	0.036	0.052	Within the range

The aggregate dry specific gravity test results presented in Tables 4.9 and 4.10 indicate that six of nine test result sets were within the calculated acceptable range.

Aggregate dry specific gravity test results for surface mixes made with limestone coarse aggregate and natural sand, and limestone coarse aggregate and a 50/50% sand blend exceed the acceptable range of test results by 0.012 and 0.003, respectively. The analysis of test results of the elements of the combined specific gravity values, as reported by the contractor with test values determined during this study, indicate the following:

- Test results for natural sand reported at 2.520 and 2.498 have a difference of 0.022 that is within the acceptable multi-laboratory ASTM C 128 range of 0.066.
- Test results for a 50/50% sand blend reported at 2.517 and 2.521 have a difference of 0.004 that is within the acceptable multi-laboratory ASTM C 128 range of 0.066.
- Test results for limestone coarse aggregate reported at 2.631 and 2.560 have a difference of 0.071 that is almost twice the acceptable multi-laboratory ASTM C 127 range of 0.038.

Aggregate dry specific gravity test result for leveling mix made with gravel coarse aggregate and manufactured sand exceeds the acceptable range by 0.028. The analysis of test results of the elements of the combined specific gravity value of 2.573 as reported by the contractor with 2.493 test value determined during this study, indicate the following:

- Test results for manufactured sand reported at 2.616 and 2.465 have a difference of 0.151 that is more than double the acceptable multi-laboratory ASTM C 128 range of 0.066.
- Test results for gravel coarse aggregate reported at 2.531 and 2.527 have a difference of 0.004 that is within the acceptable multi-laboratory ASTM C 127 range of 0.038.

As mentioned before specific gravity of aggregate in this study was determined by testing specimens that represented an actual aggregate blend while specific gravity of aggregate reported by contractors was calculated from test results of individual stockpiles. This difference in procedure may be one of possible reasons why the test results obtained by contractors and this study exceeded the acceptable range. Another reason for the observed differences in specific gravity test values may be related to changes in geological rock formation as a result of variation with time between deposits and within deposits at the quarry.

4.3. DESIGN OF JOB MIX FORMULAS

Job mix formula (JMF) was determined for all mixes and examined types of compaction test equipment used in this study. In addition, optimum asphalt cement data was available for four mixes made with a 50/50% blend of manufactured and natural sand that were prepared by contractors with aggregate from the same sources as used in this study.

Determination of JMF was based on a minimum of five levels of asphalt cement addition for each aggregate blend and Marshall method of compaction, and four levels of asphalt cement addition for gyratory compaction.

The maximum theoretical specific gravity tests were conducted on asphalt concrete specimens at 5.5% asphalt cement content for the surface mixes, and 5.0% asphalt cement content for the leveling mixes. Tables 4.11 through 4.14 present the maximum theoretical specific gravity test results for both surface and leveling mixes.

Table 4.11. Maximum theoretical specific gravity for surface mixes with limestone coarse aggregate.

Mix Type	Maximum Theoretical Specific Gravity			
	Aged Mix		Not Aged Mix	
	Dry	SSD	Dry	SSD
Limestone Coarse Aggregate Manufactured Sand	2.468	2.468	2.431	2.423
Limestone Coarse Aggregate Natural Sand	2.455	2.452	2.422	2.398
Limestone Coarse Aggregate 50/50 Sand Blend	2.469	2.467	2.430	2.411

The maximum theoretical specific gravity for the surface mix made with limestone coarse aggregate and 50/50% sand blend was determined by the contractor to be 2.430 at a 5.5% asphalt cement content.

Table 4.12. Maximum theoretical specific gravity for surface mixes with gravel coarse aggregate.

Mix Type	Maximum Theoretical Specific Gravity			
	Aged Mix		Not Aged Mix	
	Dry	SSD	Dry	SSD
Gravel Coarse Aggregate Manufactured Sand	2.487	2.480	2.464	2.462
Gravel Coarse Aggregate Natural Sand	2.477	2.472	2.450	2.442
Gravel Coarse Aggregate 50/50 Sand Blend	2.482	2.478	2.456	2.451

The maximum theoretical specific gravity for surface mix made with gravel coarse aggregate and 50/50% sand blend was determined by the contractor to be 2.432 at a 5.5% asphalt cement content.

Table 4.13. Maximum theoretical specific gravity for leveling mixes with limestone coarse aggregate.

Mix Type	Maximum Theoretical Specific Gravity			
	Aged Mix		Not Aged Mix	
	Dry	SSD	Dry	SSD
L-stone Coarse Aggregate Manufactured Sand	2.523	2.510	2.496	2.487
L-stone Coarse Aggregate Natural Sand	2.501	2.500	2.475	2.460
L-stone Coarse Aggregate 50/50 Sand Blend	2.512	2.506	2.487	2.477

The average maximum theoretical specific gravity for a leveling mix made with limestone coarse aggregate and 50/50% sand blend was determined by the contractor to be 2.474 at a 4.9% asphalt cement content.

Table 4.14. Maximum theoretical specific gravity for leveling mixes with gravel coarse aggregate.

Mix Type	Maximum Theoretical Specific Gravity			
	Aged Mix		Not aged Mix	
	Dry	SSD	Dry	SSD
Gravel Coarse Aggregate Manufactured Sand	2.479	2.469	2.456	2.437
Gravel Coarse Aggregate Natural Sand	2.456	2.451	2.426	2.405
Gravel Coarse Aggregate 50/50 Sand Blend	2.468	2.461	2.440	2.432

The maximum theoretical specific gravity for leveling mix made with gravel coarse aggregate and 50/50% sand blend was determined by the contractor to be 2.407 at a 5.0% asphalt cement content.

Theoretical specific gravity test results values available from contractors are reported at the exact level or lower than values determined by this study for not aged mixes. This could indicate that all tests were conducted on mixes that were not aged.

Air voids content of asphalt concrete mixes was calculated on the bases of the values of aged, dry maximum theoretical specific gravity for aged mixes, and not aged dry maximum theoretical specific gravity for the not aged mixes.

Voids in mineral aggregate values were calculated using dry, bulk specific gravity of aggregates.

The average test values for selected mixes (asphalt concrete surface and leveling mixes made with limestone coarse aggregate and 50/50% blend of manufactured and natural sand) are presented in Tables 4.15 through 4.28 and Figures 4.2 and 4.3. All remaining mix design data is presented in Appendix A. Tables presenting test results of specimens prepared by SHRP gyratory compactor do not include stability and flow test results as no performance testing is included in the selection of optimum asphalt cement content in the Superpave mix design process.

Table 4.15. Mix design data for surface mix with limestone coarse aggregate and 50/50% sand blend; mechanical Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.303	2.507	8.14	13.5	39.5	12,320	2.9
5.0	2.326	2.488	6.49	13.0	50.1	13,240	2.9
5.5	2.347	2.469	4.95	12.7	61.5	12,150	2.9
6.0	2.358	2.451	3.79	12.8	70.4	10,780	3.3
6.5	2.368	2.432	2.64	12.9	79.5	12,900	3.3

Table 4.16. Mix design data for surface mix with limestone coarse aggregate and 50/50% sand blend; manual Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.333	2.507	6.93	12.3	43.7	15,650	2.7
5.0	2.350	2.488	5.54	12.1	54.4	16,180	3.2
5.5	2.382	2.469	3.54	11.4	69.1	18,450	3.3
6.0	2.393	2.451	2.37	11.5	79.4	17,300	3.7
6.5	2.401	2.432	1.29	11.7	89.0	16,370	4.5

Table 4.17. Mix design data for surface mix with limestone coarse aggregate and 50/50% sand blend; rotating base Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.300	2.507	8.26	13.6	39.2	11,330	2.7
5.0	2.325	2.488	6.55	13.1	49.9	13,180	2.4
5.5	2.342	2.469	5.14	12.9	60.4	15,220	2.7
6.0	2.349	2.451	4.15	13.1	68.4	13,820	2.7
6.5	2.368	2.432	2.62	12.9	79.6	13,160	2.9

Table 4.18. Mix design data for surface mix with limestone coarse aggregate and 50/50% sand blend; SHRP gyratory compaction. Data at $N_{initial}$

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA
4.5	2.135	2.506	14.84	19.8	25.1
5.0	2.170	2.487	12.75	18.8	32.4
5.5	2.157	2.468	12.62	19.8	36.2
6.0	2.173	2.450	11.34	19.6	42.1

Table 4.19. Mix design data for surface mix with limestone coarse aggregate and 50/50% sand blend; SHRP gyratory compaction. Data at N_{design}

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA
4.5	2.388	2.506	4.74	10.2	53.8
5.0	2.417	2.487	2.85	9.6	70.5
5.5	2.420	2.468	1.98	10.0	80.2
6.0	2.416	2.450	1.42	10.6	86.6

Figure 4.3. Determination of Optimum Asphalt Cement Content for Surface Mix Made with Limestone Aggregate and 50/50% Sand Blend; Manual Marshall Compaction.

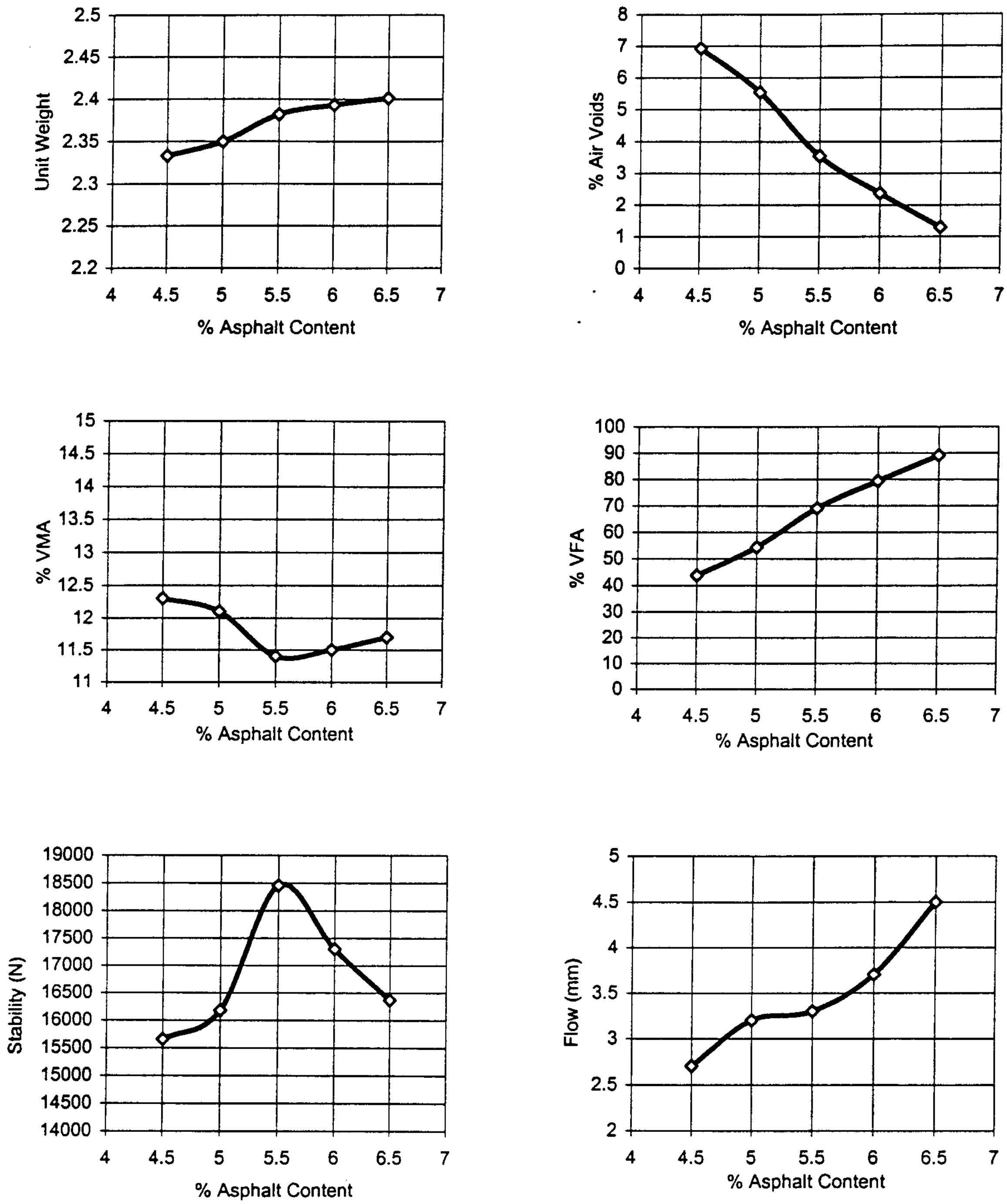


Figure 4.4. Determination of Optimum Asphalt Cement Content and Evaluation of Air Void Content at $N_{initial}$ and N_{max} for Limestone Surface Mix with 50/50% Sand Blend.

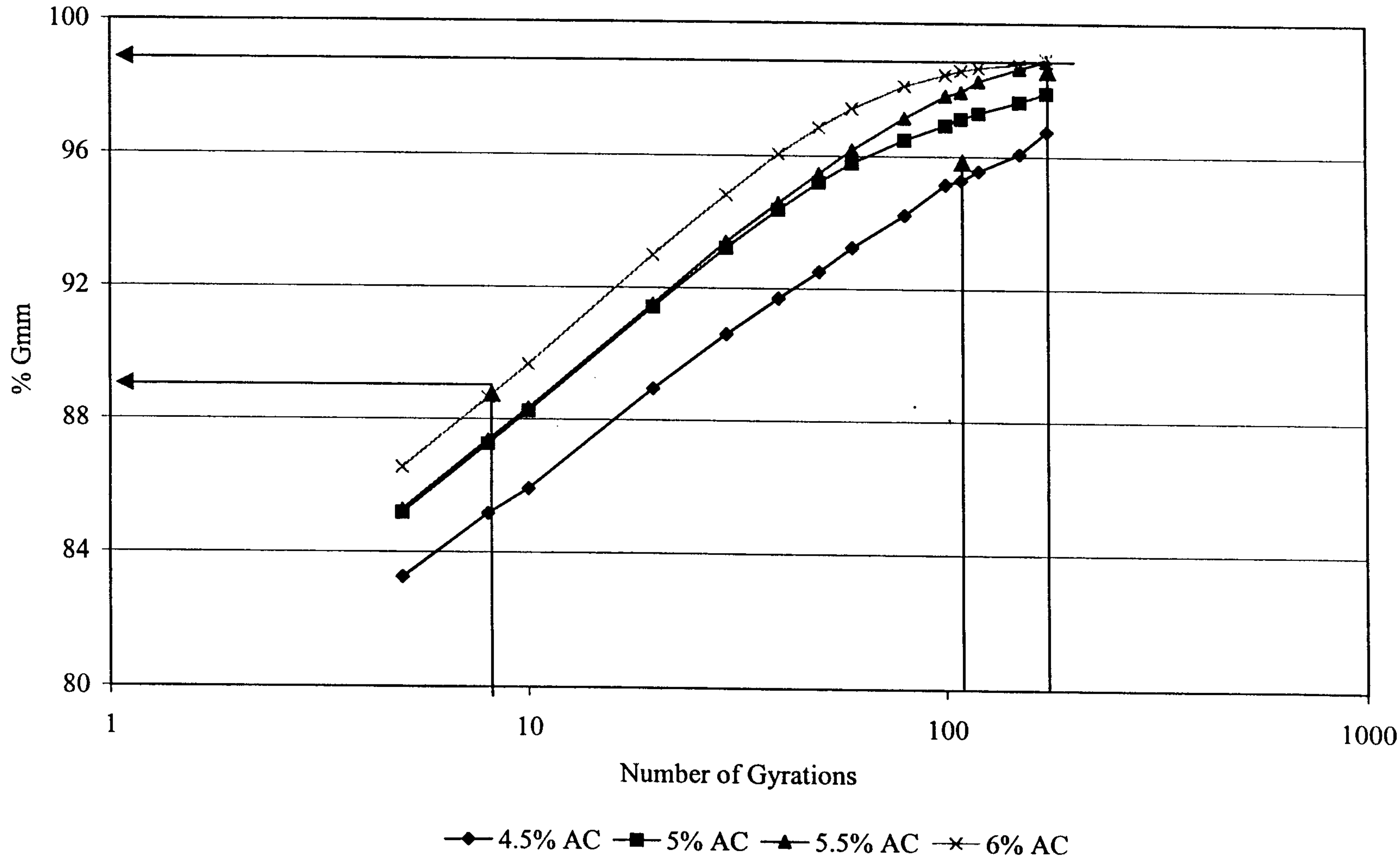


Table 4.20. Mix design data for surface mix with limestone coarse aggregate and 50/50% sand blend; SHRP gyratory compaction. Data at N_{max}

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA
4.5	2.426	2.506	3.25	8.8	63.1
5.0	2.436	2.487	2.09	8.9	76.5
5.5	2.441	2.468	1.13	9.2	87.7
6.0	2.425	2.450	1.13	10.3	89.0

Table 4.21. Mix design data for surface mix with limestone coarse aggregate and 50/50% sand blend; mechanical Marshall compaction (not aged mix).

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.302	2.466	6.65	13.5	50.7	10,570	2.8
5.0	2.321	2.448	5.19	13.2	60.9	11,910	2.9
5.5	2.337	2.430	3.82	13.1	70.8	12,880	3.0
6.0	2.360	2.412	2.16	12.7	83.1	13,880	2.9
6.5	2.371	2.395	1.01	12.8	92.3	14,340	3.2

Table 4.22. Mix design data for leveling mix with limestone coarse aggregate and 50/50% sand blend; mechanical Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.0	2.371	2.551	7.07	12.9	45.3	16,120	2.6
4.5	2.392	2.532	5.51	12.6	53.7	15,920	2.7
5.0	2.416	2.512	3.83	12.2	68.3	15,410	2.6
5.5	2.431	2.494	2.52	12.1	79.2	15,250	3.4
6.0	2.437	2.474	1.48	12.3	88.0	14,300	3.4

Table 4.23. Mix design data for leveling mix with limestone coarse aggregate and 50/50% sand blend; manual Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.0	2.404	2.551	5.78	11.7	50.6	18,280	3.1
4.5	2.423	2.532	4.30	11.4	62.4	18,650	3.1
5.0	2.443	2.512	2.73	11.2	75.6	16,960	3.2
5.5	2.447	2.494	1.88	11.5	83.7	16,440	3.9
6.0	2.450	2.474	1.00	11.9	91.7	13,920	4.3

Table 4.24. Mix design data for leveling mix with limestone coarse aggregate and 50/50% sand blend; rotating base Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.0	2.357	2.551	7.60	13.4	43.3	15,950	2.5
4.5	2.380	2.532	6.01	13.0	54.0	15,680	3.3
5.0	2.414	2.512	3.90	12.2	68.3	15,600	3.4
5.5	2.427	2.494	2.67	12.2	78.2	14,560	3.2
6.0	2.423	2.474	2.07	12.8	83.9	13,070	3.8

Table 4.25. Mix design data for leveling mix with limestone coarse aggregate and 50/50% sand blend; SHRP gyratory compaction. Data at $N_{initial}$

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA
3.5	2.180	2.573	15.30	19.5	21.6
4.0	2.190	2.551	14.14	19.6	27.6
4.5	2.216	2.532	12.50	19.1	34.3
5.0	2.236	2.512	10.99	18.7	41.3

Table 4.26. Mix design data for leveling mix with limestone coarse aggregate and 50/50% sand blend; SHRP gyratory compaction. Data at N_{design}

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA
3.5	2.414	2.573	6.20	10.9	43.0
4.0	2.421	2.551	5.10	11.1	53.9
4.5	2.442	2.532	3.55	10.7	67.1
5.0	2.455	2.512	2.26	10.7	79.0

Table 4.27. Mix design data for leveling mix with limestone coarse aggregate and 50/50% sand blend; SHRP gyratory compaction. Data at N_{max}

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA
3.5	2.446	2.573	4.92	9.7	49.1
4.0	2.455	2.551	3.76	9.8	61.7
4.5	2.471	2.532	2.39	9.7	75.3
5.0	2.479	2.512	1.29	9.9	86.9

Table 4.28. Mix design data for leveling mix with limestone coarse aggregate and 50/50% sand blend; Mechanical Marshall compaction (not aged mix).

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.0	2.379	2.525	5.80	12.6	54.1	14,480	2.5
4.5	2.400	2.506	4.23	12.3	65.6	14,660	2.9
5.0	2.416	2.487	2.87	12.2	76.6	14,100	3.2
5.5	2.419	2.468	1.99	12.5	84.1	13,560	3.4
6.0	2.426	2.450	0.97	12.7	92.3	13,180	3.7

Optimum asphalt cement contents for examined mixes was determined at asphalt cement content that would yield 4% air voids. Tables 4.29 and 4.30 present optimum asphalt cement contents for surface mixes made with limestone and gravel coarse aggregates. Tables 4.31 and 4.32 present optimum asphalt cement contents for leveling mixes made with limestone and gravel coarse aggregates.

The experimental design for this project did not include testing of samples prepared by the SHRP gyratory compactor for the following mixes; since they do not represent typical Ohio mixes:

- Surface course mix made with limestone coarse aggregate and natural sand
- Surface course mix made with gravel coarse aggregate and manufactured sand
- Surface course mix made with gravel coarse aggregate and natural sand
- Leveling course mix made with limestone coarse aggregate and natural sand
- Leveling course mix made with gravel coarse aggregate and manufactured sand
- Leveling course mix made with gravel coarse aggregate and natural sand.

Consequently, no optimum asphalt cement contents, determined by testing of specimens made by use of the SHRP gyratory compactor, are available for the above mixes.

Figures 4.5 through 4.10 present optimum asphalt cement contents for all mixes that were subjected to the full experimental design.

Table 4.29. Optimum asphalt cement content for surface mixes with limestone coarse aggregate.

Aggregate Composition	Type of Compactor				
	Mechanical Marshall	Manual Marshall	Rotating Base Marshall	SHRP Gyratory	Mechanical Marshall (not aged mix)
Limestone Aggregate, Manufactured Sand	5.8	6.0	5.6	4.5	5.3
Limestone Aggregate, Natural Sand	5.9	6.0	6.1	-	5.5
Limestone Aggregate, 50/50 Sand Blend	5.9	5.4	5.9	4.7	5.4

Optimum asphalt cement content for mix made with limestone coarse aggregate and 50/50% sand blend was determined by the contractor at 5.5%.

Table 4.30. Optimum asphalt cement content for surface mixes with gravel coarse aggregate.

Aggregate Composition	Type of Compactor				
	Mechanical Marshall	Manual Marshall	Rotating Base Marshall	SHRP Gyratory	Mechanical Marshall (not aged mix)
Gravel Aggregate, Manufactured Sand	6.2	5.5	6.6	-	5.6
Gravel Aggregate, Natural Sand	5.8	5.3	5.7	-	5.7
Gravel Aggregate, 50/50 Sand Blend	6.1	5.7	6.0	5.3	5.5

Optimum asphalt cement content for mix made with gravel coarse aggregate and 50/50% sand blend was determined by the contractor at 5.7%.

Table 4.31. Optimum asphalt cement content for leveling mixes with limestone coarse aggregate.

Aggregate Composition	Type of Compactor				
	Mechanical Marshall	Manual Marshall	Rotating Base Marshall	SHRP Gyratory	Mechanical Marshall (not aged mix)
Limestone Aggregate, Manufactured Sand	4.7	4.7	4.8	4.5	4.3
Limestone Aggregate, Natural Sand	5.2	4.7	5.3	-	4.8
Limestone Aggregate, 50/50 Sand Blend	4.9	4.6	5.0	4.4	4.6

Optimum asphalt cement content for mix made with limestone coarse aggregate and 50/50% sand blend was determined by the contractor at 4.9%

Table 4.32. Optimum asphalt cement content for leveling mixes with gravel coarse aggregate.

Aggregate Composition	Type of Compactor				
	Mechanical Marshall	Manual Marshall	Rotating Base Marshall	SHRP Gyratory	Mechanical Marshall (not aged mix)
Gravel Aggregate, Manufactured Sand	6.7	6.3	6.6	-	6.3
Gravel Aggregate, Natural Sand	5.7	5.3	5.3	-	5.3
Gravel Aggregate, 50/50 Sand Blend	6.1	5.7	6.0	5.4	5.6

Optimum asphalt cement content for mix made with gravel coarse aggregate and 50/50% sand blend was determined by the contractor at 5.4%.

Figure 4. 5. Optimum Asphalt Cement Content vs. Compaction Type. Surface Mix with Limestone Coarse Aggregate and Manufactured Sand.

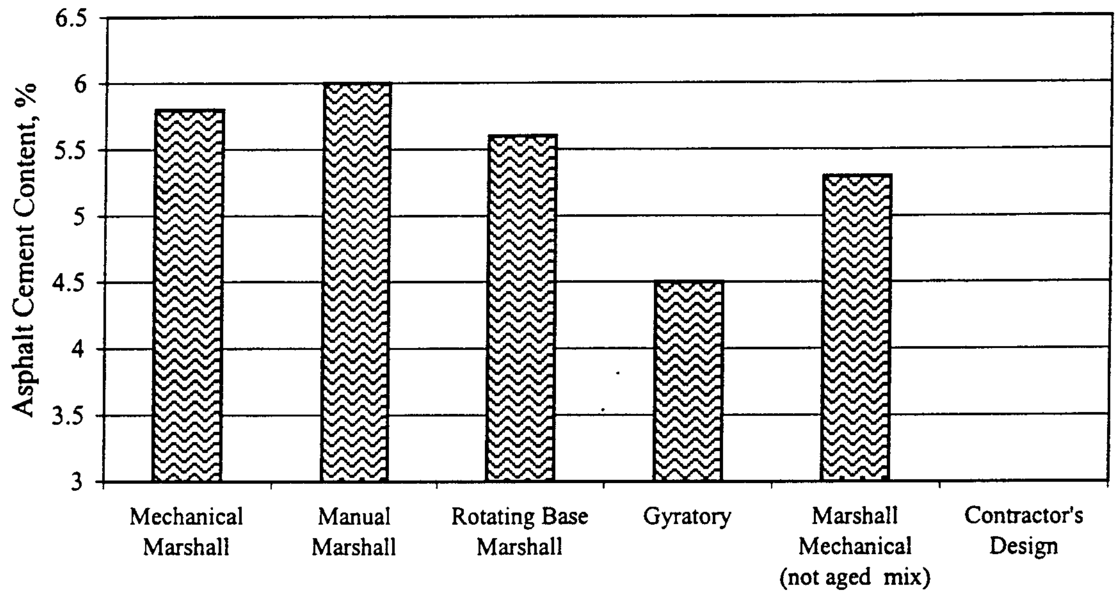


Figure 4.6. Optimum Asphalt Cement Content vs. Compaction Type Surface Mix with Limestone Coarse Aggregate and 50/50% Sand Blend.

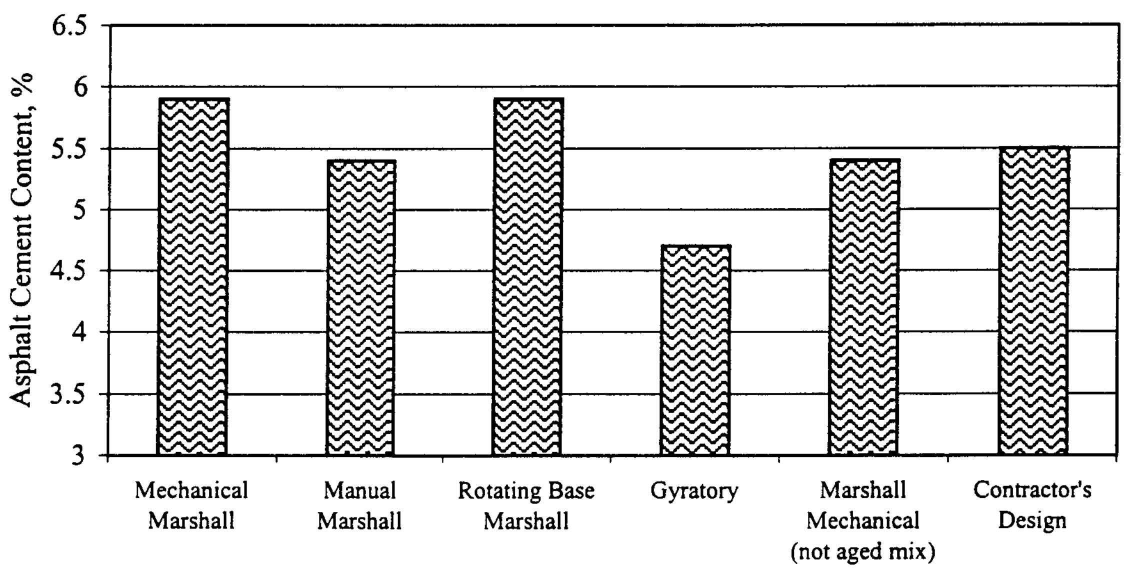


Figure 4. 7. Optimum Asphalt Cement Content vs. Compaction Type. Surface Mix with Gravel Coarse Aggregate and 50/50% Sand Blend.

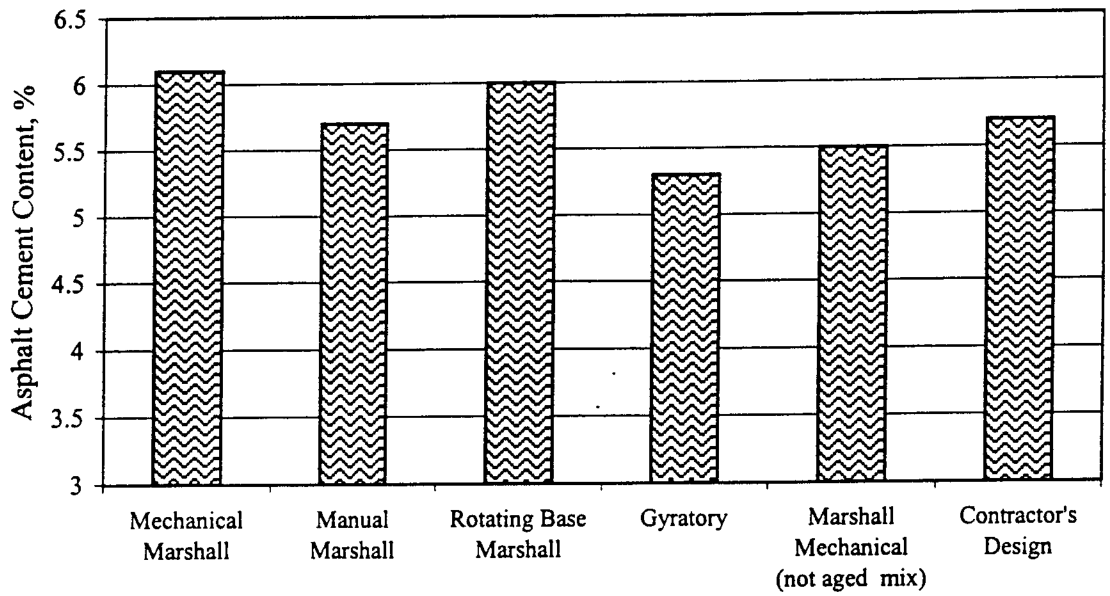


Figure 4.8. Optimum Asphalt Cement Content vs. Compaction Type Leveling Mix with Limestone Coarse Aggregateand Manufactured Sand.

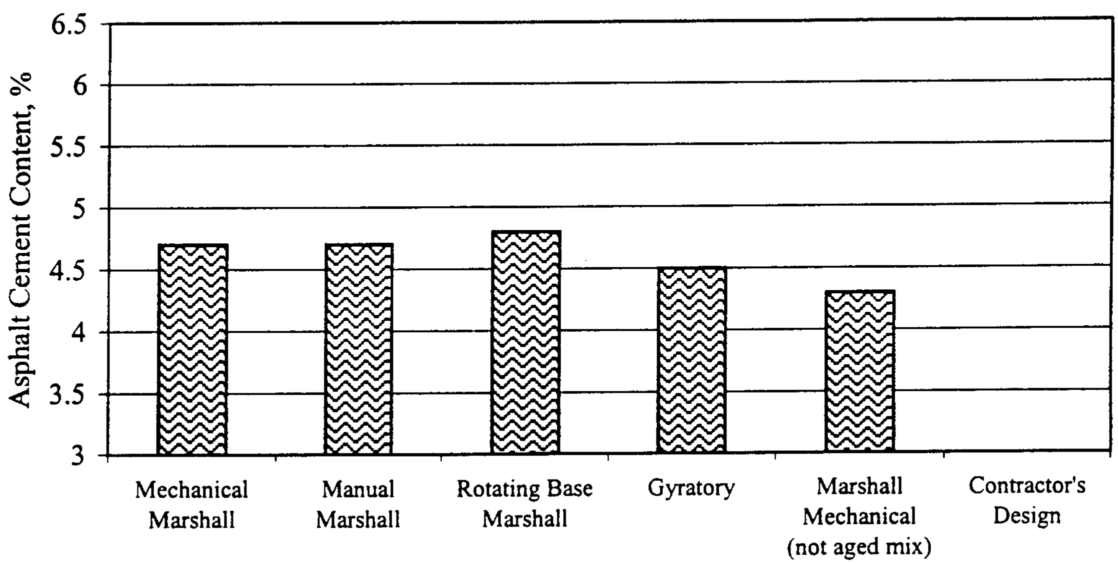


Figure 4. 9. Optimum Asphalt Cement Content vs. Compaction Type. Leveling Mix with Limestone Coarse Aggregate and 50/50% Sand Blend.

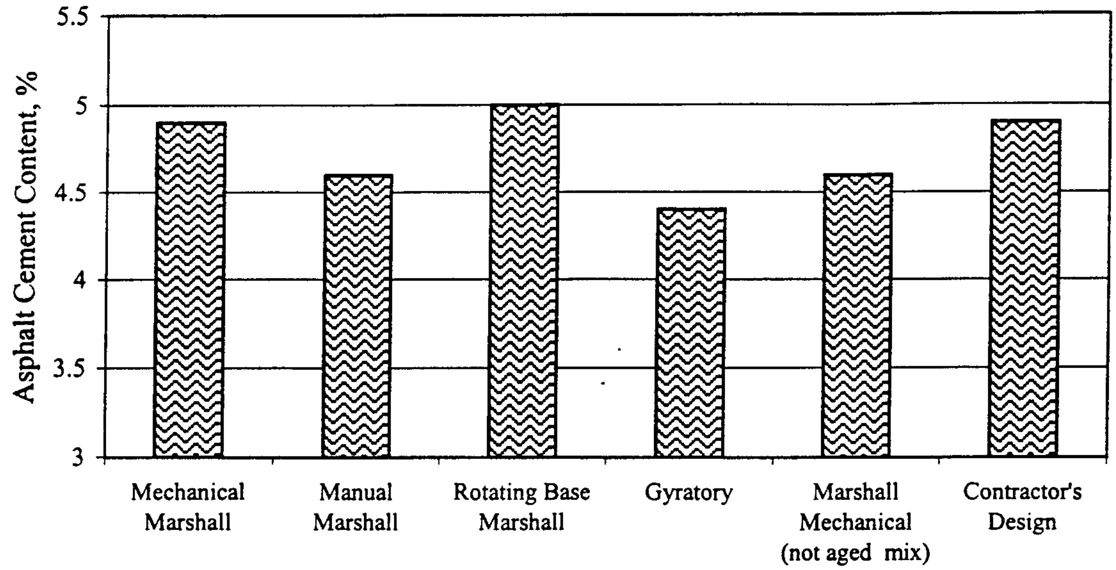
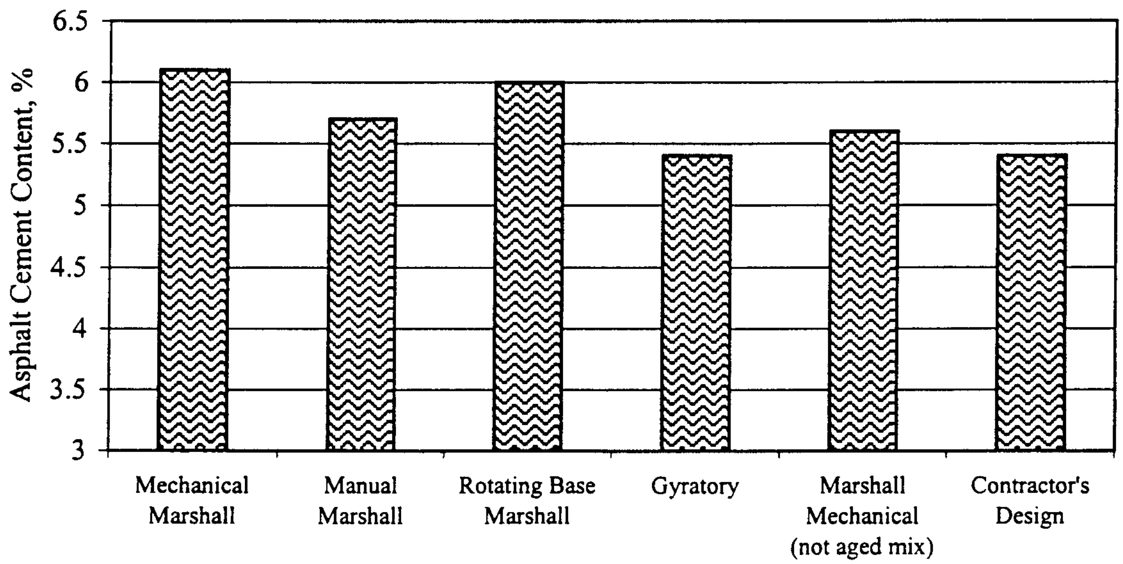


Figure 4.10. Optimum Asphalt Cement Content vs. Compaction Type Leveling Mix with Gravel Coarse Aggregate and 50/50% Sand Blend.



4.3.1. Optimum Asphalt Cement Content Determined for Aged Asphalt Concrete Mixes Using Specimens Prepared by Marshall Compactors.

Table 4.33 presents summary of optimum asphalt cement content data for aged mixes determined by testing specimens prepared by mechanical, manual, and rotating base Marshall compactors.

Table 4.33. Summary of optimum asphalt cement content data in relation to type of Marshall compactor used for specimen preparation.

Mix Type	Mean Value of Optimum AC Content	Difference of the Actual Optimum AC Content from the Mean for Mixes Prepared by		
		Mechanical Compactor	Manual Compactor	Rotating Base Compactor
Surface, Limestone and Manufactured Sand	5.8	0	+0.2	-0.2
Surface, Limestone and Natural Sand	6.0	-0.1	0	+0.1
Surface, Limestone and 50/50% Sand Blend	5.7	+0.2	-0.3	+0.2
Surface, Gravel and Manufactured Sand	6.1	-0.1	-0.6	+0.5
Surface, Gravel and Natural Sand	5.6	+0.2	-0.3	+0.1
Surface, Gravel and 50/50% Sand Blend	5.9	+0.2	-0.2	+0.1
Leveling, Limestone and Manufactured Sand	4.7	0	0	+0.1
Leveling, Limestone and Natural Sand	5.1	+0.1	-0.4	+0.2
Leveling, Limestone and 50/50% Sand Blend	4.8	+0.1	-0.2	+0.2
Leveling, Gravel and Manufactured Sand	6.5	+0.2	-0.2	+0.1
Leveling, Gravel and Natural Sand	5.4	+0.3	-0.1	-0.1
Leveling, Gravel and 50/50% Sand Blend	5.9	+0.2	-0.2	+0.1
Sum of Variations		+1.3	-2.3	+1.4

Mean values of optimum asphalt cement content determined for aged asphalt concrete mixes on specimens prepared by mechanical, manual, and rotating base Marshall compactors are presented in column 2 of Table 4.33. Differences from this mean as affected by type of compactor used for specimen preparation are presented in Columns 3, 4, and 5. Data in the last row of this table does not zero as a result of numbers rounding.

Data presented in the last row of Table 4.33 indicate that optimum asphalt cement content determined for the mixes by testing specimens that were prepared by the manual Marshall compactor are likely to be lower than those determined by testing specimens prepared by either the mechanical or rotating base Marshall compactor.

4.3.2. Optimum Asphalt Cement Content Determined for Aged Asphalt Concrete Mixes by Testing Specimens Prepared by Using the SHRP Gyratory Compactor.

Air voids analysis during the compaction process is one of the elements of acceptance of optimum asphalt cement content for mixes designed by the SHRP volumetric approach. Mixes prepared with selected optimum asphalt cement contents that meet 4% air void requirement at N_{design} have to satisfy two additional air voids criteria. Air voids at $N_{initial}$ have to be more than 11%, and at N_{max} be more than 2%.

Table 4.34 presents air voids analysis for all asphalt concrete mixes designed by testing specimens prepared using the SHRP gyratory compactor. Data presented in Table 4.34 shows that actual air voids at $N_{initial}$ and N_{max} range from 11.0 to 14.6% and from 2.1 to 3.0%, respectively, which verifies that the mixes designed by testing specimens prepared using the SHRP Gyratory compactor satisfy the initial and final air voids requirements.

Table 4.34. Air voids content determined during SHRP gyratory compaction process for mixes at optimum asphalt cement content.

Mix Type	Optimum AC Content	Air Voids at $N_{initial}$		Air Voids at N_{max}	
		Actual	Minimum Required	Actual	Minimum Required
Surface, Limestone and Manufactured Sand	4.5	14.6	11.0	2.1	2.0
Surface, Limestone and 50/50% Sand Blend	4.7	14.0	11.0	2.8	2.0
Surface, Gravel and 50/50% Sand Blend	5.3	13.6	11.0	2.8	2.0
Leveling, Limestone and Manufactured Sand	4.5	14.2	11.0	2.8	2.0
Leveling, Limestone and 50/50% Sand Blend	4.4	12.8	11.0	2.7	2.0
Leveling, Gravel and 50/50% Sand Blend	5.4	11.0	11.0	3.0	2.0

4.3.3. Optimum Asphalt Cement Content Analysis for All Mixes.

The analysis of all optimum asphalt cement content data that is presented in Tables 4.29, 4.30, 4.31, and 4.32 is based on the following conditions:

1. Optimum asphalt cement content determined for an aged mix by testing specimens prepared using the SHRP gyratory compactor is compared with an average optimum asphalt cement content determined for this mix by testing specimens prepared by mechanical, manual, and rotating base Marshall compactor.

2. Data from asphalt concrete specimens prepared by mechanical Marshall compactor is used to compare optimum asphalt cement content determined for a mix in both an aged and not aged condition.

Data presented in Tables 4.29, 4.30, 4.31, and 4.32 shows that optimum asphalt cement content depends on type of coarse and fine aggregate, aging method, and type of compactor used for specimen preparation.

- Surface mixes with limestone coarse aggregate.

  Optimum asphalt cement content of aged asphalt mixes made with limestone coarse aggregate and manufactured sand, as determined by testing specimens prepared using different types of Marshall compactor, ranges from 5.6 to 6.0%, with the mean at 5.8%. Optimum asphalt cement content determined for the same mix by testing specimens prepared using the gyratory compactor is 4.5% which is 1.3% lower than that established on the basis of Marshall compaction. Elimination of the aging process results in an optimum asphalt cement content that is 0.5% lower for not aged than aged mixes.

  The optimum asphalt cement content of aged mixes made with limestone coarse aggregate and natural sand, as determined by testing specimens prepared by different types of Marshall compactor, range from 5.9 to 6.1%. Elimination of the aging process decreases the optimum asphalt cement content from 5.9 to 5.5%, a reduction of 0.4%.

  Optimum asphalt cement content of aged asphalt mixes made with limestone coarse aggregate and a 50/50% blend of manufactured and natural sand, as determined by testing specimens prepared using different types of Marshall compactor, ranges from 5.4 to 5.9%, with a mean at 5.7%. Optimum asphalt cement content determined for the same mix by testing specimens prepared using SHRP gyratory compactor is 4.7%, which is 1.0% lower than that determined by testing specimens prepared using Marshall compaction. Elimination of the aging process results in an optimum asphalt cement content that is 0.5% lower for not aged than aged mixes. The optimum asphalt cement content for mix made with a

50/50% sand blend was reported by the contractor at 5.5%, which is similar to the 5.4% value determined during this study for a not aged mix.

- Surface mixes with gravel coarse aggregate.

The optimum asphalt cement content of aged asphalt concrete mix made with gravel coarse aggregate and manufactured sand, as determined by testing specimens prepared using different types of Marshall compactor, ranges from 5.5 to 6.6%. Elimination of the aging process results in an optimum asphalt cement content that is 0.6% lower for not aged than aged mix.

The optimum asphalt cement content of aged mix made with gravel coarse aggregate and natural sand, as determined by testing specimens prepared by different types of Marshall compactor ranges from 5.3 to 5.8%. Elimination of the aging process results in an optimum asphalt cement content that is 0.1% lower for not aged than aged mixes.

The optimum asphalt cement content of aged mix made with gravel coarse aggregate and a 50/50% manufactured and natural sand blend, as determined by testing specimens prepared using different types of Marshall compactor, ranges from 5.7 to 6.1% with a mean at 5.9%. The use of specimens prepared by SHRP gyratory compactor decreases this optimum by 0.6% to 5.3%. Elimination of the aging process decreases the average optimum asphalt cement content by 0.6%. The optimum asphalt cement content for gravel mix made with a 50/50% sand blend was reported by the contractor to be 5.7% which falls between the optimum for aged and not aged mix as determined by this study. This may suggest that contractor used some aging process when determining optimum asphalt cement content was for this mix.

- Leveling mixes with limestone coarse aggregate.

Optimum asphalt cement content of aged asphalt mixes made with limestone coarse aggregate and manufactured sand, as determined by testing specimens prepared using different types of Marshall, compactor ranges from 4.7 to 4.8%, with a mean at 4.7%. Optimum asphalt cement content of the same mix, as determined by testing specimens prepared using the SHRP gyratory compactor, is 4.5%, which is 0.2% lower than that established on the basis of testing specimens prepared using the Marshall compactors. Elimination of the aging process lowers the optimum asphalt cement content by 0.4% from 4.7 to 4.3%.

The optimum asphalt cement content of aged limestone mix with natural sand, as determined by testing specimens prepared by using different types of Marshall compactor, range from 4.7 to 5.3%. Elimination of the aging process results in a 0.4% decrease of the optimum asphalt cement content from 5.2 to 4.8%.

Optimum asphalt cement content of aged asphalt mixes made limestone coarse aggregate and a 50/50% blend of manufactured and natural sand, as determined on specimens prepared using different types of Marshall compactor, ranges from 4.6 to 5.0%, with an average of 4.8%. Optimum asphalt cement content of the same mix, as determined by testing specimens prepared using the SHRP gyratory compactor is 4.4% which is 0.4% lower than that established by testing specimens prepared using different types of Marshall compactor. Elimination of the aging process lowers the optimum asphalt cement content by 0.3% from 4.9 to 4.6%. The optimum asphalt cement content for mix made with a 50/50% sand blend is reported by the contractor to be 4.9%, which is identical to the 4.9% value determined during this study for an aged mix.

- Leveling mixes with gravel coarse aggregate.

  The optimum asphalt cement content of aged asphalt concrete mix made with gravel coarse aggregate and manufactured sand, as determined by testing specimens prepared using different types of Marshall compactor, ranges from 6.3 to 6.7% with the mean at 6.5%. Optimum asphalt cement content of the same mix in a not aged condition is 6.3%.

  The optimum asphalt cement content of aged mix made with gravel coarse aggregate and natural sand, as determined by testing specimens prepared using different types of Marshall compactor, ranges from 5.3 to 5.7%. Elimination of the aging process results in an optimum asphalt cement content that is 0.4% lower for not aged than aged mixes.

  The optimum asphalt cement content of aged mix made with gravel aggregate and a 50/50% manufactured and natural sand blend, as determined by testing specimens prepared using different types of Marshall compactor ranges from 5.7 to 6.1% with the mean at 5.9%. Use of specimens prepared using the SHRP gyratory compactor decreases this optimum by 0.5% to 5.4%. Elimination of the aging process decreases the average optimum asphalt cement content by 0.5%. The optimum asphalt cement content for mix made with a 50/50% sand blend was reported by the contractor to be 5.4% which is lower than the optimum for both aged and not aged mix determined during this study. This fact is possibly due to the high (5%) absorption of manufactured sand used in this study.

Table 4.35 summarizes a comparison of average optimum asphalt cement content data for aged mixes, as determined by testing specimens prepared using different types of Marshall compactors and the SHRP gyratory compactor, with that of a not aged mixes, as determined by testing specimens prepared using mechanical Marshall compaction.

Data presented in Table 4.35 shows that the optimum asphalt cement contents of all aged mixes, as determined by testing specimens prepared using the SHRP gyratory compactor were lower than the average optimum asphalt cement content determined on specimens prepared by Marshall compactors. The average difference between optimum asphalt cement contents was more significant for surface mixes than for leveling mixes 16.7% versus 7.0%, respectively. Surface mixes with limestone coarse aggregate exhibit larger reductions in optimum asphalt cement content than mixes with gravel coarse aggregate. The greatest difference in optimum asphalt cement content was determined for aged surface mix with limestone coarse aggregate and manufactured sand. This difference will result in 22.4 % less asphalt cement content in mixes designed with specimens prepared using the SHRP gyratory compactor as compared with mixes designed with an average optimum asphalt cement content as determined by testing specimens prepared by mechanical, manual, and rotating base Marshall compactors. The optimum asphalt cement content of aged surface mix with gravel coarse aggregate, as determined by testing specimens prepared using SHRP gyratory compactor is 10.2% lower than the average optimum asphalt cement content determined on specimens prepared using different types of Marshall compactor.

Optimum asphalt cement content, as determined by testing specimens prepared using the SHRP gyratory compactor is lower than an optimum asphalt cement content as determined by testing specimens prepared using different types of Marshall compactor. The reduction is 4.3 and 8.3% for mixes with manufactured sand and a 50/50% sand blend, respectively. Optimum asphalt cement content for leveling mix made with gravel coarse aggregate and a 50/50% sand blend was 8.5% lower when established by testing specimens prepared using the SHRP gyratory compactor than an average optimum asphalt cement content obtained by testing specimens prepared using different types of Marshall compactor.

Optimum asphalt cement content for not aged mixes designed by Marshall mix design method, using a mechanical Marshall compactor is lower on average by 9.0% for surface and 7.6% for leveling mixes than the optimum asphalt cement content determined for aged mixes.

Table 4.35. Comparison of optimum asphalt cement content for mixes subjected to full experimental design.

Mix Type	Optimum Asphalt Cement Content, %					
	Averaged Aged Marshall	SHRP Gyratory	Reduction, %	Mechanical Marshall		Reduction, %
				Aged	Not Aged	
Surface, Limestone and Manufactured Sand	5.8	4.5	22.4	5.8	5.3	8.6
Surface, Limestone and 50/50% Sand Blend	5.7	4.7	17.5	5.9	5.4	8.5
Surface, Gravel and 50/50% Sand Blend	5.9	5.3	10.2	6.1	5.5	9.8
Average Asphalt Cement Use Reduction for Surface Mixes			16.7			9.0
Leveling, Limestone and Manufactured Sand	4.7	4.5	4.3	4.7	4.3	8.5
Leveling, Limestone and 50/50% Sand Blend	4.8	4.4	8.3	4.9	4.6	6.1
Leveling, Gravel and 50/50% Sand Blend	5.9	5.4	8.5	6.1	5.6	8.2
Average Asphalt Cement Use Reduction for Leveling Mixes			7.0			7.6

Optimum asphalt cement content, as determined by testing specimens prepared using the SHRP gyratory compactor is on average 11% lower and approximately the same for surface and leveling mixes, respectively, than the optimum asphalt cement content determined for not aged mixes by testing specimens prepared using a mechanical Marshall compactor.

Data collected during this study shows that surface mixes designed with specimens prepared using the SHRP gyratory compactor are likely to have significantly lower asphalt cement contents than the same mixes designed using the traditional Marshall method. A decreased asphalt cement content resulting from use of specimens prepared with the SHRP gyratory compactor may present future durability problems for constructed pavements. These problems, that can originate from an inadequate thickness of asphalt cement film on the aggregate particles, can produce premature aging and hardening of the asphalt cement in a concrete mix. Hard, aged, asphalt cement in an asphalt concrete mix is prone to cause premature manifestations of pavement distress such as cracking and raveling. In addition, low asphalt cement content usually results in a higher air void content of an asphalt pavement layer. Higher air void contents increase the permeability of the pavement, which increases moisture infiltration. High permeability of a pavement before it has consolidated under traffic may lead to saturation and loss of strength in the pavement and underlying road support layers. Surface course mixes, directly exposed to air, sun and water, are especially susceptible to premature aging and increased permeability. For this reason, the effects of significantly decreased asphalt cement content in surface mixes in comparison with those provided by traditional designs, should be a cause for possible concern and further examination.

4.4. PROPERTIES OF THE MIXES AT OPTIMUM ASPHALT CEMENT CONTENT.

Properties of the asphalt concrete at optimum asphalt cement content are presented in Tables 4.36 through 4.41 and Tables 4.42 through 4.47 for surface and leveling mixes, respectively.

Table 4.36. Properties of asphalt concrete at optimum asphalt cement content for surface mix made with limestone coarse aggregate and manufactured sand.

Compaction Method	Property					
	Optimum AC content, %	Unit Weight	%VMA	%VFA	Stability (N)	Flow (mm)
Mechanical Marshall	5.8	2.360	13.1	70.0	14,430	2.9
Manual Marshall	6.0	2.348	13.7	69.7	13,880	4.3
Rotating Base Marshall	5.6	2.362	12.8	67.6	14,840	3.1
Gyratory at N_{design}	4.5	2.409	10.0	61.2	-	-
Mechanical Marshall (not aged mix)	5.3	2.346	13.1	71.8	12,910	3.0

Table 4.37. Properties of asphalt concrete at optimum asphalt cement content for surface mix made with limestone coarse aggregate and natural sand.

Compaction Method	Property					
	Optimum AC Content, %	Unit Weight	%VMA	%VFA	Stability (N)	Flow (mm)
Mechanical Marshall	5.9	2.340	13.0	68.4	12,460	3.0
Manual Marshall	6.0	2.340	13.1	69.9	13,120	3.2
Rotating Base Marshall	6.1	2.334	13.5	69.7	12,470	3.1
Gyratory at N_{design}	-	-	-	-	-	-
Mechanical Marshall (not aged mix)	5.5	2.321	13.4	68.8	11,860	2.9

Table 4.38. Properties of asphalt concrete at optimum asphalt cement content for surface mix made with limestone coarse aggregate and 50/50% sand blend.

Compaction Method	Property					
	Optimum AC Content, %	Unit Weight	%VMA	%VFA	Stability (N)	Flow (mm)
Mechanical Marshall	5.9	2.356	12.8	68.6	11,050	3.2
Manual Marshall	5.4	2.376	11.6	66.2	18,000	3.3
Rotating Base Marshall	5.9	2.348	13.1	66.8	14,100	2.7
Gyratory at N_{design}	4.7	2.400	10.0	60.5	-	-
Mechanical Marshall (not aged mix)	5.4	2.334	13.1	68.9	12,680	2.9
Mechanical Marshall (Contractor's data)	5.5	2.332	14.9	75.9	11,050	2.5

Table 4.39. Properties of asphalt concrete at optimum asphalt cement content for surface mix made with gravel coarse aggregate and manufactured sand.

Compaction Method	Property					
	Optimum AC Content, %	Unit Weight	%VMA	%VFA	Stability (N)	Flow (mm)
Mechanical Marshall	6.2	2.365	13.5	71.3	13,490	2.5
Manual Marshall	5.5	2.391	11.9	67.3	19,320	2.6
Rotating Base Marshall	6.6	2.341	14.5	73.0	10,500	3.2
Gyratory at N_{design}	-	-	-	-	-	-
Mechanical Marshall (not aged mix)	5.6	2.364	13.0	70.0	12,830	2.5

Table 4.40. Properties of asphalt concrete at optimum asphalt cement content for surface mix made with gravel coarse aggregate and natural sand.

Compaction Method	Property					
	Optimum AC content	Unit Weight	%VMA	%VFA	Stability (N)	Flow (mm)
Mechanical Marshall	5.8	2.369	13.0	69.9	14,550	2.7
Manual Marshall	5.3	2.382	12.1	65.7	16,700	2.5
Rotating Base Marshall	5.7	2.366	12.9	67.9	14,450	2.7
Gyratory at N_{design}	-	-	-	-	-	-
Mechanical Marshall (not aged mix)	5.7	2.349	13.5	70.3	11,710	2.3

Table 4.41. Properties of asphalt concrete at optimum asphalt cement content for surface mix made with gravel coarse aggregate and 50/50% sand blend.

Compaction Method	Property					
	Optimum AC Content, %	Unit Weight	%VMA	%VFA	Stability (N)	Flow (mm)
Mechanical Marshall	6.1	2.358	13.6	70.0	14,110	2.5
Manual Marshall	5.7	2.377	12.7	68.2	16,040	2.6
Rotating Base Marshall	6.0	2.367	13.2	70.5	14,230	2.7
Gyratory at N_{design}	5.3	2.385	11.9	64.7	-	-
Mechanical Marshall (not aged mix)	5.5	2.355	13.2	69.1	12,070	2.4
Mechanical Marshall (Contractor's data)	5.7	2.324	14.1	71.6	11,120	2.5

Table 4.42. Properties of asphalt concrete at optimum asphalt cement content for leveling mix made with limestone coarse aggregate and manufactured sand.

Compaction Method	Property					
	Optimum AC Content, %	Unit Weight	%VMA	%VFA	Stability (N)	Flow (mm)
Mechanical Marshall	4.7	2.434	11.8	66.6	16,450	4.5
Manual Marshall	4.7	2.429	12.0	65.5	19,390	4.4
Rotating Base Marshall	4.8	2.429	12.1	67.1	17,540	4.2
Gyratory at N_{design}	4.5	2.437	11.5	63.8	-	-
Mechanical Marshall (not aged mix)	4.3	2.423	11.9	66.7	16,760	3.4

Table 4.43. Properties of asphalt concrete at optimum asphalt cement content for leveling mix made with limestone coarse aggregate and natural sand.

Compaction Method	Property					
	Optimum AC Content, %	Unit Weight	%VMA	%VFA	Stability (N)	Flow (mm)
Mechanical Marshall	5.2	2.393	12.6	68.6	14,000	2.8
Manual Marshall	4.7	2.409	11.6	64.6	17,470	3.0
Rotating Base Marshall	5.3	2.385	12.9	67.8	14,410	2.6
Gyratory at N_{design}	-	-	-	-	-	-
Mechanical Marshall (not aged mix)	4.8	2.380	12.7	67.9	13,170	2.7

Table 4.44. Properties of asphalt concrete at optimum asphalt cement content for leveling mix made with limestone coarse aggregate and 50/50% sand blend.

Compaction Method	Property					
	Optimum AC Content, %	Unit Weight	%VMA	%VFA	Stability (N)	Flow (mm)
Mechanical Marshall	4.9	2.411	12.3	65.4	15,510	2.7
Manual Marshall	4.6	2.427	11.4	65.0	18,320	3.1
Rotating Base Marshall	5.0	2.414	12.2	68.3	15,600	3.4
Gyratory at N_{design}	4.4	2.438	10.8	64.5	-	-
Mechanical Marshall (not aged mix)	4.6	2.403	12.3	67.8	14,550	3.0
Loaded Wheel (Contractor's data)	4.9	2.358	12.6	68.2	13,920	2.4

Table 4.45. Properties of asphalt concrete at optimum asphalt cement content for leveling mix made with gravel coarse aggregate and manufactured sand.

Compaction Method	Property					
	Optimum AC Content	Unit Weight	%VMA	%VFA	Stability (N)	Flow (mm)
Mechanical Marshall	6.7	2.322	13.1	70.1	15,910	3.4
Manual Marshall	6.3	2.331	12.4	66.9	16,910	3.6
Rotating Base Marshall	6.6	2.326	12.8	70.0	16,090	3.4
Gyratory at N_{design}	-	-	-	-	-	-
Mechanical Marshall (not aged mix)	6.3	2.305	13.4	67.7	13,310	4.5

Table 4.46. Properties of asphalt concrete at optimum asphalt cement content for leveling mix made with gravel coarse aggregate and natural sand.

Compaction Method	Property					
	Optimum AC Content, %	Unit Weight	%VMA	%VFA	Stability (N)	Flow (mm)
Mechanical Marshall	5.7	2.337	13.8	72.0	9,750	2.4
Manual Marshall	5.3	2.344	13.1	68.7	12,100	2.5
Rotating Base Marshall	5.3	2.343	13.1	68.8	10,760	2.4
Gyratory at N_{design}	-	-	-	-	-	-
Mechanical Marshall (not aged mix)	5.3	2.316	14.2	71.1	5,520	2.6

Table 4.47. Properties of asphalt concrete at optimum asphalt cement content for leveling mix made with gravel coarse aggregate and 50/50% sand blend.

Compaction Method	Property					
	Optimum AC Content, %	Unit Weight	%VMA	%VFA	Stability (N)	Flow (mm)
Mechanical Marshall	6.1	2.327	13.7	69.8	12,480	2.7
Manual Marshall	5.7	2.345	12.7	68.5	14,830	2.8
Rotating Base Marshall	6.0	2.332	13.2	70.8	14,710	2.7
Gyratory at N_{design}	5.4	2.356	12.0	66.9	-	-
Mechanical Marshall (not aged mix)	5.6	2.322	13.4	70.4	10,010	2.4
Mechanical Marshall (Contractor's data)	5.4	2.293	15.5	74.2	8,890	3.1

4.5. DISCUSSION OF ASPHALT CONCRETE PROPERTIES.

Properties examined for all asphalt concrete test specimens included: unit weight, VMA, and VFA. In addition Marshall specimens were tested for stability and flow. The analysis of each asphalt concrete property for mixes subjected to full experimental design was conducted in two steps. The first step presents a discussion of data collected by testing specimens of aged mixes prepared using different Marshall compactors. The second step presents a discussion of data obtained for aged mixes by testing specimens prepared using both Marshall and SHRP gyratory compactors. Data representing results determined for mixes using specimens which were prepared with Marshall compactors was calculated as an average obtained for mixes compacted by mechanical, manual, and rotating base compactor. The second step also includes a discussion of asphalt concrete properties for aged and not aged specimens of asphalt mixes prepared by a mechanical Marshall compactor.

4.5.1. Unit Weight.

Table 4.48 presents summary unit weight values of aged asphalt concrete mixes. These unit weight values were determined by testing specimens having 4% air voids content which were prepared by mechanical, manual, and rotating base Marshall compactors.

Data presented in Table 4.48 indicate that aged asphalt concrete mix compacted using a manual Marshall compactor is more likely to a have higher unit weight than the same mix compacted using mechanical or rotating base Marshall compactors.

Table 4.48. Summary of mix unit weight data in relation to type of Marshall compactor.

Mix Type	Mean Value of Unit Weight	Difference of the Actual Unit Weight from the Mean for Mixes prepared by		
		Mechanical Compactor	Manual Compactor	Rotating Base Compactor
Surface, Limestone and Manufactured Sand	2.357	+0.003	-0.009	+0.005
Surface, Limestone and Natural Sand	2.338	+0.002	+0.002	-0.004
Surface, Limestone and 50/50% Sand Blend	2.360	-0.004	+0.016	-0.012
Surface, Gravel and Manufactured Sand	2.366	-0.001	+0.025	-0.025
Surface, Gravel and Natural Sand	2.372	-0.003	+0.010	-0.006
Surface, Gravel and 50/50% Sand Blend	2.367	-0.009	+0.010	0
Leveling, Limestone and Manufactured Sand	2.431	+0.003	-0.002	-0.002
Leveling, Limestone and Natural Sand	2.396	-0.003	+0.013	-0.011
Leveling, Limestone and 50/50% Sand Blend	2.417	-0.006	+0.010	-0.003
Leveling, Gravel and Manufactured Sand	2.326	-0.004	+0.005	0
Leveling, Gravel and Natural Sand	2.341	-0.004	+0.003	+0.002
Leveling, Gravel and 50/50% Sand Blend	2.335	-0.008	+0.010	-0.003
Sum of Variations		-0.034	+0.093	-0.059

Table 4.49 presents average unit weight values of aged asphalt concrete mixes, at 4% air void content, subjected to the full experimental design. The last two columns of this table show unit weight values of aged and not aged mix as determined by testing specimens prepared by use of mechanical Marshall compactor.

Table 4.49. Comparison of unit weight data for mixes subjected to the full experimental design.

Mix Type	Unit Weight					
	Averaged Aged Marshall	SHRP Gyratory	Change, %	Mechanical Marshall		Change, %
				Aged	Not Aged	
Surface, Limestone and Manufactured Sand	2.357	2.409	2.2	2.360	2.346	-0.6
Surface, Limestone and 50/50% Sand Blend	2.360	2.400	1.7	2.356	2.334	-0.9
Surface, Gravel and 50/50% Sand Blend	2.367	2.385	0.8	2.358	2.355	-0.1
Average Unit Weight Change for Surface Mixes			1.6			-0.5
Leveling, Limestone and Manufactured Sand	2.341	2.437	0.2	2.434	2.423	-0.4
Leveling, Limestone and 50/50% Sand Blend	2.417	2.438	0.9	2.411	2.403	-0.3
Leveling, Gravel and 50/50% Sand Blend	2.335	2.356	0.9	2.327	2.322	-0.2
Average Unit Weight Change for Leveling Mixes			0.7			-0.3

Data presented in Table 4.49 shows that the unit weight of aged mixes compacted using the SHRP gyratory compactor is greater than an average unit weight of the same mixes compacted using the Marshall compactor. The average difference is greater for surface than for leveling mixes. This data also indicates that unit weight is greater for aged than for not aged mixes.

Figures 4.11 through 4.16 show unit weight data for mixes subjected to the full experimental design.

Figure 4. 11. Relationship Between Unit Weight at 4% Air Voids and Compaction Type for Surface Mix with Limestone Coarse Aggregate and Manufactured Sand.

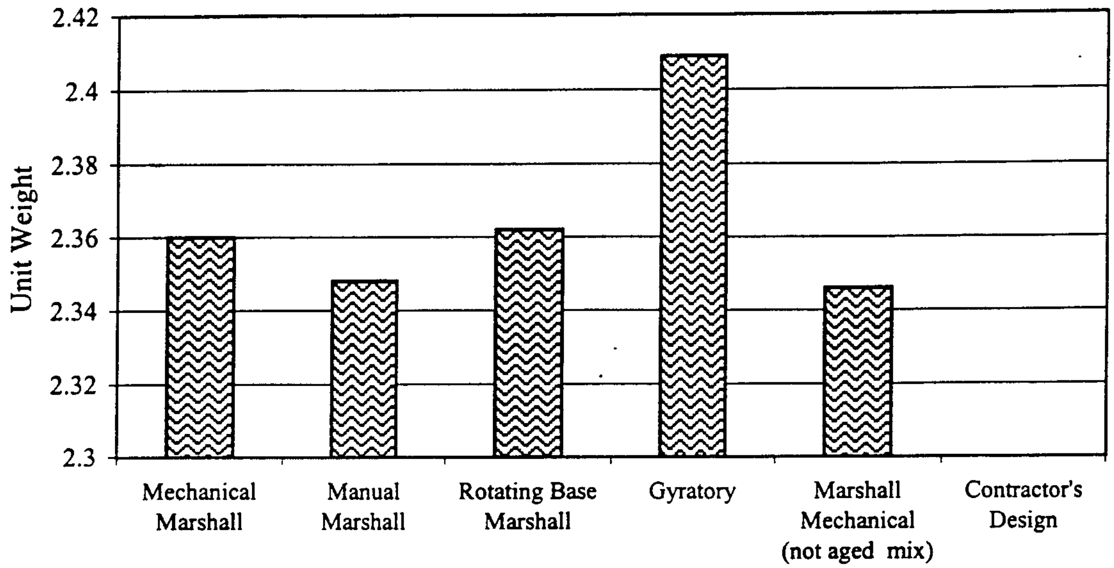


Figure 4.12. Relationship Between Unit Weight at 4% Air Voids and Compaction Type for Surface Mix with Limestone Coarse Aggregate and 50/50% Sand Blend.

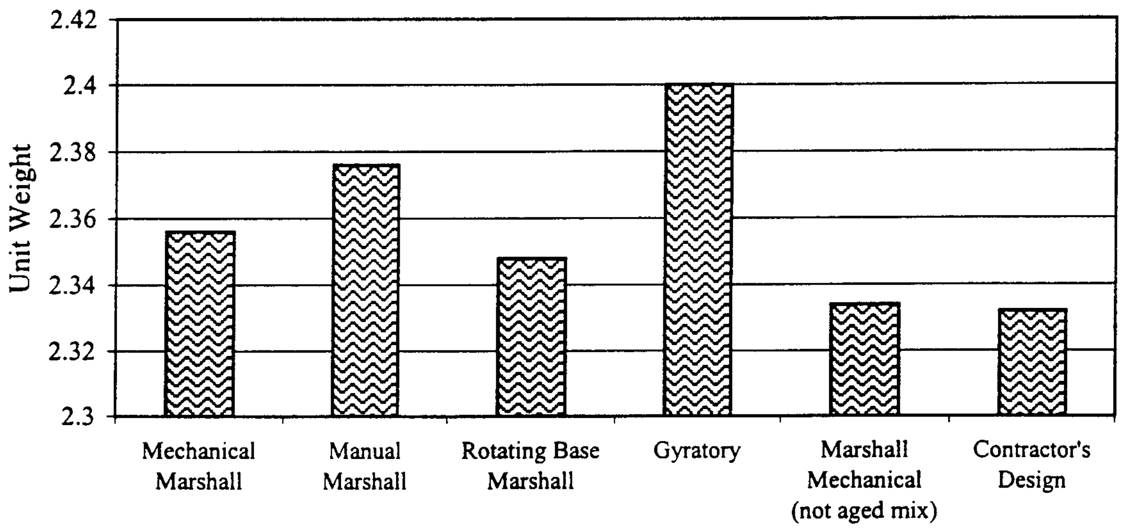


Figure 4.13. Relationship Between Unit Weight at 4% Air Voids Content and Compaction Type for Surface Mix with Gravel Coarse Aggregate and 50/50% Sand Blend.

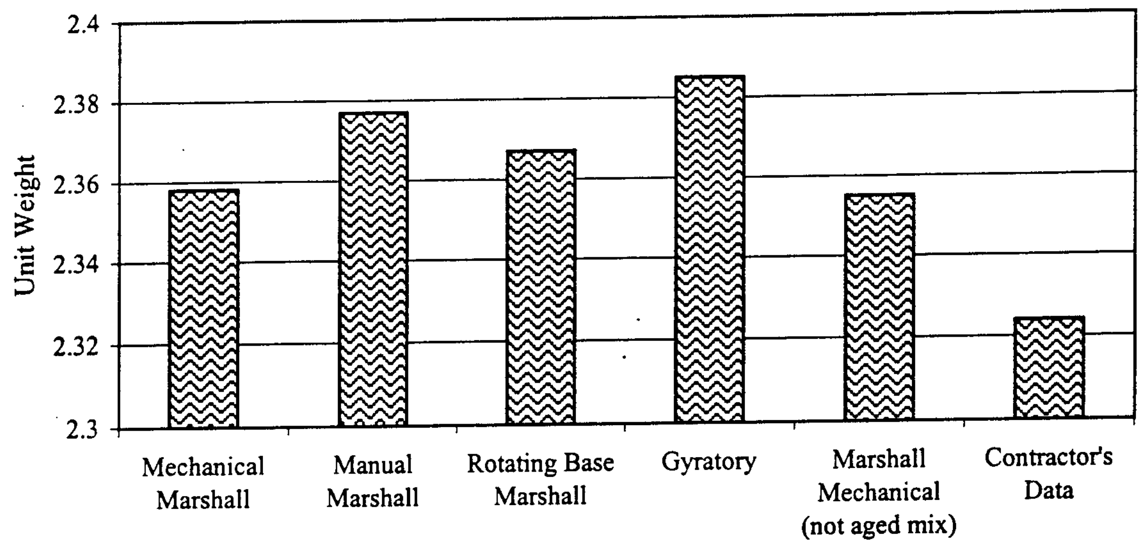


Figure 4.14. Relationship Between Unit Weight at 4% Air Voids Content and Compaction Type for Leveling Mix with Limestone Coarse Aggregate and Manufactured Sand.

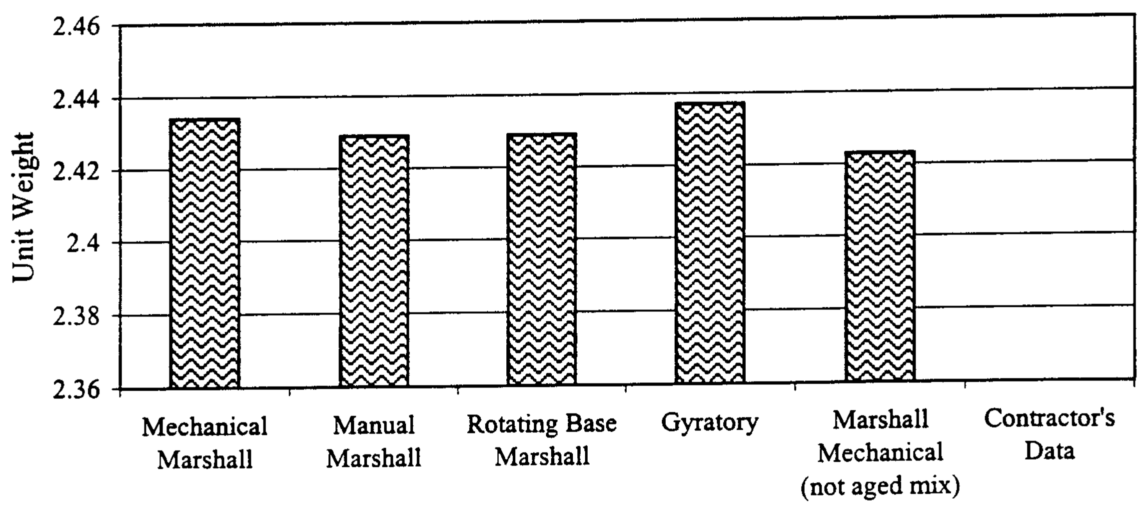


Figure 4.15. Relationship Between Unit Weight at 4% Air Voids Content and Compaction Type for Leveling Mix with Limestone Coarse Aggregate and 50/50% Sand Blend.

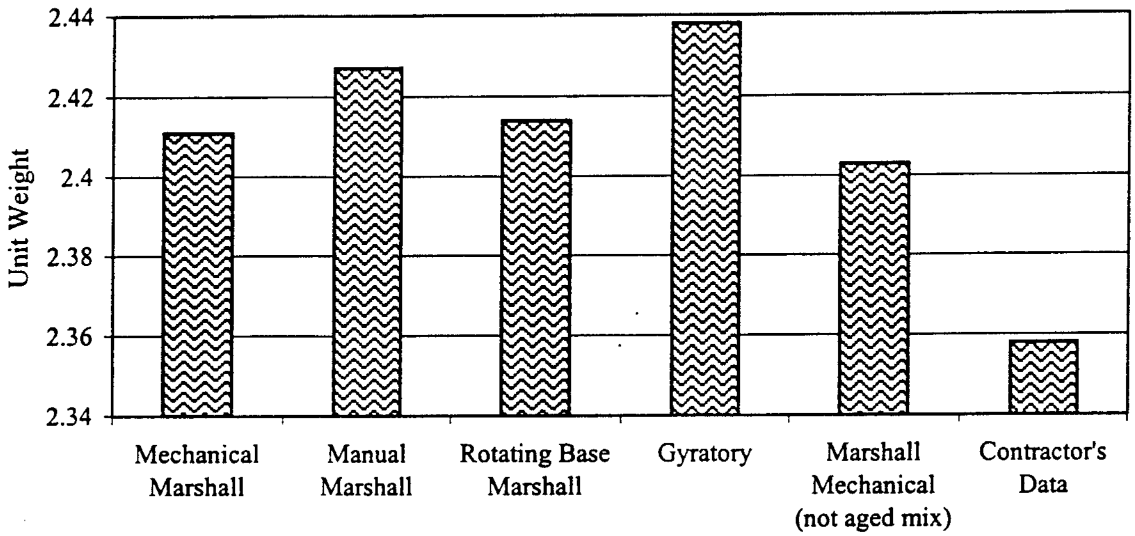
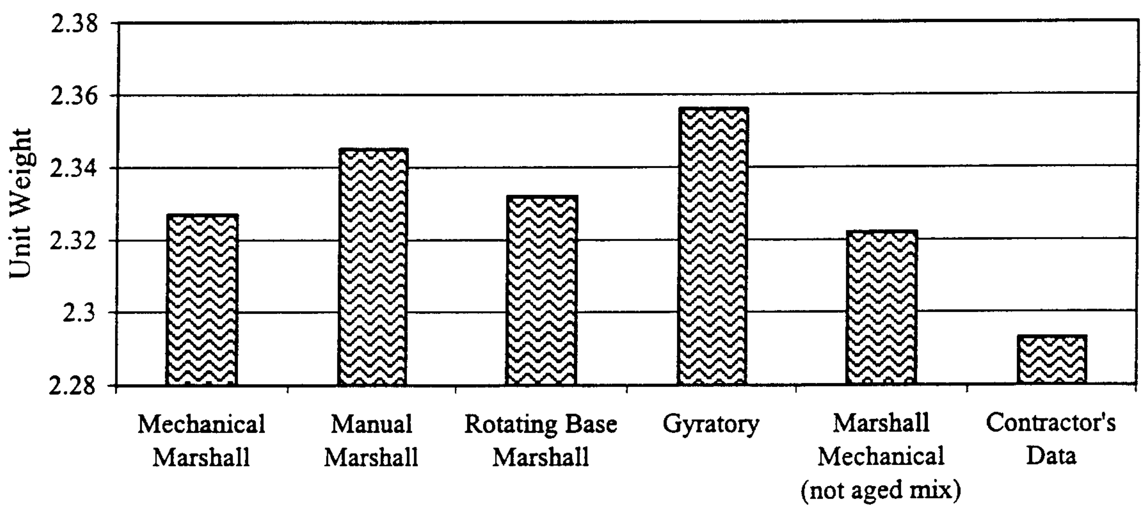


Figure 4.16. Relationship Between Unit Weight at 4% Air Voids Content and Compaction Type for Leveling Mix with Gravel Coarse Aggregate and 50/50 Sand Blend.



4.5.2. Voids in Mineral Aggregate (VMA).

Table 4.50 presents summary of VMA data, at 4% air voids content, for aged mixes prepared by mechanical, hand, and rotating base Marshall compactors.

Table 4.50. Summary of VMA data in relation to type of Marshall compactor.

Mix Type	VMA Mean Value	Difference of the Actual VMA Data from the Mean for Mixes Prepared by		
		Mechanical Compactor	Manual Compactor	Rotating Base Compactor
Surface, Limestone and Manufactured Sand	13.2	-0.1	+0.5	-0.3
Surface, Limestone and Natural Sand	13.2	-0.2	-0.1	+0.3
Surface, Limestone and 50/50% Sand Blend	12.5	+0.3	-0.9	+0.6
Surface, Gravel and Manufactured Sand	13.3	+0.2	-1.4	+1.2
Surface, Gravel and Natural Sand	12.7	+0.3	-0.6	+0.3
Surface, Gravel and 50/50% Sand Blend	13.2	+0.4	-0.5	0
Leveling, Limestone and Manufactured Sand	12.0	-0.2	0	+0.1
Leveling, Limestone and Natural Sand	12.4	+0.2	-0.8	+0.5
Leveling, Limestone and 50/50% Sand Blend	12.0	+0.3	-0.6	+0.2
Leveling, Gravel and Manufactured Sand	12.8	+0.3	-0.4	0
Leveling, Gravel and Natural Sand	13.3	+0.5	-0.2	-0.2
Leveling, Gravel and 50/50% Sand Blend	13.2	+0.5	-0.5	0
Sum of Variations		2.5	-5.5	2.7

Data presented in Table 4.50 indicate that aged asphalt concrete mix compacted using a manual Marshall compactor is more likely to have lower VMA than the same mix compacted by the mechanical or rotating base Marshall compactors.

Table 4.51 presents an average VMA content, determined at 4% air void content, for mixes subjected to the full experimental design. The last two columns of this table show VMA content for aged and not aged mixes as determined by testing specimens prepared using the mechanical Marshall compactor.

Table 4.51. Comparison of VMA data for mixes subjected to the full experimental design.

Mix Type	Voids in Mineral Aggregate (VMA),%					
	Averaged Aged Marshall	SHRP Gyratory	Change, %	Mechanical Marshall		Change, %
				Aged	Not Aged	
Surface, Limestone and Manufactured Sand	13.2	10.0	-24.2	13.1	13.1	0
Surface, Limestone and 50/50% Sand Blend	12.5	10.0	-20.0	12.8	13.1	+2.3
Surface, Gravel and 50/50% Sand Blend	13.2	11.9	-9.9	13.6	13.2	-2.9
Average VMA Content Reduction for Surface Mixes			-18.0			-0.2
Leveling, Limestone and Manufactured Sand	12.0	11.5	-4.2	11.8	11.9	+0.8
Leveling, Limestone and 50/50% Sand Blend	12.0	10.8	-10.0	12.3	12.3	0
Leveling, Gravel and 50/50% Sand Blend	13.2	12.0	-9.1	13.7	13.4	-2.2
Average VMA Content Reduction for Leveling Mixes			-7.8			-0.5

Data presented in Table 4.51 shows that VMA content of aged mix determined on specimens prepared using the SHRP gyratory compactor was lower than the average VMA content calculated for the same mix using specimens prepared with Marshall compactors. An average difference was more significant for surface than for leveling mixes 18.0 versus 7.8%, respectively. Surface mixes with limestone coarse aggregate have a greater VMA reduction than mixes with gravel aggregate. The greatest reduction in VMA content, 24.2%, was observed in aged surface mix with limestone coarse aggregate and manufactured sand.

Leveling mixes with limestone coarse aggregate have a 4.2 and 10% VMA content reduction for mixes with manufactured and a 50/50% sand blend, respectively. VMA content in leveling mixes made with gravel coarse aggregate and a 50/50% sand blend was 9.1% lower for test specimens prepared using the SHRP gyratory compactor than an average VMA value calculated for test specimens prepared with mechanical, manual, and rotating base Marshall compactors.

The VMA content determined on specimens prepared using the mechanical Marshall compactor was slightly lower for not aged than for aged mixes.

A average VMA content of aged mixes, determined on specimens prepared using the SHRP gyratory compactor, is 19% and 9% lower than the average VMA content, determined on specimens of not aged mixes prepared using the mechanical Marshall compactor, for surface and leveling course, respectively.

It is important to note that VMA content in mixes prepared during this study was lower than VMA content reported by contractors for the same mixes. This is due to previously reported difference in aggregate specific gravity values. These aggregate specific gravity value differences, even though it is within the acceptable by ASTM C 127 and C 128 multilaboratory range, result in significant differences in VMA and may be a reason that a mix does or does not fulfill VMA requirements.

The Asphalt Institute requires that mixes at 4% air void content, have a minimum VMA level of 14% for a mix with 12.5mm nominal size aggregate, and 13% for a mix with 19mm nominal size aggregate. The 1997 ODOT Construction and Material Specification Manual requires 13% VMA content for surface and leveling course mixes design for heavy traffic. None of the study mixes, when compacted using the SHRP gyratory compactor, meet Asphalt Institute or ODOT Specifications. Most surface mixes compacted by mechanical and rotating base Marshall compactors satisfy the ODOT specification. Two of six surface mixes prepared using the manual Marshall compactor meet ODOT specification requirements. Only one mix, surface with gravel coarse aggregate and manufactured sand, satisfies the Asphalt Institute 14.0% minimum VMA content requirement. All of the aged leveling course mixes with gravel coarse aggregate and none with limestone coarse aggregate met the 13% minimum VMA requirement when test specimens were prepared using the mechanical Marshall compactor. The minimum 13% VMA requirement was also met by two aged leveling course mixes with gravel coarse aggregate when test specimens were prepared using the rotating base Marshall compactor and one not aged mix with gravel coarse aggregate when test specimens were prepared using the mechanical Marshall compactor. One of the aged leveling course mixes, gravel with natural sand, tested on specimens prepared using the manual Marshall compactor met ODOT and Asphalt Institute VMA requirements.

Figures 4.17 through 4.22 present VMA values for mixes subjected to the full experimental design.

Figure 4.17. Relationship Between VMA at 4% Air Voids and Compaction Type for Surface Mix with Limestone Coarse Aggregate and Manufactured Sand.

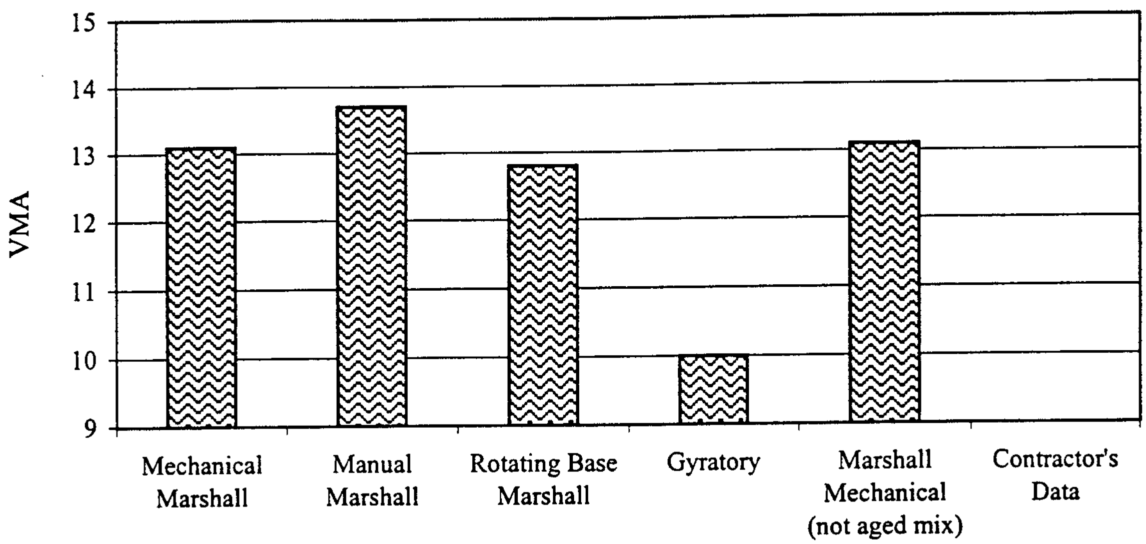


Figure 4.18. Relationship Between VMA at 4% Air Voids and Compaction Type for Surface Mix with Limestone Coarse Aggregate and 50/50% Sand Blend.

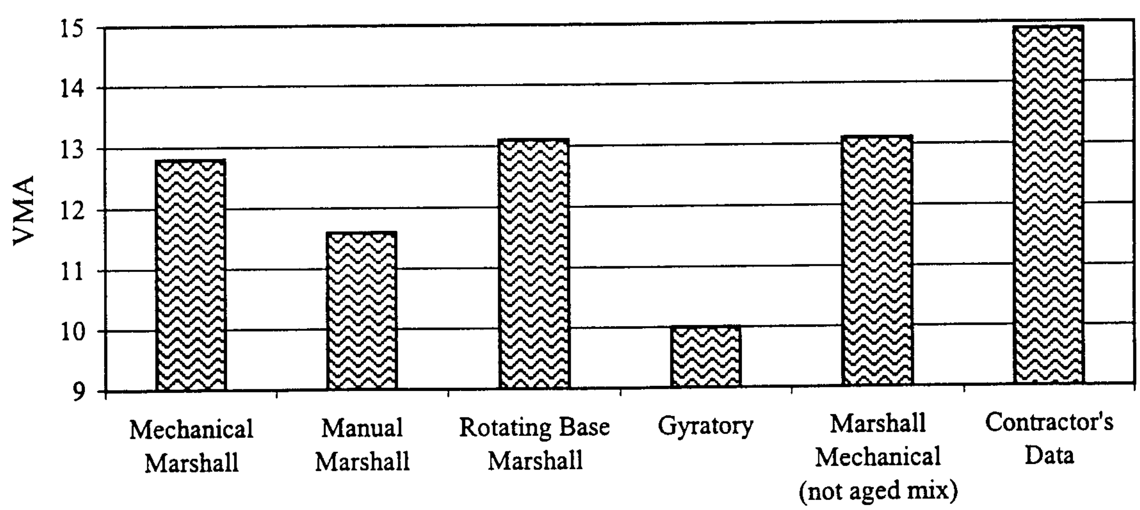


Figure 4.19. Relationship Between VMA at 4% Air Voids and Compaction Type for Surface Mix with Gravel Coarse Aggregate and 50/50% Sand Blend.

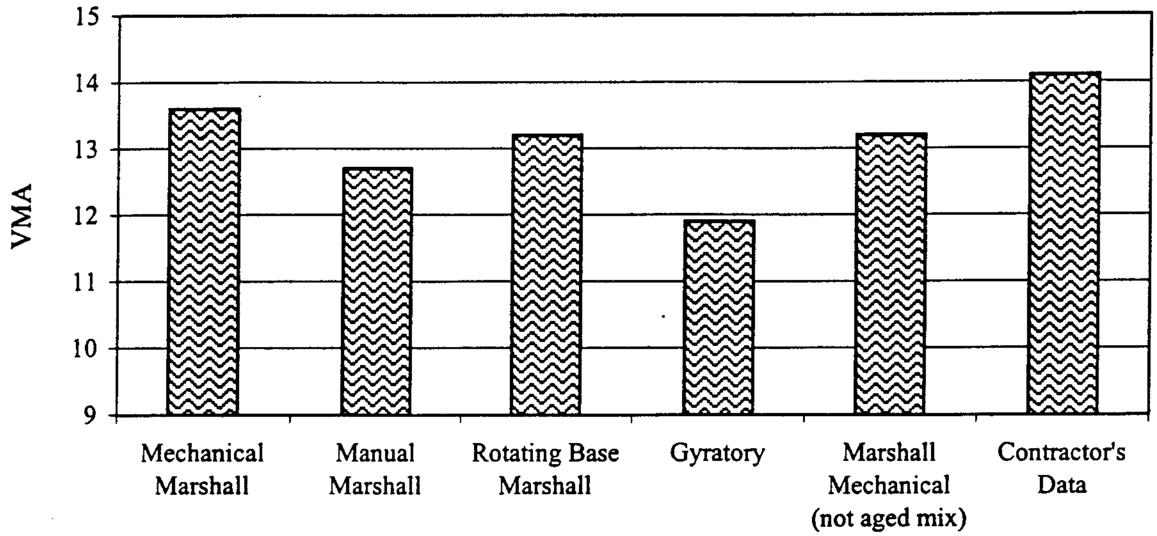


Figure 4.20. Relationship Between VMA at 4% Air Voisd and Compaction Type for Leveling Mix with Limestone Coarse Aggregate and Manufactured Sand.

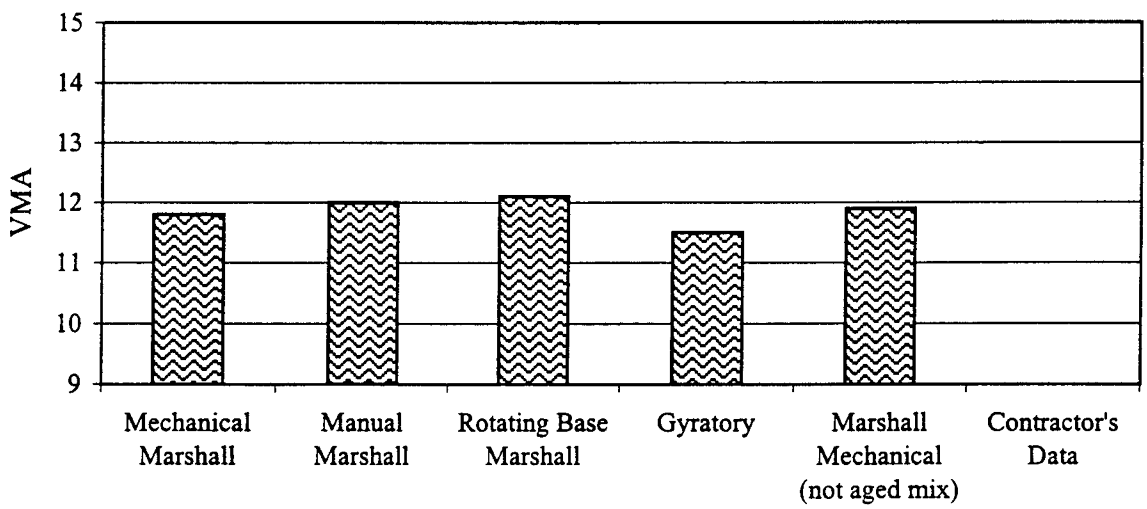


Figure 4.21. Relationship Between VMA at 4% Air Voids and Compaction Type for Leveling Mix with Limestone Coarse Aggregate and 50/50% Sand Blend.

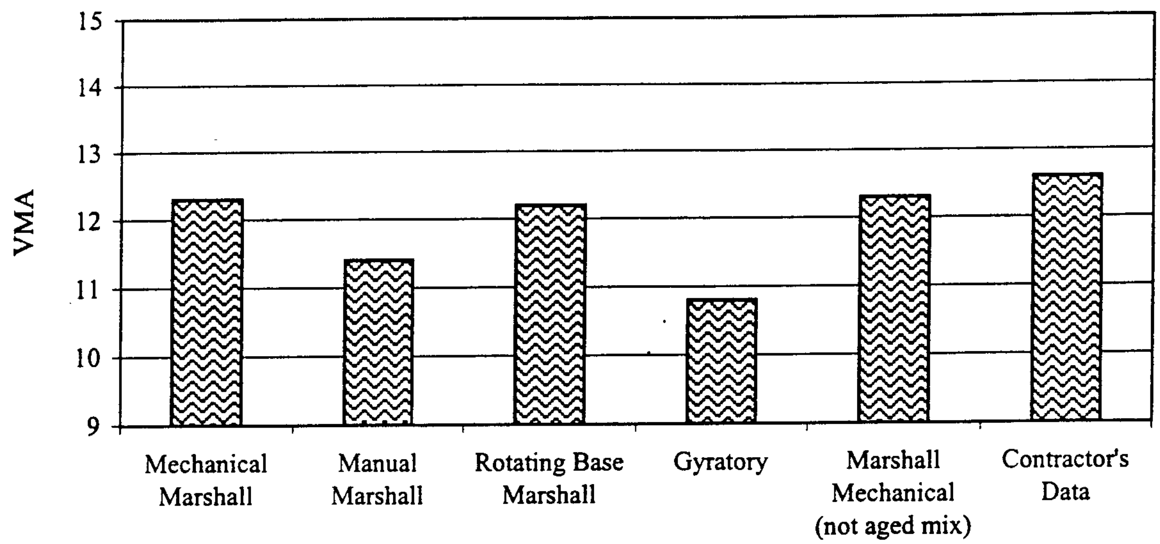
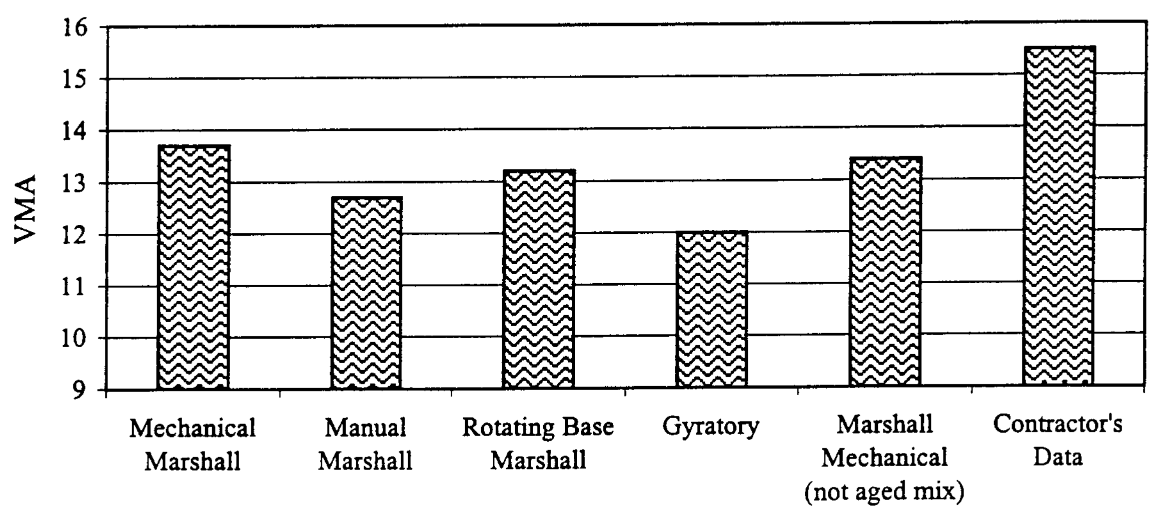


Figure 4.22. Relationship Between VMA at 4% Air Voids and Compaction Type for Leveling Mix with Gravel Coarse Aggregate and 50/50% Sand Blend.



4.5.3. Voids Filled with Asphalt (VFA).

Table 4.52 presents summary VFA data, at 4% air voids content, for aged mixes determined on specimens prepared by mechanical, manual, and rotating base Marshall compactors.

Table 4.52. Summary of VFA data in relation to type of Marshall compactor.

Mix Type	Mean Value of VFA	Difference of the Actual VFA from the Mean for mixes prepared by		
		Mechanical Compactor	Manual Compactor	Rotating Base Compactor
Surface, Limestone and Manufactured Sand	69.1	+0.9	+0.6	-1.5
Surface, Limestone and Natural Sand	69.3	-0.9	+0.6	+0.4
Surface, Limestone and 50/50% Sand Blend	67.2	+1.4	-1.0	-0.4
Surface, Gravel and Manufactured Sand	70.5	+0.8	-3.2	+2.5
Surface, Gravel and Natural Sand	67.8	+2.1	-2.1	-0.1
Surface, Gravel and 50/50% Sand Blend	69.6	+0.4	-1.4	+0.9
Leveling, Limestone and Manufactured Sand	66.4	+0.2	-0.9	+0.7
Leveling, Limestone and Natural Sand	67.0	+1.6	-2.4	+0.8
Leveling, Limestone and 50/50% Sand Blend	66.2	-0.8	-1.2	+2.1
Leveling, Gravel and Manufactured Sand	69.0	+1.1	-2.1	+1.0
Leveling, Gravel and Natural Sand	69.8	+2.2	-1.1	-1.0
Leveling, Gravel and 50/50% Sand Blend	69.7	+0.1	-1.2	+1.1
Sum of Variations		+9.1	-15.4	+6.5

Data presented in Table 4.52 indicate that VFA content determined for an aged asphalt concrete mix by testing specimens prepared using the manual Marshall compactor is more likely to be lower than VFA content of the same mix determined on specimens prepared by use of mechanical or rotating base Marshall compactors.

A comparison of average VFA content, at 4% air voids content, for aged mixes subjected to the full experimental design, is summarized in Table 4.53. The last two columns of this table show VFA values for aged and not aged mixes as determined on specimens prepared using the mechanical Marshall compactor.

Table 4.53. Comparison of VFA data for mixes subjected to the full experimental design.

Mix Type	Voids Filled with Asphalt (VFA), %					
	Averaged Aged Marshall	SHRP Gyratory	Change, %	Mechanical Marshall		Change, %
				Aged	Not Aged	
Surface, Limestone and Manufactured Sand	69.1	61.2	-11.6	70.0	71.8	+2.6
Surface, Limestone and 50/50% Sand Blend	67.2	60.5	-10.0	68.6	68.9	+0.4
Surface, Gravel and 50/50% Sand Blend	69.6	64.7	-7.0	70.0	69.1	-1.3
Average VFA Content Reduction for Surface Mixes			-9.5			+0.6
Leveling, Limestone and Manufactured Sand	66.4	63.8	-3.9	66.6	66.7	+0.1
Leveling, Limestone and 50/50% Sand Blend	66.2	64.5	-2.6	65.4	67.8	+3.7
Leveling, Gravel and 50/50% Sand Blend	69.7	66.9	-4.0	69.8	70.4	+0.9
Average VFA Content Reduction for Leveling Mixes			-3.5			+1.6

Data presented in Table 4.53 shows that VFA content of aged mix, as determined on specimens prepared using the SHRP gyratory compactor is lower than VFA content of the same mix calculated as an average of test results determined on specimens prepared using different Marshall compactors. The difference is approximately three times greater for surface than for leveling mixes. Surface mixes with limestone coarse aggregate have a greater VFA reduction than mix with gravel coarse aggregate.

Not aged asphalt concrete mix is more likely to have a higher level of voids filled with asphalt than the same mix after the aging process. The difference is approximately three times greater for leveling than surface mixes.

The Asphalt Institute requires that mixes designed for heavy traffic have a VFA content in the 65 to 75% range. All of the surface course mixes and two of the leveling course mixes, when tested on specimens prepared using the SHRP gyratory compactor, had a VFA level below 65%, and consequently did not meet this requirement. Only one of the all mixes compacted using any type of Marshall compactors, mix made with limestone coarse aggregate and natural sand and compacted using the manual Marshall compactor, did not meet the Asphalt Institute minimum VFA requirement.

Figures 4.23 through 4.28 present VFA data for mixes subjected to the full experimental design.

4.5.4. Marshall Stability.

Table 4.54 presents Marshall stability data, as determined for aged mixes by testing specimens with 4% air void content, prepared by mechanical, manual, and rotating base Marshall compactors.

Figure 4.23. Relationship Between VFA at 4% Air Voids and Compaction Type for Surface Mix with Limestone Coarse Aggregate and Manufactured Sand.

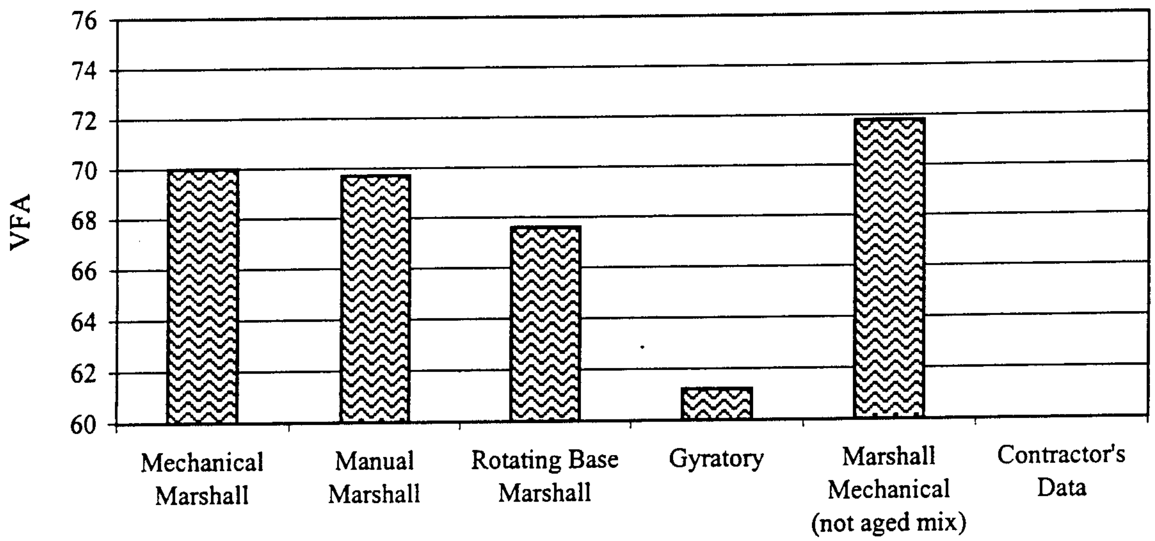


Figure 4.24. Relationship Between VFA at 4% Air Voids and Compaction Type for Surface Mix with Limestone Coarse Aggregate and 50/50% Sand Blend.

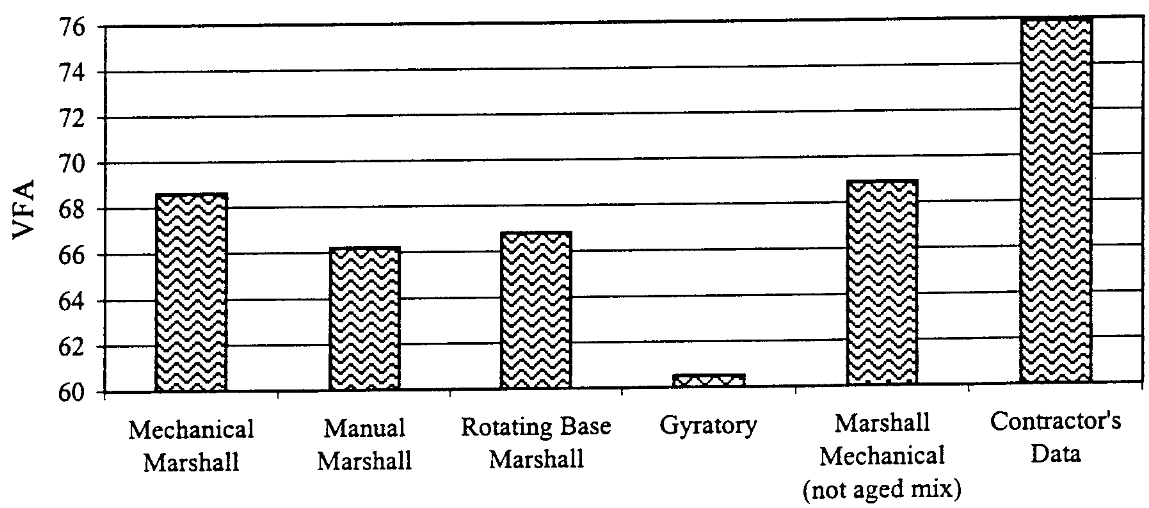


Figure 4.25. Relationship Between VFA at 4% Air Voids and Compaction Type for Surface Mix with Gravel Coarse Aggregate and 50/50% Sand Blend.

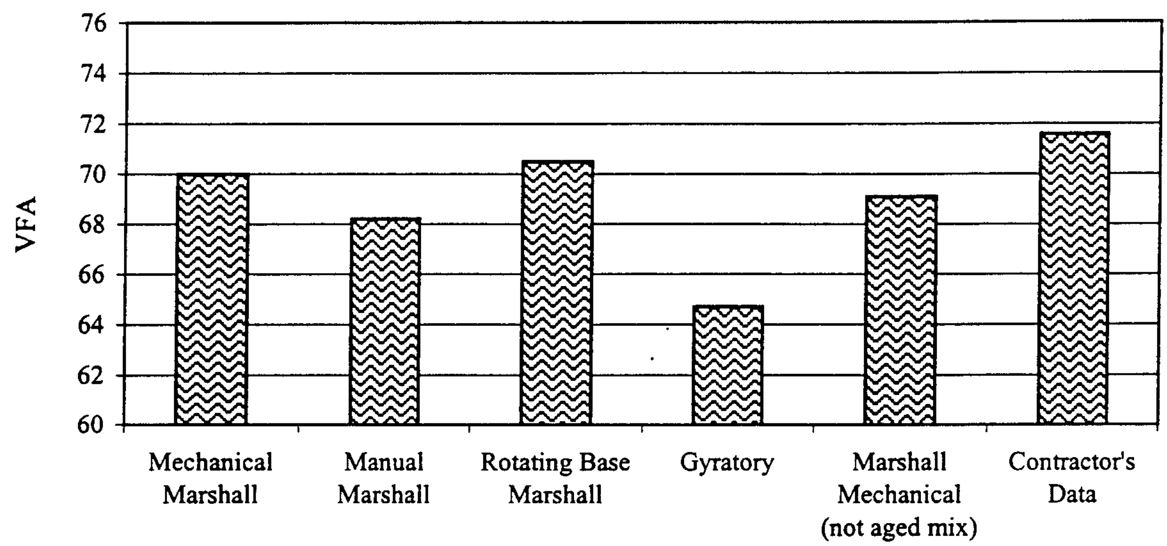


Figure 4.26. Relationship Between VFA at 4% Air Voids and Compaction Type for Leveling Mix with Limestone Coarse Aggregate and Manufactured Sand.

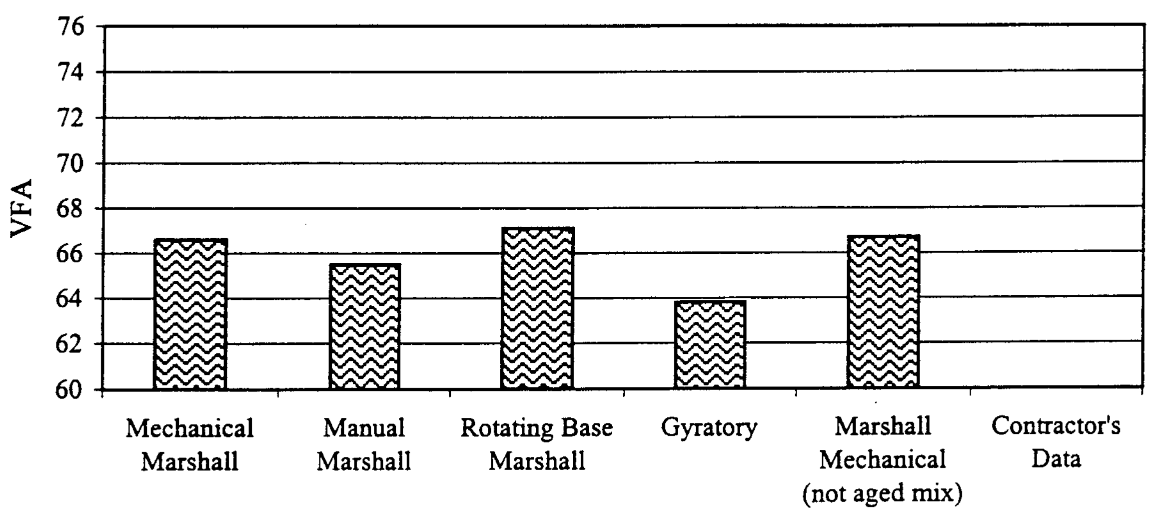


Figure 4.27. Relationship Between VFA at 4% Air Voids and Compaction Type for Leveling Mix with Limestone Coarse Aggregate and 50/50% Sand Blend.

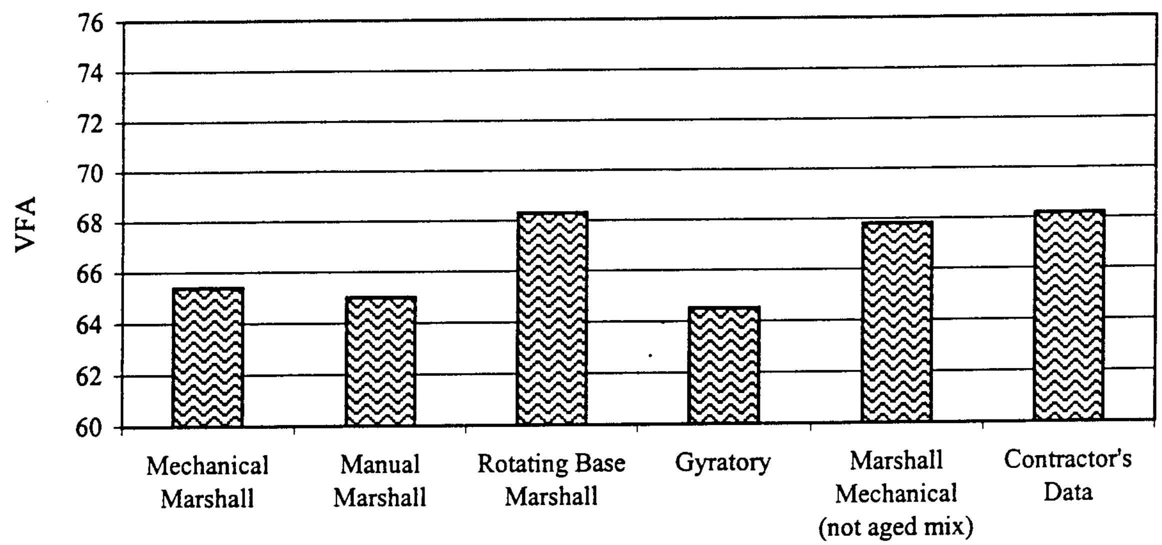


Figure 4.28. Relationship Between VFA at 4% Air Voids and Compaction Type for Leveling Mix with Gravel Coarse Aggregate and 50/50% Sand Blend.

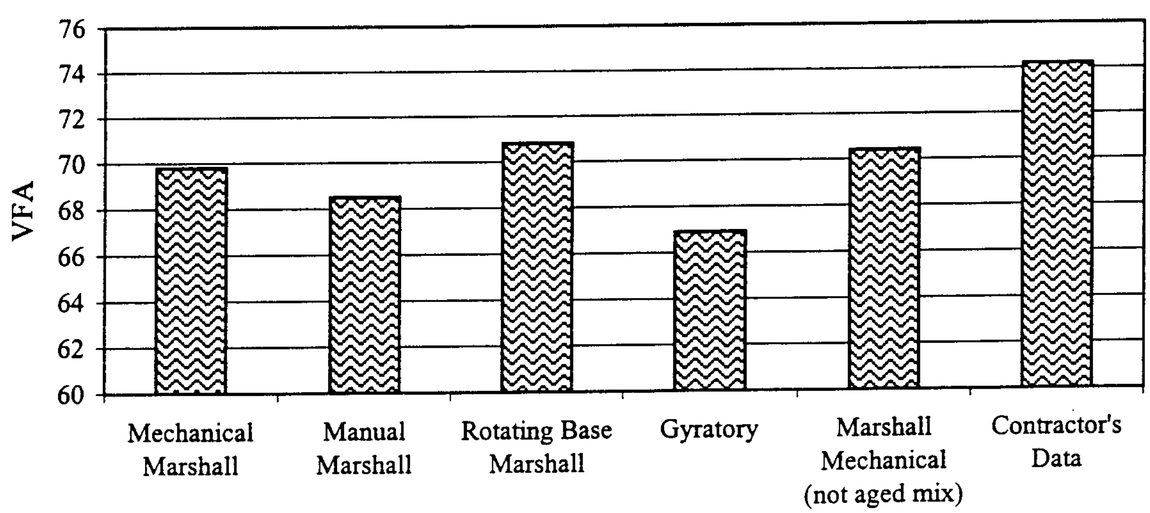


Table 4.54. Summary of Marshall stability data in relation to type of Marshall compactor.

Mix Type	Mean Value of Marshall Stability, (N)	Difference of the Actual Marshall Stability from the Mean for Mixes Prepared by		
		Mechanical Compactor	Manual Compactor	Rotating Base Compactor
Surface, Limestone and Manufactured Sand	14,380	+50	-500	+460
Surface, Limestone and Natural Sand	12,680	-220	+440	-210
Surface, Limestone and 50/50% Sand Blend	14,380	-3,320	+3,620	-280
Surface, Gravel and Manufactured Sand	14,440	-940	+4,480	-3,940
Surface, Gravel and Natural Sand	15,230	-680	+1,470	-780
Surface, Gravel and 50/50% Sand Blend	14,790	-680	+1,250	-560
Leveling, Limestone and Manufactured Sand	17,790	-1,340	+1,600	-250
Leveling, Limestone and Natural Sand	15,290	-1,290	+2,180	-880
Leveling, Limestone and 50/50% Sand Blend	16,480	-970	+1,840	-880
Leveling, Gravel and Manufactured Sand	16,300	-390	+610	-210
Leveling, Gravel and Natural Sand	10,870	-1,120	+1,230	-110
Leveling, Gravel and 50/50% Sand Blend	14,010	-1,530	+820	+700
Sum of Variations		-12,430	+19,040	-6,940

Data presented in Table 4.54 shows that aged asphalt concrete mix is more likely to have a higher Marshall stability when test specimens are prepared by manual Marshall compactor than the same mix when test specimens are prepared by using the mechanical or rotating base Marshall compactors.

Table 4.55 presents Marshall stability data for aged and not aged mixes determined on specimens prepared using the mechanical Marshall compactor.

Table 4.55. Change in Marshall stability due to mix aging.

Mix Type	Marshall Stability for Mixes Compacted by Mechanical Marshall Compactor, (N)	
	Aged Mix	Not Aged Mix
Surface, Limestone and Manufactured Sand	14,430	12,910
Surface, Limestone and Natural Sand	12,460	11,860
Surface, Limestone and 50/50% Sand Blend	11,050	12,680
Surface, Gravel and Manufactured Sand	13,490	12,830
Surface, Gravel and Natural Sand	14,550	11,710
Surface, Gravel and 50/50% Sand Blend	14,110	12,070
Leveling, Limestone and Manufactured Sand	16,450	16,760
Leveling, Limestone and Natural Sand	14,000	13,170
Leveling, Limestone and 50/50% Sand Blend	15,510	14,550
Leveling, Gravel and Manufactured Sand	15,910	13,310
Leveling, Gravel and Natural Sand	9,750	5,520
Leveling, Gravel and 50/50% Sand Blend	12,480	10,010
Average Value	13,680	12,280

Data presented in Table 4.55 shows that not aged asphalt concrete mix will have, on average, 10% lower Marshall stability than the same mix aged at 135° C for two hours.

Figures 4.29 through 4.34 present Marshall stability data for mixes subjected to the full experimental design.

Figure 4.29. Relationship Between Marshall Stability at 4% Air Voids and Compaction Type for Surface Mix with Limestone Coarse Aggregate and Manufactured Sand.

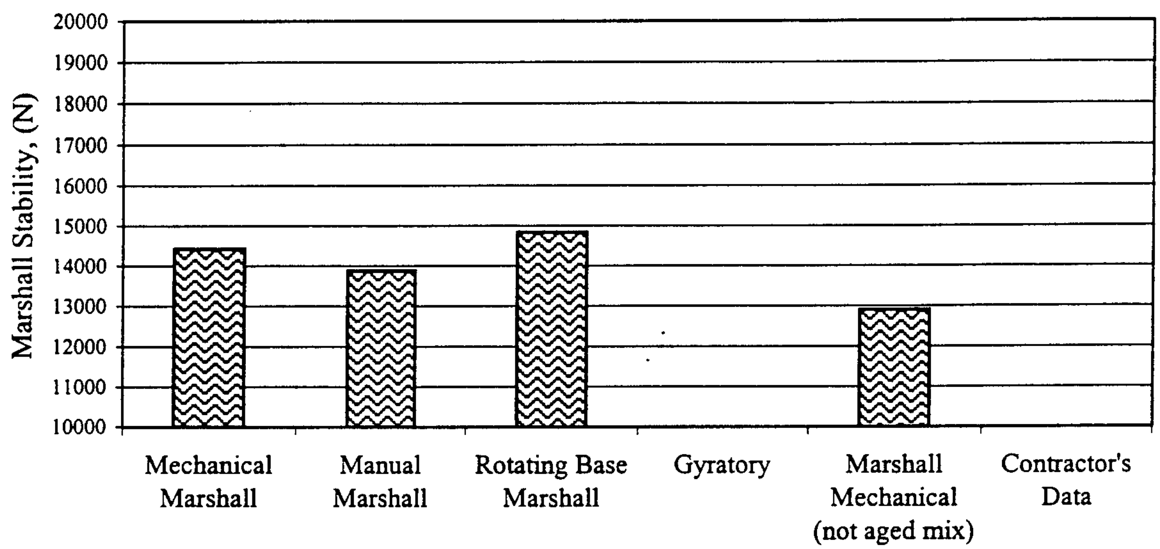


Figure 4.30. Relationship Between Marshall Stability at 4% Air Voids and Compaction Type for Surface Mix with Limestone Coarse Aggregate and 50/50% Sand Blend.

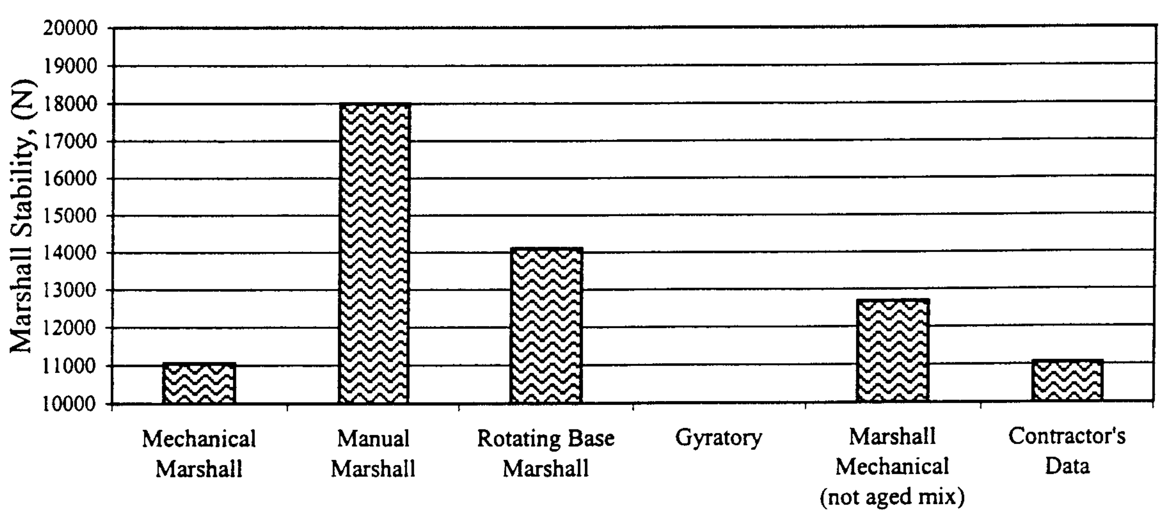


Figure 4.31. Relationship Between Marshall Stability at 4% Air Voids and Compaction Type for Surface Mix with Gravel Coarse Aggregate and 50/50% Sand Blend.

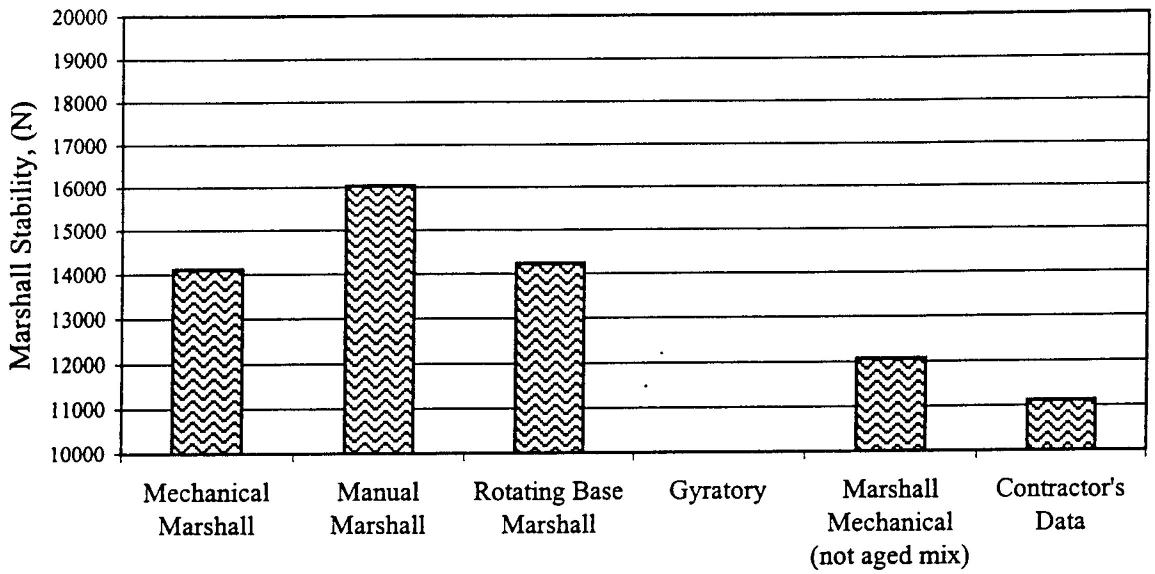


Figure 4.32. Relationship Between Marshall Stability at 4% Air Voids and Compaction Type for Leveling Mix with Limestone Coarse Aggregate and Manufactured Sand.

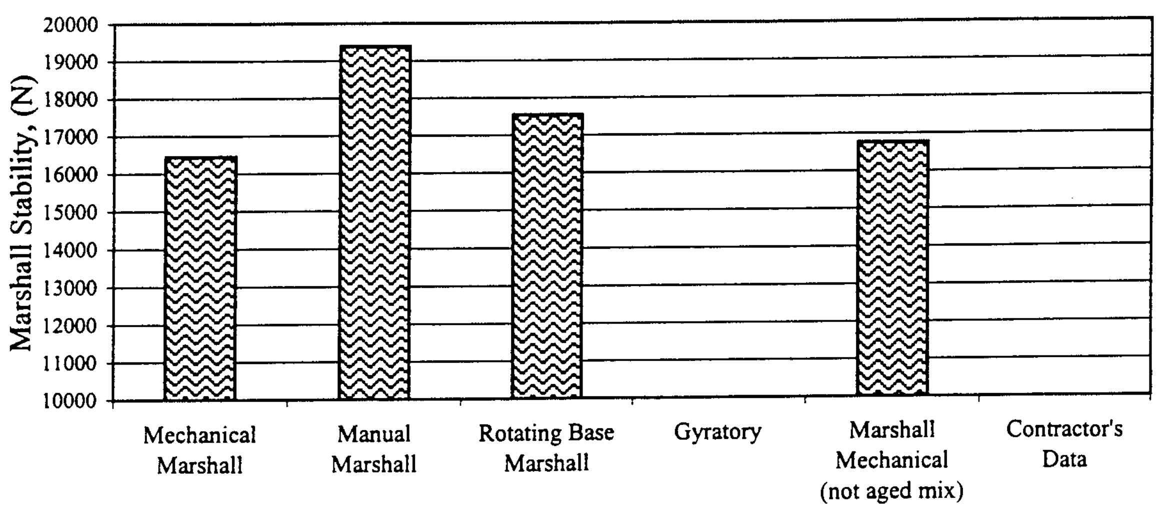


Figure 4.33. Relationship Between Marshall Stability at 4% Air Voids and Compaction Type for Leveling Mix with Limestone Coarse Aggregate and 50/50% Sand Blend.

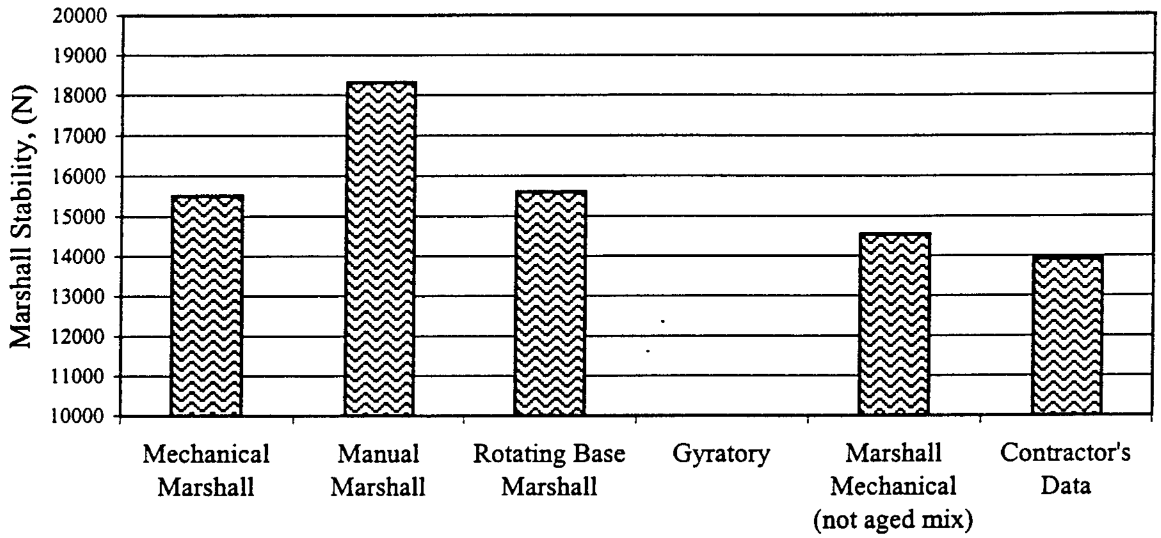
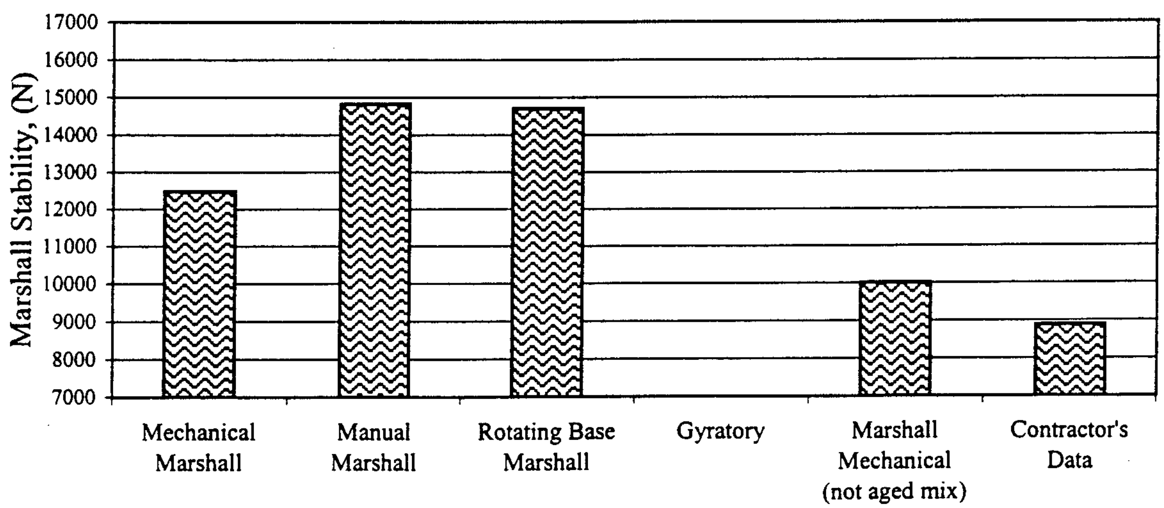


Figure 4.34. Relationship Between Marshall Stability at 4% Air Voids and Compaction Type for Leveling Mix with Gravel Coarse Aggregate and 50/50% Sand Blend.



4.5.5. Marshall Flow.

Table 4.56 presents Marshall flow data, as determined for aged mixes by testing specimens with 4% air voids content, that were prepared using mechanical, manual, or rotating base Marshall compactors.

Table 4.56. Summary of Marshall flow data in relation to type of Marshall compactor.

Mix Type	Mean Value of Marshall Flow, (mm)	Difference of the Actual Marshall Flow from the Mean for mixes prepared by		
		Mechanical Compactor	Manual Compactor	Rotating Base Compactor
Surface, Limestone and Manufactured Sand	3.4	-0.5	+0.9	-0.3
Surface, Limestone and Natural Sand	3.1	-0.1	+0.1	0
Surface, Limestone and 50/50% Sand Blend	3.1	+0.1	+0.2	-0.4
Surface, Gravel and Manufactured Sand	2.8	-0.3	-0.2	+0.4
Surface, Gravel and Natural Sand	2.6	+0.1	-0.1	-0.1
Surface, Gravel and 50/50% Sand Blend	2.6	-0.1	0	+0.1
Leveling, Limestone and Manufactured Sand	4.4	+0.1	0	-0.2
Leveling, Limestone and Natural Sand	2.8	0	+0.2	-0.2
Leveling, Limestone and 50/50% Sand Blend	3.1	+0.4	0	-0.3
Leveling, Gravel and Manufactured Sand	3.5	-0.1	+0.1	-0.1
Leveling, Gravel Natural Sand	2.4	0	+0.1	0
Leveling, Gravel and 50/50% Sand Blend	2.7	0	+0.1	0
Sum of Variations		-0.4	+1.4	-1.1

Data presented in Table 5.56 indicate that aged asphalt concrete mix is more likely to have a higher flow value, when it is determined on specimens prepared using the manual

Marshall compactor, than the same mix compacted using the mechanical or rotating base Marshall compactors. This higher flow value may be explained by the fact that test specimens of all but one mix compacted by the manual compactor had higher stability values than specimens of the same mixes compacted using the mechanical or rotating base Marshall compactors.

Table 4.57 presents Marshall flow data for aged and not aged mixes compacted by the mechanical Marshall compactor.

Table 4.57. Change in Marshall flow due to mix aging.

Mix Type	Marshall Flow for Mixes Compacted by Mechanical Marshall Compactor, (mm)	
	Aged Mix	Not Aged Mix
Surface, Limestone and Manufactured Sand	2.9	3.0
Surface, Limestone and Natural Sand	3.0	2.9
Surface, Limestone and 50/50% Sand Blend	3.2	2.9
Surface, Gravel and Manufactured Sand	2.5	2.5
Surface, Gravel and Natural Sand	2.7	2.3
Surface, Gravel and 50/50% Sand Blend	2.5	2.4
Leveling, Limestone and Manufactured Sand	4.5	3.4
Leveling, Limestone and Natural Sand	2.8	2.7
Leveling, Limestone and 50/50% Sand Blend	2.7	3.0
Leveling, Gravel and Manufactured Sand	3.4	4.5
Leveling, Gravel and Natural Sand	2.4	2.6
Leveling, Gravel and 50/50% Sand Blend	2.7	2.4
Average Value	2.9	2.9

Data presented in Table 4.57 shows that an average Marshall flow value for asphalt concrete mix is the same for a mix tested in an aged and not aged condition.

Figures 4.35 through 4.40 present Marshall flow values for mixes subjected to the full experimental design.

Figure 4.35. Relationship Between Marshall Flow at 4% Air Voids and Compaction Type for Surface Mix with Limestone Coarse Aggregate and Manufactured Sand.

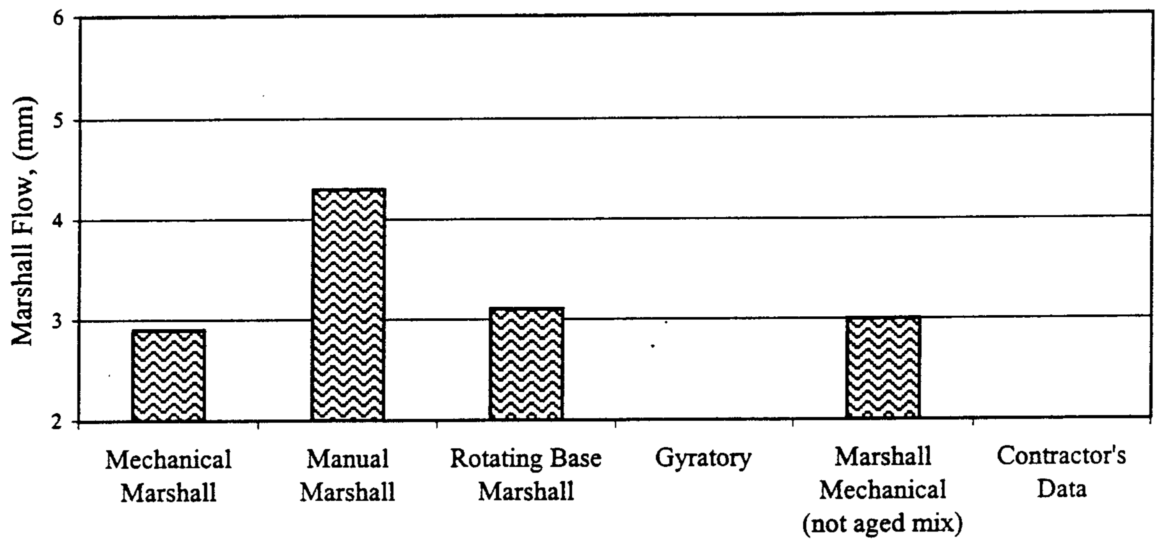


Figure 4.36. Relationship Between Marshall Flow at 4% Air Voids and Compaction Type for Surface Mix with Limestone Coarse Aggregate and 50/50% Sand Blend.

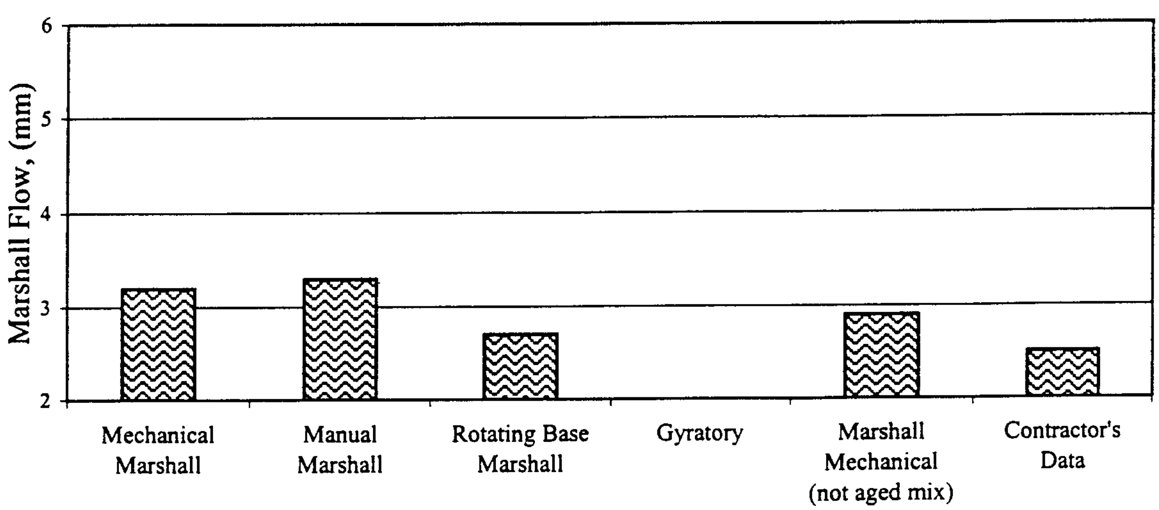


Figure 4.37. Relationship Between Marshall Flow at 4% Air Voids and Compaction Type for Surface Mix with Gravel Coarse Aggregate and 50/50% Sand Blend.

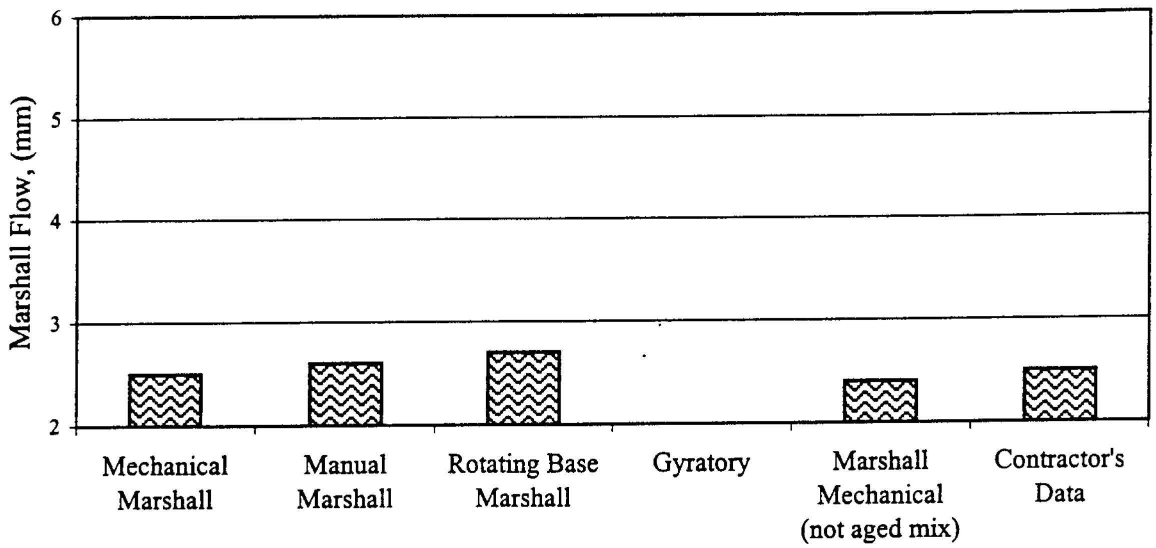


Figure 4.38. Relationship Between Marshall Flow at 4% Air Voids and Compaction Type for Leveling Mix with Limestone Coarse Aggregate and Manufactured Sand.

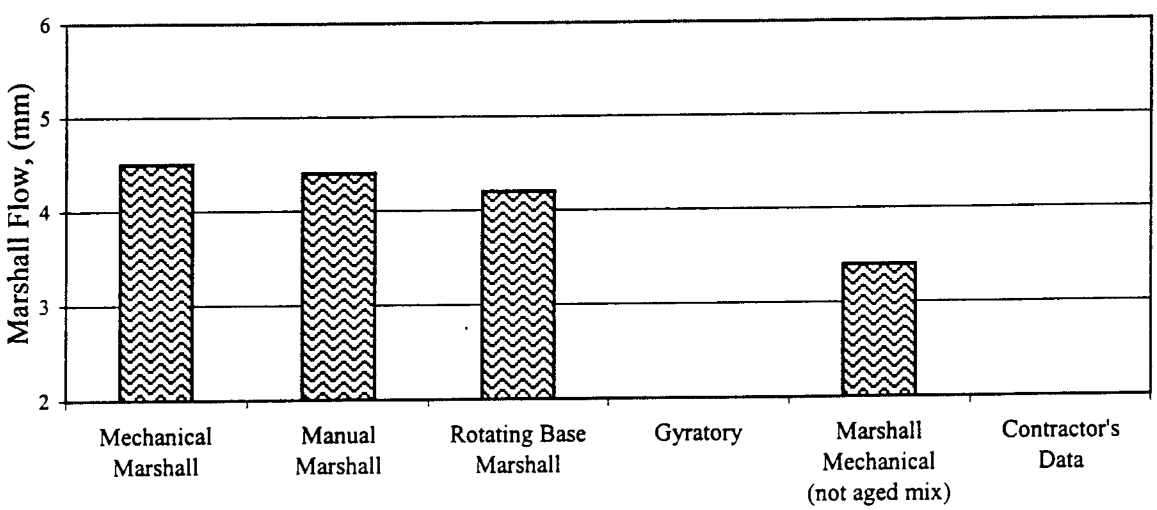


Figure 4.39. Relationship Between Marshall Flow at 4% Air Voids and Compaction Type for Leveling Mix with Limestone Coarse Aggregate and 50/50% Sand Blend.

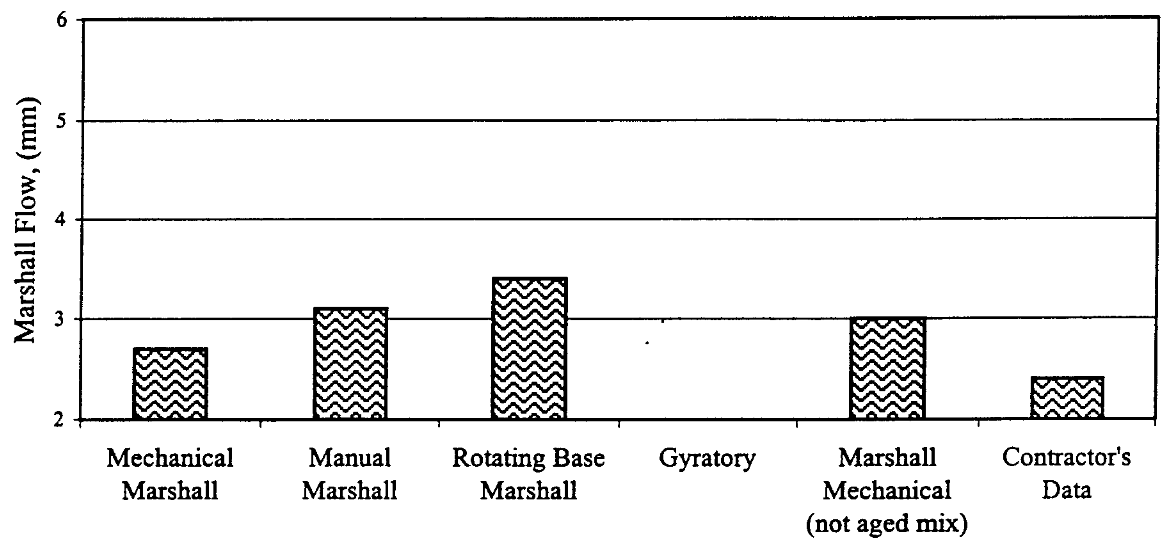
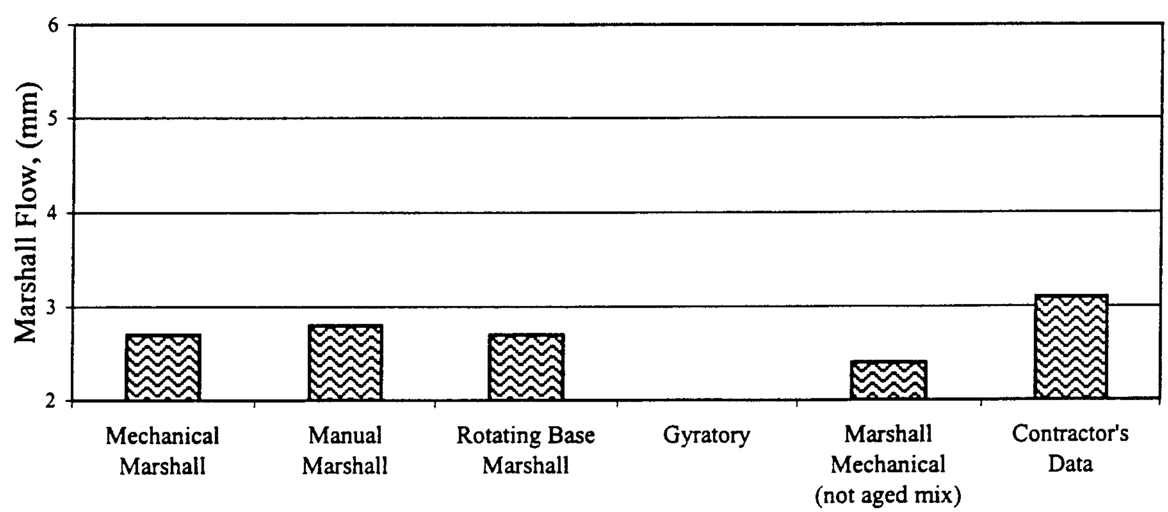


Figure 4.40. Relationship Between Marshall Flow at 4% Air Voids and Compaction Type for Leveling Mix with Gravel Coarse Aggregate and 50/50% Sand Blend.



4.6. CHANGES OF AIR VOIDS AND VOIDS IN MINERAL AGGREGATE CONTENT DURING SHRP GYRATORY COMPACTION PROCESS.

Figures 4.41 through 4.46 present changes in air voids (AV) and voids in mineral aggregate (VMA) content observed during the SHRP gyratory compaction process. Each graph has a mark at the gyration number at which the mix would have an optimum asphalt cement content if it was determined by an average Marshall compactor. Available data allowed an interpolation of a number of gyrations for five of the six mixes. The sixth mix, leveling with gravel coarse aggregate and a 50/50% sand blend, had the average optimum asphalt cement content, as determined from testing of test specimens prepared using three types of Marshall compactor, at 5.9%. The 5.9% value was above the range of asphalt cement contents used in SHRP gyratory compaction mix design process; therefore, the number of gyrations for this mix was conservatively extrapolated. Table 4.58 presents the estimated number of gyrations needed for a mix with optimum asphalt cement content determined using the Marshall mix design process to achieve 4.0% air void content.

Table 4.58. Number of gyrations needed for a mix with average optimum asphalt cement content determined by Marshall mix design process to achieve 4.0% air void content.

Mix Type	Number of Gyrations	Average Number of Gyrations
Surface, Limestone and Manufactured Sand	40	60
Surface, Limestone and 50/50% Sand Blend	50	
Surface, Gravel and 50/50% Sand Blend	90	
Leveling, Limestone and Manufactured Sand	90	<80
Leveling, Limestone and 50/50% Sand Blend	70	
Leveling, Gravel and 50/50% Sand Blend	<80	

Figure 4.41. Air Voids/VMA Content vs. Number of Gyrations for Surface Mix with Limestone Coarse Aggregate and Manufactured Sand.

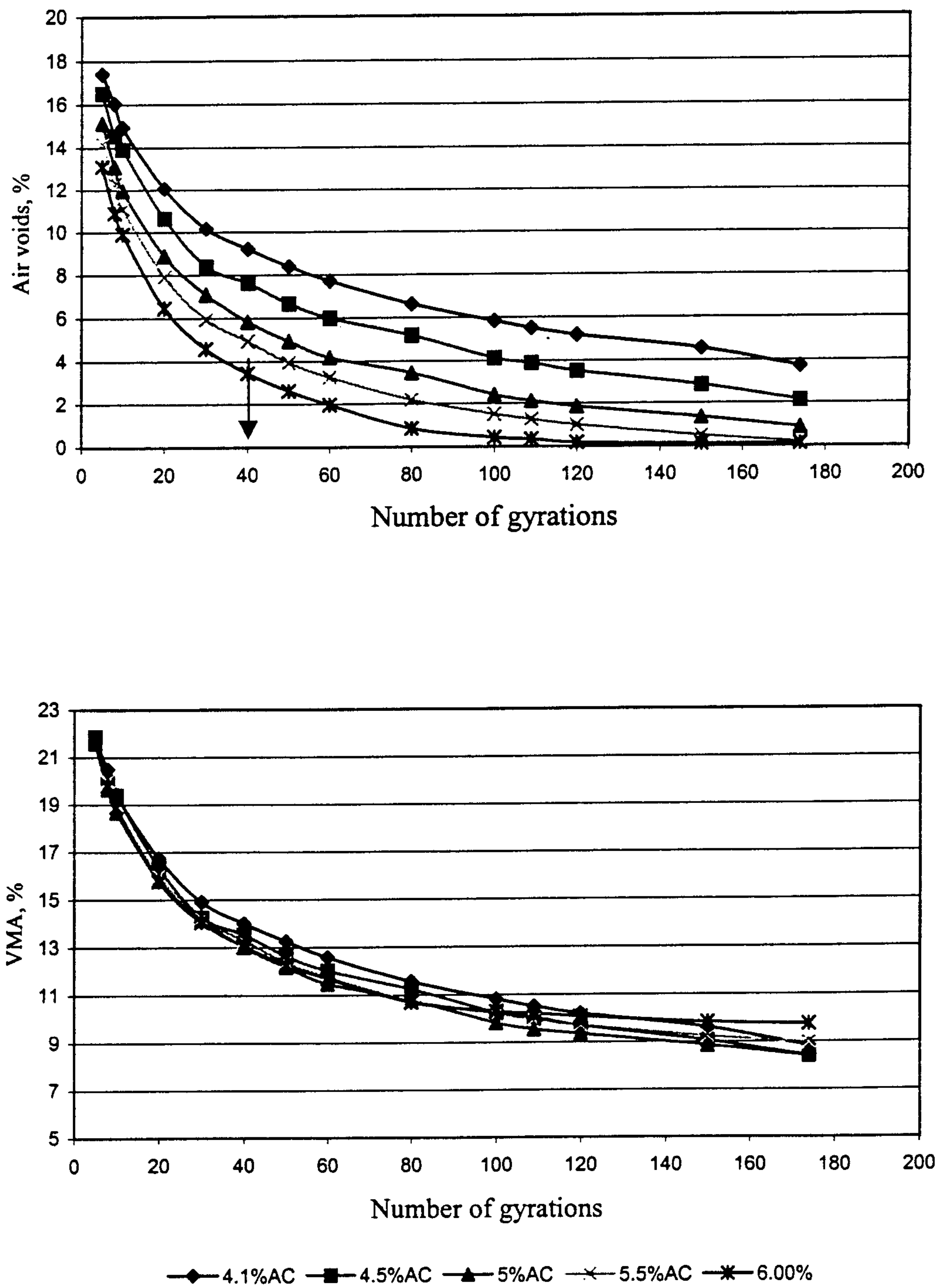


Figure 4.42. Air Voids/VMA Content vs. Number of Gyrations for Surface Mix with Limestone Coarse Aggregate and 50/50% Sand Blend.

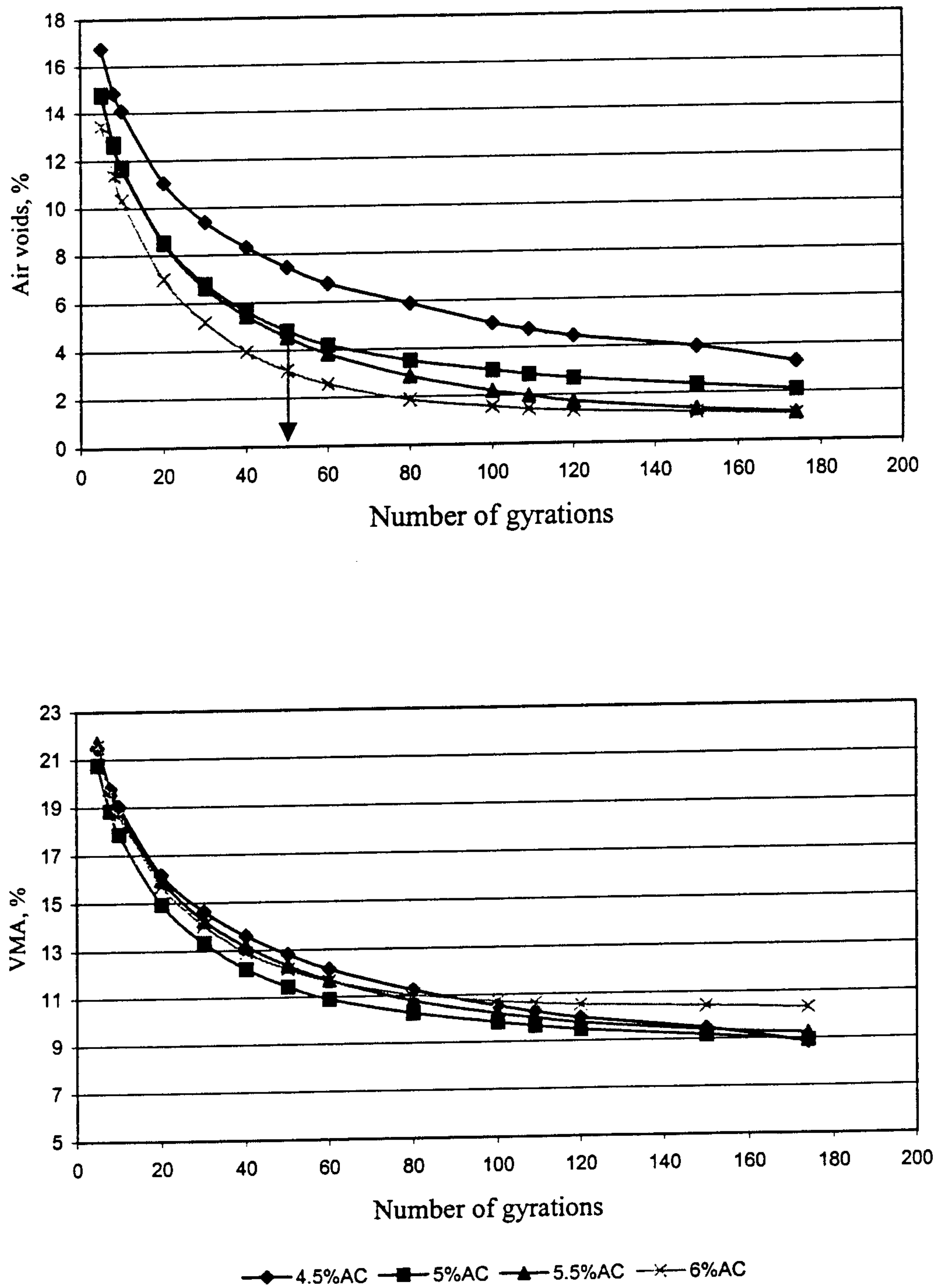
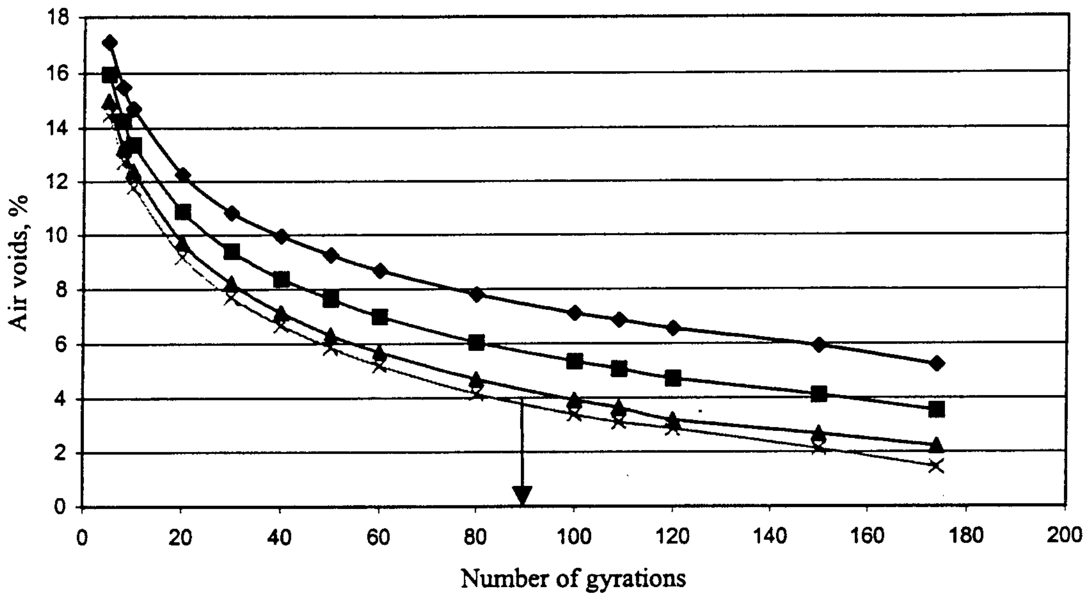


Figure 4.43. AirVoids/VMA Content vs. Number of Gyrations for Surface Mix with Gravel Coarse Aggregate and 50/50% Sand Blend.



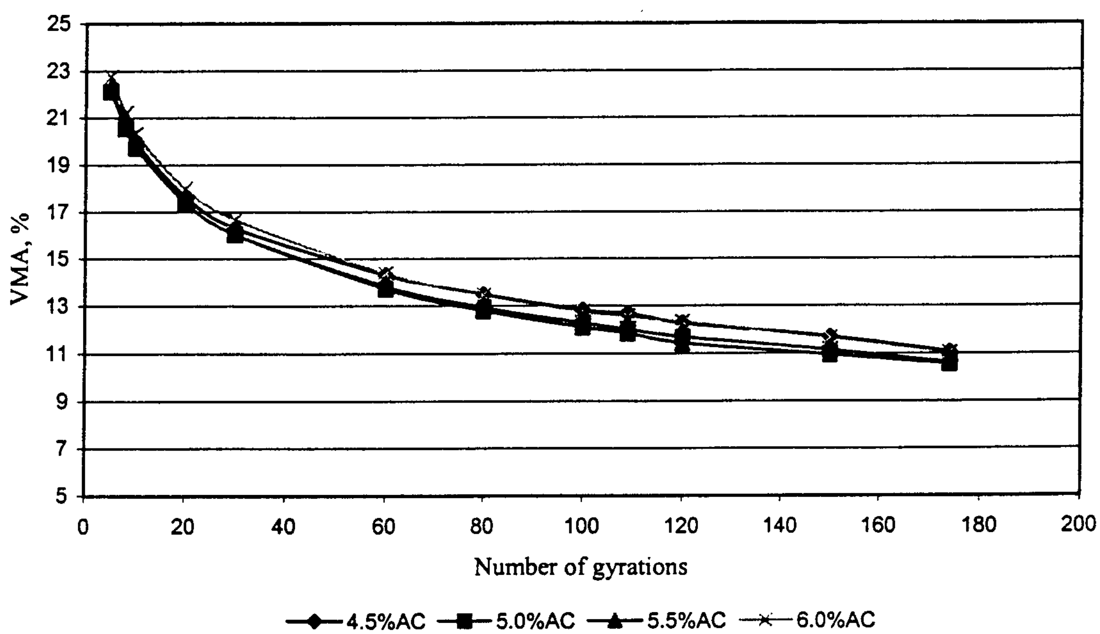


Figure 4.44. Air Voids/VMA Content vs. Number of Gyrations for Leveling Mix with Limestone Aggregate and Manufactured Sand.

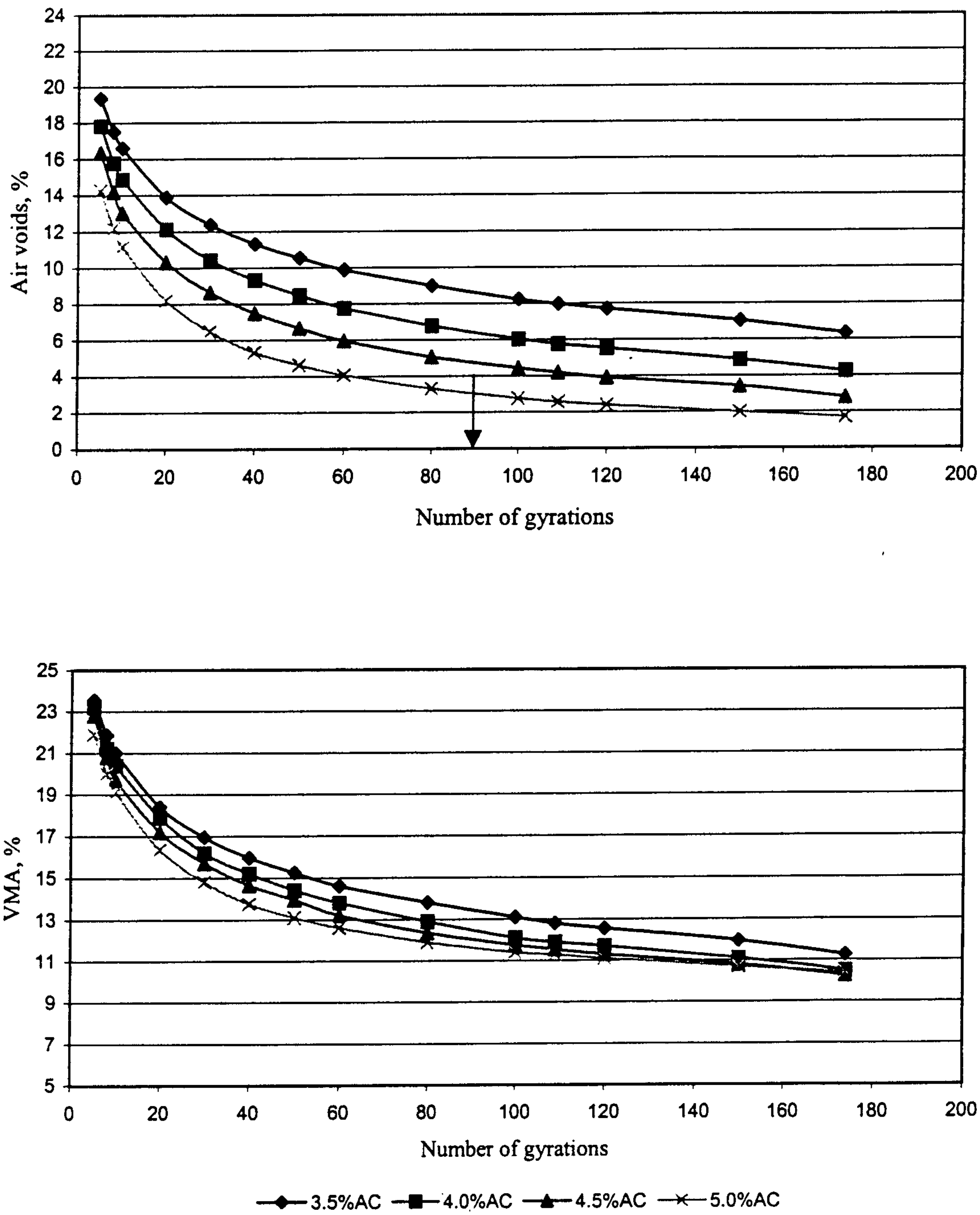


Figure 4.45. Air/Voids/VMA Content vs. Number of Gyrations for Leveling Mix with Limestone Coarse Aggregate and 50/50% Sand Blend.

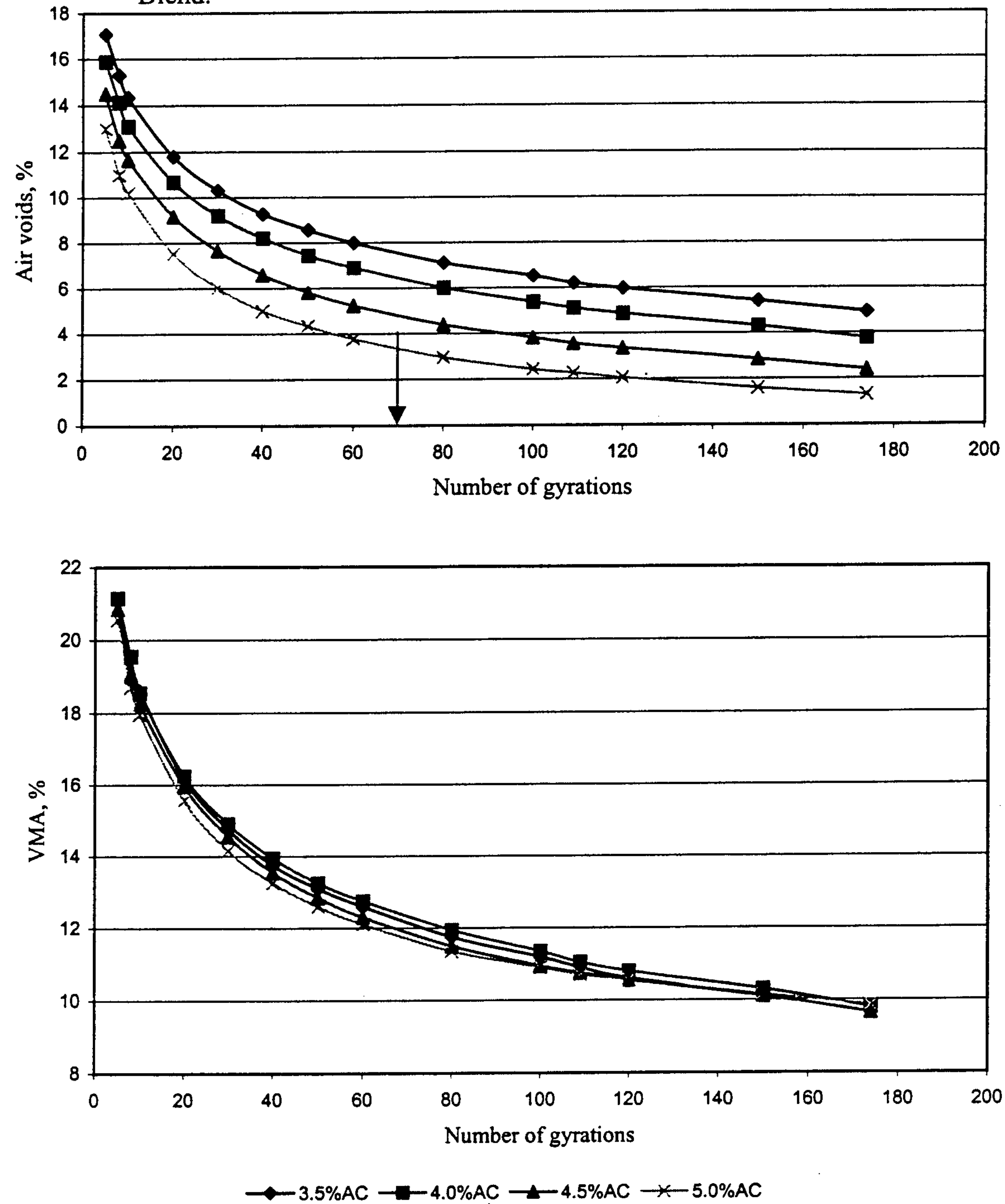
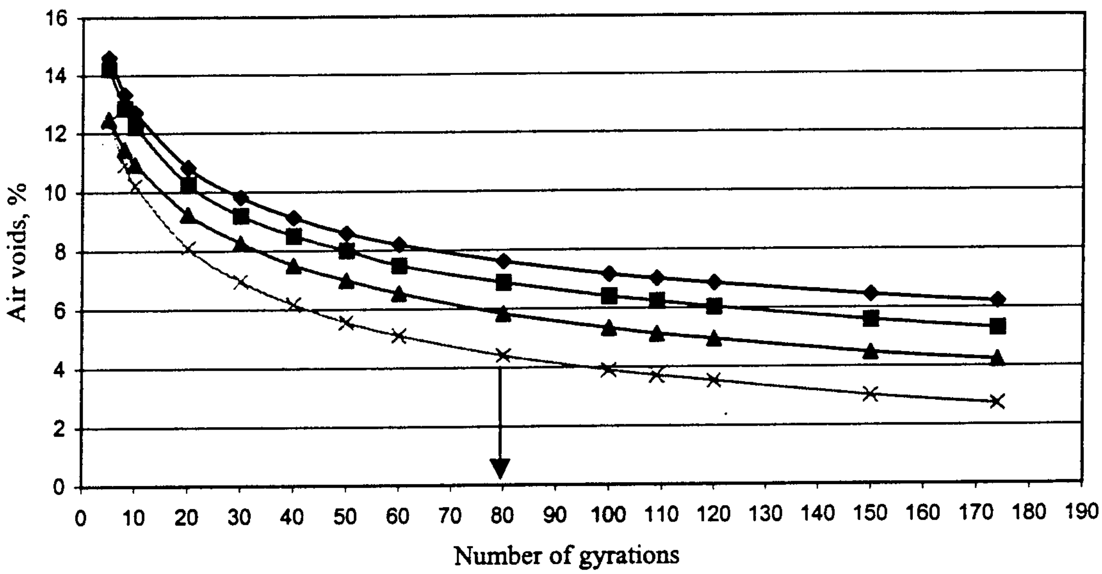
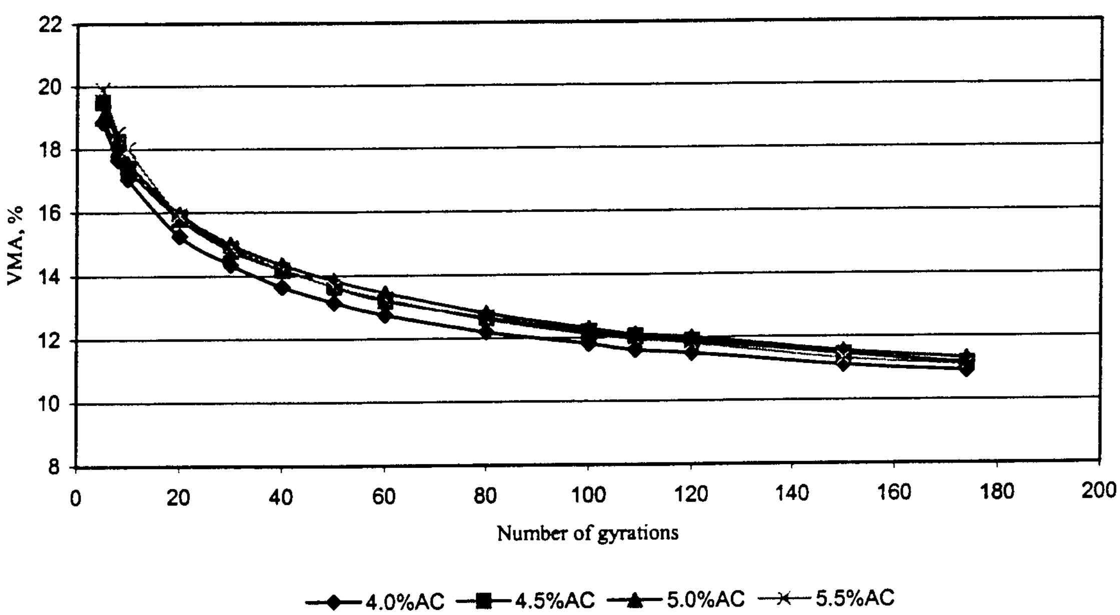


Figure 4.46. Air Voids/ VMA Content vs. Numer of Gyrations for Gravel Coarse Aggregate and 50/50% Sand Blend.





Data presented in Table 4.58 indicate that to obtain, by using the volumetric SHRP mix design process, the optimum asphalt cement content similar to that determined by Marshall mix design process, number of gyration at N_{design}, for all the mixes examined in this study, should be lower than 109 which is currently required for Ohio mixes. Collected data, although limited, suggests that number gyration at N_{design} is likely to depend on maximum size of aggregates used in the mix, and to be lower for surface than for leveling mixes.

4.7. COMPARISON OF MIX DESIGN PARAMETERS AS DETERMINED BY DIFFERENT COMPACTORS.

Tables 4.59 through 4.62 present comparisons of the average values of: optimum asphalt cement content and VMA, VFA, and unit weight at optimum AC content, respectively, as determined using the four different types of compactors for test specimen preparation.

Table 4.59. Comparison of average optimum AC content as determined by testing specimens prepared by different compactors.

Type of Compactor	Average Optimum AC Content by Mix Type, %					
	Surface[1]		Leveling[1]		Combined[2]	
	AC	Ranking	AC	Ranking	AC	Ranking
SHRP Gyratory	4.8	1	4.8	1	4.8	1
Mechanical Marshall (non-aged mix)	5.5	2	5.1	2	5.3	2
Manual Marshall	5.6	3	5.2	3	5.4	3
Mechanical Marshall (aged mix)	5.9	4	5.5	4	5.7	4
Rotating Base Marshall	6.0	5	5.5	5	5.7	5

[1]Average for the SHRP gyratory compactor is based on 3 mixes.
Average for all Marshall compactors is based on 6 mixes.

[2]Average for the SHRP gyratory compactor is based on 6 mixes.
Average for all Marshall compactors is based on 12 mixes.

Table 4.59 shows that specimens of non-aged asphalt mix prepared by a mechanical Marshall compactor achieved an average optimum AC content closest to the value obtained by testing specimens prepared by SHRP gyratory compactor.

Table 4.60. Comparison of average VMA content as determined by testing specimens prepared by different compactors.

Type of Compactor	Average VMA Content at Optimum AC Content by Mix Type, %					
	Surface[1]		Leveling[1]		Combined[2]	
	VMA	Ranking	VMA	Ranking	VMA	Ranking
SHRP Gyratory	10.6	1	11.4	1	11.0	1
Mechanical Marshall (non-aged mix)	13.2	3	13.0	5	13.1	4
Manual Marshall	12.5	2	12.2	2	12.4	2
Mechanical Marshall (aged mix)	13.2	3	12.9	4	13.0	3
Rotating Base Marshall	13.3	4	12.7	3	13.0	3

[1]Average for the SHRP gyratory compactor is based on 3 mixes.
Average for all Marshall compactors is based on 6 mixes.

[2]Average for the SHRP gyratory compactor is based on 6 mixes.
Average for all Marshall compactors is based on 12 mixes.

Table 4.60 shows that specimens of aged asphalt mix prepared by a manual Marshall compactor achieved an average VMA content closest to the value obtained by testing specimens prepared by the SHRP gyratory compactor.

Table 4.61. Comparison of average VFA content as determined by testing specimens prepared by different compactors.

Type of Compactor	Average VFA Content at Optimum AC Content by Mix Type, %					
	Surface[1]		Leveling[1]		Combined[2]	
	VFA	Ranking	VFA	Ranking	VFA	Ranking
SHRP Gyratory	62.1	1	65.1	1	63.6	1
Mechanical Marshall (non-aged mix)	69.8	5	68.6	3	69.2	4
Manual Marshall	67.8	2	66.5	2	67.2	2
Mechanical Marshall (aged mix)	69.7	4	68.8	4	69.2	4
Rotating Base Marshall	69.2	3	68.8	4	69.0	3

[1]Average for the SHRP gyratory compactor is based on 3 mixes.
Average for all Marshall compactors is based on 6 mixes.

[2]Average for the SHRP gyratory compactor is based on 6 mixes.
Average for all Marshall compactors is based on 12 mixes.

Table 4.61 shows that specimens of aged asphalt mix prepared by a manual Marshall compactor achieved an average VFA content closest to the value obtained by testing specimens prepared by the SHRP gyratory compactor.

Table 4.62. Comparison of average unit weight as determined by testing specimens prepared by different compactors.

Type of Compactor	Average Unit Weight at Optimum AC Content by Mix Type					
	Surface[1]		Leveling[1]		Combined[2]	
	Unit Weight	Ranking	Unit Weight	Ranking	Unit Weight	Ranking
SHRP Gyratory	2.398	1	2.399	1	2.398	1
Mechanical Marshall (non-aged mix)	2.345	5	2.358	4	2.352	5
Manual Marshall	2.369	2	2.38	2	2.375	2
Mechanical Marshall (aged mix)	2.358	3	2.371	3	2.365	3
Rotating Base Marshall	2.353	4	2.371	3	2.362	4

[1]Average for the SHRP gyratory compactor is based on 3 mixes.
Average for all Marshall compactors is based on 6 mixes.

[2]Average for the SHRP gyratory compactor is based on 6 mixes.
Average for all Marshall compactors is based on 12 mixes.

Table 4.62 shows that specimens of aged asphalt mix prepared by a manual Marshall compactor achieved an average unit weight closest to the value obtained by testing specimens prepared by the SHRP gyratory compactor.

5. BACKGROUND, FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS.

5.1. BACKGROUND.

The current state-of-art identifies several distress modes in asphalt concrete pavements. These distress modes, excluding the effects of granular base, subbase, and subgrade support include: 1) fatigue cracking, 2) rutting, 3) bleeding, 4) low temperature cracking, 5) cyclic freeze and thaw cracking, 6) stripping, 7) ravelling, 8) oxidation and weathering, 9) potholes.

The current design procedure has some tools to provide safeguards against the first four distress modes that were mentioned above. Since Ohio can experience severe weather conditions, the ODOT has historically had more problems with items 4 through 9. The ODOT has worked for more than a decade with the asphalt pavement industry and Ohio highway stakeholders to address these problems. It was agreed that the previously mentioned distresses are often manifest as durability problems. Gradation adjustments, design and construction procedures, and increases in binder content appear to have adequately addressed the Ohio durability problem. This research was undertaken to examine the effect of different laboratory compaction equipment on density, air voids, and asphalt binder content for asphalt concrete mixes that are currently used in Ohio for heavy volume traffic.

5.2. FINDINGS.

1. For both surface and leveling asphalt mixes, optimum asphalt cement content, as determined using specimens prepared by a mechanical Marshall compactor, was approximately 0.5% higher for aged than non-aged asphalt.

2. The optimum asphalt cement content of asphalt concrete determined using test specimens prepared by a manual Marshall compactor was found to be lower than the optimum asphalt cement content determined for the same mix using test specimens prepared by the mechanical or rotating-base Marshall compactor.

3. The optimum asphalt cement content determined for an aged mix with 12.5mm nominal maximum size aggregate by using laboratory specimens prepared by the SHRP gyratory compactor was approximately 1% lower than the average asphalt cement content determined for the same mix using laboratory specimens prepared by the mechanical, manual, and rotating-base Marshall compactors.

4. The optimum asphalt cement content determined for an aged mix with 19.0mm nominal maximum size aggregate by using laboratory specimens prepared by the SHRP gyratory compactor was approximately 0.4% lower than the average asphalt cement content determined for the same mix using laboratory specimens prepared by the mechanical, manual, and rotating-base Marshall compactors.

5. The aggregate specific gravity test was found to be the most critical test for void analysis. A small variation in the test results can greatly influence the VMA and VFA calculations.

5.3. OTHER FINDINGS.

The Ohio Department of Transportation has established a Superpave Evaluation Team to oversee the transition to the Superpave mix design process for heavy traffic volume mixes. This team consists of representatives from FHWA, ODOT, industry, and academia and meets on-site regularly to discuss new Ohio Superpave paving projects, collect pertinent information, and exchange experience that govern the design process and placement practices. During the July, 1998 meeting, the Evaluation Team was presented by Mr. Gary

Behmke with design data for three Superpave mixes [10]. Each mix had a different nominal maximum size aggregate; namely, 9.5, 12.5, and 19.0mm. Data was collected to compare air voids content in the designed mixes with regard to the compaction method. The goal was to achieve the same air voids content in a mix regardless of the laboratory compaction method utilized. The experiment was conducted in the following manner. The same mix was produced over a period of several days and compacted daily in the laboratory using SHRP gyratory and Marshall compactors. The number of gyrations was constant at 109, however, the number of blows per specimen face in the Marshall compaction varied, starting at 75 and increasing in increments of 25. The results of this experiment showed that mix with 9.5 nominal maximum size aggregate required 150 blows per specimen face to achieve air voids content equal to 109 gyrations, 3.73 vs. 3.75% respectively. Mix with 12.5mm nominal maximum size aggregate at 100 blows per specimen face had 4.0% air voids vs. 3.40% at 109 gyrations. Mix with 19.0mm nominal maximum size aggregate required 125 blows per specimen face to achieve 4.02% air voids vs. 3.99% at 109 gyrations. Graphs illustrating this experiment are presented in Appendix B. Authors understand the fact that the above described experiment was not carried to completion and that comparison between SHRP gyratory and Marshall compactors may not be appropriate. The findings of the above mentioned experiment do, however, support the conclusions of our research which is that the use of specimens prepared by the SHRP gyratory compaction process may result in lower asphalt cement contents for Ohio pavements.

5.4. CONCLUSIONS.

1. Adoption of the SHRP gyratory compaction process in Ohio will result in a reduction of the design asphalt cement content.

2. Use of test specimens prepared by the mechanical Marshall compactor and a non-aged mix yields optimum asphalt cement content values closest to the values obtained by using test specimens prepared by the SHRP gyratory compactor from an aged mix.

3. Use of test specimens prepared by the manual Marshall compactor and an aged asphalt mix yields VMA, VFA, and unit weight values closest to the values obtained by using test specimens prepared by the SHRP gyratory compactor.

4. The number of gyrations as recommended by the Superpave gyratory compaction process may not be appropriate for Ohio heavy traffic volume mixes.

5. The complete elimination of natural sand may result in construction problems with respect to compaction especially at higher gyration levels.

6. It appears that some traditional Ohio mixes perform well in the field even though their gradation passes through the restricted zone as determined by the Superpave criteria.

5.5. RECOMMENDATIONS.

1. The number of gyrations currently recommended under the Superpave system should be reduced for Ohio mixes designed for heavy volume traffic. It is the authors' opinion that the currently used number of gyrations should be multiplied by a factor of 0.67 for mixes with 12.5mm nominal maximum size aggregate, and 0.75 for mixes with 19.0mm nominal maximum size aggregate. The reduction of the number of gyrations will result in a higher optimum asphalt cement content that is more consistent with current Ohio experience.

2. Natural sand plays an important role in mix densification during compaction, particularly at mid-range compaction temperatures (93-115°C). On the other hand, too much natural sand in the mix will produce unstable and tender mixes. It is the authors' opinion that up to 10% natural sand should be allowed in Ohio mixes.

3. The current VMA and VFA requirements were established for mixes designed using laboratory specimens prepared by Marshall type of compactor. Since the SHRP gyratory compactor uses larger molds and produces much higher density specimens, a change of the VMA and VFA requirements should be considered for Ohio mixes. If the number of gyrations is lowered by the proposed factor, as described in the first recommendation, the current VMA and VFA requirements need not be changed.

5.6. OTHER RECOMMENDATIONS.

1. The current optimum asphalt cement content determination by the Superpave mix design method depends primarily on volumetric analysis. A performance test is highly recommended prior to mix acceptance. The Loaded Wheel, Indirect Tensile Creep, or Triaxial tests are examples of such a performance test.

2. It is the authors' opinion that the current Superpave 0.45 gradation chart, which is based on the aggregate percent passing by weight, is not appropriate for determination of the maximum density line. It is recommended that the gradation of the total mix (including voids, asphalt cement, and additives) be plotted on a 1/3 power gradation chart using volumes rather than weights. A straight line drawn from the origin to the maximum aggregate size on this new chart will approximate the maximum density of the total mix based on volume

concentration of all materials and voids. This new power chart approximates more closely asphalt concrete mixes as they are produced and compacted.

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APPENDIX A

Table A1. Mix design data for surface mix with limestone coarse aggregate and manufactured sand; mechanical Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
5.0	2.336	2.487	6.09	13.2	54.0	15,730	3.1
5.5	2.355	2.468	4.56	13.0	64.8	14,944	2.8
6.0	2.364	2.450	3.49	13.1	73.4	14,090	2.9
6.5	2.393	2.432	1.60	12.5	87.7	13,110	3.3
7.0	2.380	2.414	1.41	13.4	89.5	12,920	3.7

Table A2. Mix design data for surface mix with limestone coarse aggregate and natural sand; mechanical Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.283	2.492	8.38	13.9	39.7	12,525	2.6
5.0	2.307	2.473	6.73	13.5	50.0	12,740	2.8
5.5	2.329	2.455	5.14	13.1	61.0	13,650	2.9
6.0	2.340	2.437	3.92	13.1	70.3	12,161	3.0
6.5	2.339	2.419	3.29	13.6	75.9	11,247	3.7

Table A3. Mix design data for surface mix made with gravel coarse aggregate and manufactured sand; mechanical Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.297	2.525	9.04	14.5	37.6	11,280	1.9
5.0	2.315	2.506	7.64	14.3	46.5	10,820	2.3
5.5	2.330	2.487	6.31	14.2	55.7	11,030	2.1
6.0	2.356	2.468	4.52	13.6	66.9	13,390	2.5
6.5	2.378	2.450	2.94	13.3	78	13,630	2.5

Table A4. Mix design data for surface mix made with gravel coarse aggregate and natural sand; mechanical Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.330	2.515	7.35	13.2	44.4	14,650	2.2
5.0	2.339	2.496	6.29	13.3	52.9	15,050	2.2
5.5	2.348	2.477	5.21	13.5	61.4	15,010	2.6
6.0	2.383	2.459	3.10	12.6	75.5	14,240	2.8
6.5	2.382	2.440	2.40	13.2	81.8	14,550	2.7

Table A5. Mix design data for surface mix made with gravel coarse aggregate and 50/50 sand blend; mechanical Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.314	2.520	8.16	13.8	40.9	14,250	2.3
5.0	2.333	2.501	6.72	13.6	50.4	14,440	2.4
5.5	2.350	2.482	5.33	13.4	60.2	13,800	2.4
6.0	2.354	2.463	4.41	13.7	67.8	13.950	2.4
6.5	2.376	2.445	2.84	13.4	78.8	14,730	2.8

Table A6. Mix design data for surface mix made with limestone coarse aggregate and manufactured sand; manual Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.297	2.506	8.33	14.2	41.6	11,410	3.8
5.0	2.336	2.487	6.07	13.2	54.3	12,520	3.5
5.5	2.347	2.468	4.90	13.3	63.9	14,180	3.5
6.0	2.348	2.450	4.17	13.7	69.7	13,880	4.3
6.5	2.379	2.432	2.17	13.0	83.4	13,000	3.5

Table A7. Mix design data for surface mix made with limestone coarse aggregate and natural sand; manual Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.299	2.492	7.75	13.3	41.7	11,910	2.9
5.0	2.331	2.473	5.73	12.5	54.4	13,330	3.0
5.5	2.345	2.455	4.46	12.5	64.3	15,120	3.0
6.0	2.34	2.437	3.97	13.1	69.9	13,120	3.2
6.5	2.366	2.419	2.19	12.6	82.7	13,380	3.3

Table A8. Mix design data for surface mix made with gravel coarse aggregate and manufactured sand; manual Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.333	2.525	7.61	13.1	42.1	17,500	2.5
5.0	2.362	2.506	5.75	12.5	54.3	17,110	2.4
5.5	2.391	2.487	3.87	11.9	67.3	19,320	2.6
6.0	2.397	2.468	2.88	12.2	76.4	16,920	2.9
6.5	2.406	2.450	1.78	12.3	85.5	16,390	3.2

Table A9. Mix design data for surface mix made with gravel coarse aggregate and natural sand; manual Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.360	2.515	6.17	12.1	49.1	17,490	2.2
5.0	2.373	2.496	4.95	12.1	59.1	16,710	2.5
5.5	2.388	2.477	3.58	12.0	70.1	16,650	2.5
6.0	2.393	2.459	2.68	12.2	78.3	16,700	2.7
6.5	2.411	2.440	1.19	12.1	90.1	16,660	2.9

Table A10. Mix design data for surface mix made with gravel coarse aggregate and 50/50% sand blend; manual Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.343	2.520	7.03	12.7	44.8	18,310	2.9
5.0	2.352	2.501	5.96	12.9	53.7	16,080	2.6
5.5	2.370	2.482	4.52	12.7	64.3	15,560	2.7
6.0	2.382	2.463	3.28	12.7	74.1	16,750	2.4
6.5	2.391	2.445	2.22	12.8	82.7	15,510	3.3

Table A11. Mix design data for surface mix made with limestone coarse aggregate and manufactured sand; Rotating Base Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.311	2.506	7.80	13.7	43.3	14,630	2.6
5.0	2.325	2.487	6.52	13.6	52.3	14,480	3.2
5.5	2.357	2.468	4.51	12.9	65.1	14,520	3.0
6.0	2.381	2.450	2.81	12.5	77.5	16,120	3.1
6.5	2.368	2.432	2.62	13.4	80.6	12,980	3.0

Table A12. Mix design data for surface mix made with limestone coarse aggregate and natural sand; Rotating Base Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.298	2.492	7.80	13.3	41.6	13,420	2.6
5.0	2.327	2.473	5.92	12.7	53.6	13,870	2.8
5.5	2.331	2.455	5.04	13.0	61.2	13,550	2.7
6.0	2.331	2.437	4.34	13.5	67.7	12,700	3.3
6.5	2.347	2.419	2.97	13.3	77.7	11,550	2.9

Table A13. Mix design data for surface mix made with gravel coarse aggregate and manufactured sand; Rotating Base Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.297	2.525	9.05	14.5	37.7	11,700	2.6
5.0	2.309	2.506	7.86	14.5	45.9	11,380	2.7
5.5	2.314	2.487	6.96	14.7	53.1	11,760	2.5
6.0	2.348	2.468	4.86	14.0	65.2	11,210	2.8
6.5	2.347	2.450	4.20	14.4	71.1	10,690	3.1

Table A14. Mix design data for surface mix made with gravel coarse aggregate and natural sand; Rotating Base Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.326	2.515	7.51	13.4	43.9	13,680	2.2
5.0	2.335	2.496	6.45	13.5	52.5	13,660	2.2
5.5	2.359	2.477	4.75	13.0	63.6	14,060	2.7
6.0	2.378	2.459	3.29	12.8	74.4	15,140	2.8
6.5	2.388	2.440	2.12	12.9	83.7	15,050	2.5

Table A15. Mix design data for surface mix made with gravel coarse aggregate and 50/50% sand blend; Rotating Base Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.328	2.520	7.64	13.3	42.6	15,190	2.4
5.0	2.338	2.501	6.53	13.4	51.3	15,130	2.5
5.5	2.355	2.482	5.11	13.2	61.5	15,070	2.3
6.0	2.367	2.463	3.91	13.2	70.5	14,230	2.6
6.5	2.381	2.445	2.63	13.2	80.1	14,510	2.8

Table A16. Mix design data for surface mix made with limestone coarse aggregate and manufactured sand; Gyratory compaction. Data at $N_{initial}$

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA
4.1	2.120	2.525	16.03	20.5	21.8
4.5	2.141	2.506	14.56	20.0	27.2
5.0	2.161	2.487	13.08	19.7	33.6
5.5	2.164	2.468	12.30	20.0	38.5
6.0	2.182	2.450	10.93	19.8	44.8

Table A17. Mix design data for surface mix made with limestone coarse aggregate and manufactured sand; Gyratory compaction. Data at N_{design}

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA
4.1	2.386	2.525	5.51	10.5	47.5
4.5	2.409	2.506	3.88	10.0	61.2
5.0	2.435	2.487	2.11	9.6	78.0
5.5	2.437	2.468	1.26	9.9	87.3
6.0	2.442	2.450	0.33	10.2	96.8

Table A18. Mix design data for surface mix made with limestone coarse aggregate and manufactured sand; Gyratory compaction. Data at N_{max}

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA
4.1	2.431	2.525	3.72	8.8	57.7
4.5	2.453	2.506	2.13	8.4	74.6
5.0	2.465	2.487	0.87	8.4	89.6
5.5	2.464	2.468	0.18	9.0	98.0
6.0	2.450	2.450	0.0	9.9	100.0

Table A19. Mix design data for surface mix made with gravel coarse aggregate and 50/50% sand blend; Gyratory compaction. Data at $N_{initial}$

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA
4.5	2.130	2.520	15.48	20.7	25.1
5.0	2.144	2.501	14.26	20.6	30.6
5.5	2.154	2.482	13.24	20.6	35.8
6.0	2.150	2.463	12.71	21.2	40.0

Table A20. Mix design data for surface mix made with gravel coarse aggregate and 50/50% sand blend; Gyratory compaction. Data at N_{design}

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA
4.5	2.347	2.520	6.86	12.8	46.5
5.0	2.374	2.501	5.06	12.0	58.0
5.5	2.392	2.482	3.64	11.8	69.2
6.0	2.386	2.463	3.10	12.6	75.2

Table A21. Mix design data for surface mix made with gravel coarse aggregate and 50/50% sand blend; Gyratory compaction. Data at N_{max}

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA
4.5	2.389	2.520	5.22	11.0	52.7
5.0	2.412	2.501	3.55	10.6	66.6
5.5	2.427	2.482	2.22	10.5	80.1
6.0	2.428	2.463	1.43	11.0	87.0

Table A22. Mix design data for surface mix made with limestone coarse aggregate and manufactured sand; mechanical Marshall compaction (not aged mix).

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.307	2.468	6.48	13.8	53.3	12,720	2.9
5.0	2.320	2.449	5.27	13.8	61.9	12,380	3.0
5.5	2.363	2.431	2.80	12.7	78.4	13,270	3.0
6.0	2.387	2.413	1.09	12.3	91.2	13,540	3.2
6.5	2.390	2.396	0.26	12.6	98.0	14,250	3.8

Table A23. Mix design data for surface mix with made limestone coarse aggregate and natural sand; mechanical Marshall compaction (not aged mix mix).

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.277	2.458	7.36	14.1	47.9	10,470	2.7
5.0	2.306	2.440	5.47	13.5	59.4	12,440	2.5
5.5	2.321	2.422	4.19	13.4	68.8	11,860	2.9
6.0	2.335	2.404	2.87	13.3	78.5	11,030	3.0
6.5	2.345	2.386	1.73	13.4	87.1	11,750	3.1

Table A24. Mix design data for surface mix made with gravel coarse aggregate and manufactured sand; mechanical Marshall compaction (not aged mix).

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.323	2.502	7.16	13.5	47.1	12,170	2.2
5.0	2.341	2.483	5.72	13.3	57.0	12,440	2.3
5.5	2.357	2.464	4.34	13.2	67.0	12,660	2.5
6.0	2.391	2.446	2.24	12.4	81.9	13,510	2.7
6.5	2.383	2.428	1.84	13.1	86.0	14,000	3.0

Table A25. Mix design data for surface mix made with gravel coarse aggregate and natural sand; mechanical Marshall compaction (not aged mix).

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.319	2.487	6.74	13.6	50.6	11,520	2.4
5.0	2.323	2.468	5.89	13.9	57.9	11,440	2.2
5.5	2.337	2.450	4.62	13.8	64.0	11,070	2.2
6.0	2.366	2.432	2.71	13.3	79.7	12,680	2.3
6.5	2.384	2.414	1.26	13.1	90.4	12,790	2.5

Table A26. Mix design data for surface mix made with gravel coarse aggregate and 50/50% sand blend; mechanical Marshall compaction (not aged mix).

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.315	2.492	7.08	13.8	48.6	13,020	2.3
5.0	2.332	2.473	5.70	13.6	58.1	12,740	2.3
5.5	2.355	2.456	4.10	13.2	69.1	12,070	2.3
6.0	2.378	2.437	2.43	12.8	81.1	13,480	2.4
6.5	2.370	2.04	2.04	13.6	85.0	13,820	2.6

Table A27. Mix design data for leveling mix made with limestone coarse aggregate and manufactured sand; mechanical Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.0	2.391	2.562	6.69	12.8	47.9	20,160	4.0
4.5	2.425	2.543	4.63	12.0	61.4	16,540	4.6
5.0	2.448	2.423	2.99	11.6	74.3	16,310	4.3
5.5	2.452	2.504	2.06	11.9	82.8	13,680	4.6
6.0	2.444	2.484	1.60	12.7	87.4	13,700	5.8

Table A28. Mix design data for leveling mix with limestone coarse aggregate and natural sand; mechanical Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.0	2.353	2.540	7.36	13.0	43.5	13,950	2.5
4.5	2.371	2.520	6.06	12.9	53.6	14,790	2.5
5.0	2.378	2.501	4.90	13.0	62.4	13,820	2.6
5.5	2.416	2.482	2.67	12.1	77.9	14,280	3.0
6.0	2.419	2.463	1.79	12.4	85.7	14,570	2.9

Table A29. Mix design data for leveling mix made with gravel coarse aggregate and manufactured sand; mechanical Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.237	2.498	10.47	14.3	26.9	11,960	3.0
5.0	2.254	2.479	9.07	14.1	35.7	13,010	3.0
5.5	2.269	2.460	7.75	14.0	44.6	12,850	2.8
6.0	2.283	2.442	6.51	13.9	53.2	13,980	3.3
6.5	2.313	2.424	4.56	13.2	65.5	15,850	3.3
7.0	2.335	2.406	2.95	12.9	77.1	16,010	3.6

Table A30. Mix design data for leveling mix made with gravel coarse aggregate and natural sand; mechanical Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.312	2.474	6.56	13.6	51.9	11,530	2.2
5.0	2.310	2.456	5.96	14.2	57.9	8,300	2.2
5.5	2.334	2.438	4.27	13.7	68.8	9,730	2.2
6.0	2.342	2.420	3.22	13.9	76.8	9,800	2.6
6.5	2.352	2.403	2.11	14.0	84.9	7,320	2.6

Table A31. Mix design data for leveling mix made with gravel coarse aggregate and 50/50 sand blend; mechanical Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.292	2.487	7.85	13.6	42.1	12,650	2.5
5.0	2.311	2.468	6.35	13.3	52.2	12,740	2.6
5.5	2.302	2.450	6.05	14.1	57.1	11,760	2.5
6.0	2.324	2.432	4.44	13.7	67.8	12,560	2.7
6.5	2.341	2.414	3.04	13.6	77.6	12,160	2.8

Table A32. Mix design data for leveling mix made with limestone coarse aggregate and manufactured sand; manual Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.0	2.400	2.562	6.31	12.4	49.3	22,460	3.2
4.5	2.419	2.543	4.86	12.2	60.1	20,510	4.4
5.0	2.445	2.523	3.08	11.7	73.7	17,700	4.3
5.5	2.444	2.504	2.40	12.2	80.4	17,220	5.7
6.0	2.439	2.484	1.81	12.9	86.0	13,130	6.7

Table A33. Mix design data for leveling mix made with limestone coarse aggregate and natural sand; manual Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.0	2.381	2.540	6.26	12.0	47.8	16,510	2.7
4.5	2.402	2.520	4.68	11.7	59.9	17,440	2.8
5.0	2.419	2.501	3.26	11.5	71.7	17,490	3.2
5.5	2.432	2.482	2.02	11.5	82.6	16,940	3.2
6.0	2.439	2.463	1.00	11.7	91.6	17,310	4.5

Table A34. Mix design data for leveling mix made with gravel coarse aggregate and manufactured sand; manual Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.266	2.498	9.29	13.2	29.6	16,160	2.9
5.0	2.291	2.479	7.57	12.9	40.1	16,840	2.9
5.5	2.297	2.460	6.64	12.9	48.7	16,820	3.6
6.0	2.320	2.442	5.01	12.5	60.1	16,470	3.2
6.5	2.339	2.424	3.50	12.3	71.5	17,200	3.6
7.0	2.356	2.406	2.08	12.1	82.8	17,680	4.0

Table A35. Mix design data for leveling mix made with gravel coarse aggregate and natural sand; manual Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.335	2.474	5.64	12.8	55.9	9,940	2.3
5.0	2.332	2.456	5.03	13.3	62.2	11,490	2.5
5.5	2.352	2.438	3.53	13.0	73.0	12,500	2.6
6.0	2.373	2.420	1.95	12.7	84.7	11,080	3.6
6.5	2.359	2.403	1.82	13.7	86.7	9,090	3.8

Table A36. Mix design data for surface mix with gravel coarse aggregate and 50/50 sand blend; manual Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.331	2.487	6.29	12.1	48.1	15,280	2.3
5.0	2.329	2.468	5.61	12.6	55.4	15,970	2.5
5.5	2.338	2.450	4.56	12.7	64.2	14,330	2.7
6.0	2.355	2.432	3.16	12.6	74.9	15,570	3.0
6.5	2.358	2.414	2.32	12.9	82.0	14,770	3.3

Table A37. Mix design data for leveling mix made with limestone coarse aggregate and manufactured sand; rotating base Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.0	2.378	2.562	7.19	13.2	46.6	20,150	3.8
4.5	2.415	2.543	5.03	12.3	59.3	18,870	4.1
5.0	2.438	2.523	3.35	12.0	72.3	16,650	4.1
5.5	2.459	2.504	1.81	11.7	84.6	15,930	5.6
6.0	2.462	2.484	0.87	12.0	92.8	14,790	7.1

Table A38. Mix design data for leveling mix made with limestone coarse aggregate and natural sand; rotating base Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.0	2.349	2.540	7.53	13.2	42.9	15,450	2.9
4.5	2.357	2.520	6.45	13.3	51.5	14,570	2.6
5.0	2.378	2.501	4.92	13.0	62.2	15,500	2.9
5.5	2.390	2.482	3.71	13.0	71.6	13,680	2.4
6.0	2.397	2.463	2.66	13.2	79.9	14,510	3.0

Table A39. Mix design data for leveling mix made with gravel coarse aggregate and manufactured sand; rotating base Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
5.0	2.268	2.479	8.50	13.6	37.3	13,330	2.9
5.5	2.284	2.460	7.17	13.4	46.7	14,170	3.0
6.0	2.299	2.442	5.87	13.3	56.0	15,120	3.1
6.5	2.324	2.424	4.11	12.8	68.0	16,350	3.4
7.0	2.336	2.406	2.91	12.9	77.4	15,060	3.4

Table A40. Mix design data for leveling mix made with gravel coarse aggregate and natural sand; rotating base Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.319	2.474	6.25	13.3	53.2	10,650	2.3
5.0	2.319	2.456	5.58	13.8	59.6	8,310	2.1
5.5	2.360	2.438	3.19	12.7	74.9	12,390	2.6
6.0	2.352	2.42	2.81	13.5	79.2	9,660	2.6
6.5	2.346	2.403	2.37	14.2	83.3	7,850	3.4

Table A41. Mix design data for leveling mix made with gravel coarse aggregate and 50/50% sand blend; rotating base Marshall compaction.

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.300	2.487	7.51	13.2	43.3	13,640	2.3
5.0	2.312	2.468	6.31	13.2	52.7	13,350	2.3
5.5	2.328	2.450	4.99	13.1	62.1	14,110	2.7
6.0	2.332	2.432	3.86	13.2	70.8	14,710	2.7
6.5	2.352	2.414	2.56	13.2	80.5	13,630	2.9

Table A42. Mix design data for leveling mix made with limestone coarse aggregate and manufactured sand; Gyratory compaction. Data at $N_{initial}$

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA
3.5	2.131	2.583	17.50	21.8	19.9
4.0	2.158	2.562	15.77	21.2	25.8
4.5	2.183	2.543	14.18	20.8	31.8
5.0	2.216	2.523	12.18	20.0	39.1

Table A43. Mix design data for leveling mix made with limestone coarse aggregate and manufactured sand; Gyratory compaction. Data at N_{design}

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA
3.5	2.378	2.583	7.96	12.8	37.9
4.0	2.414	2.562	5.76	11.9	51.6
4.5	2.437	2.543	4.18	11.5	63.8
5.0	2.458	2.523	2.56	11.2	77.2

Table A44. Mix design data for leveling mix made with limestone coarse aggregate and manufactured sand; Gyratory compaction. Data at N_{max}

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA
3.5	2.420	2.583	6.32	11.6	43.8
4.0	2.454	2.562	4.23	10.5	59.6
4.5	2.472	2.543	2.79	10.3	72.8
5.0	2.481	2.523	1.68	10.4	83.9

Table A45. Mix design data for leveling mix made with gravel coarse aggregate and 50/50% sand; blend; Gyratory compaction. Data at $N_{initial}$

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA
4.0	2.171	2.506	13.34	17.7	24.5
4.5	2.167	2.487	12.86	18.3	29.3
5.0	2.185	2.468	11.44	18.0	35.6
5.5	2.182	2.450	10.91	18.5	41.1

Table 4.46. Mix design data for leveling mix made with gravel coarse aggregate and 50/50% sand blend; Gyratory compaction. Data at N_{design}

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA
4.0	2.331	2.506	7.00	11.6	39.9
4.5	2.332	2.487	6.23	12.1	48.2
5.0	2.342	2.468	5.11	12.1	57.9
5.5	2.360	2.450	3.70	12.0	69.1

Table 47. Mix design data for leveling mix made with gravel coarse aggregate and 50/50% sand blend; Gyratory compaction. Data at N_{max}

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA
4.0	2.351	2.506	6.18	10.9	43.1
4.5	2.355	2.487	5.29	11.2	52.6
5.0	2.364	2.468	4.21	11.3	62.7
5.5	2.383	2.450	2.71	11.1	75.4

Table 4.48. Mix design data for surface mix with limestone coarse aggregate and manufactured sand; mechanical Marshall compaction (not aged mix).

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.0	2.412	2.535	4.84	12.0	59.6	18,340	2.8
4.5	2.430	2.515	3.39	11.8	71.4	15,700	3.9
5.0	2.446	2.494	1.94	11.7	83.5	13,460	4.5
5.5	2.447	2.477	1.23	12.1	89.9	13,210	5.3
6.0	2.448	2.458	0.42	12.6	96.7	12,400	6.5

Table 4.49. Mix design data for leveling mix made with limestone coarse aggregate and natural sand; mechanical Marshall compaction (not aged mix).

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.0	2.364	2.511	5.85	12.6	53.9	13,490	2.3
4.5	2.377	2.493	4.68	12.6	63.2	13,250	2.3
5.0	2.382	2.475	3.72	12.8	71.1	13,120	2.8
5.5	2.392	2.458	2.68	13.0	79.4	12,070	2.5
6.0	2.405	2.438	1.35	12.9	89.7	12,470	2.7

Table 4.50. Mix design data for leveling mix made with gravel coarse aggregate and manufactured sand; mechanical Marshall compaction (not aged mix).

% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.262	2.494	8.57	13.3	35.8	13,630	2.6
5.0	2.273	2.475	7.45	13.4	44.4	13,620	3.1
5.5	2.293	2.456	5.90	13.1	54.9	14,380	3.1
6.0	2.295	2.438	5.18	13.5	61.6	13,930	3.8
6.5	2.312	2.420	3.76	13.3	71.8	12,900	5.0

Table 4.51. Mix design data for leveling mix made with gravel coarse aggregate and natural sand; mechanical Marshall compaction (not aged mix).

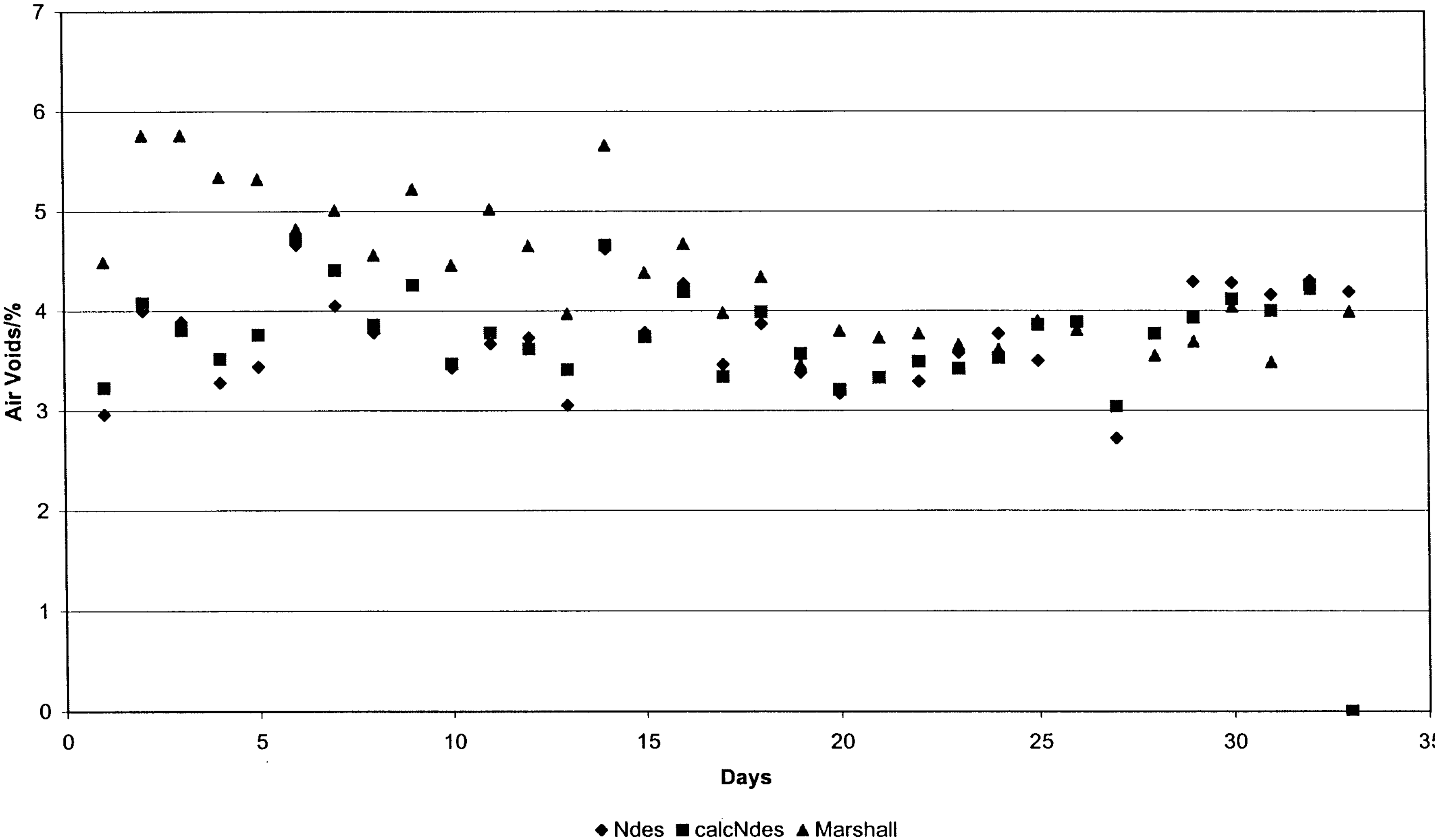
% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.312	2.444	5.42	13.6	60.3	6,870	1.9
5.0	2.310	2.426	4.78	14.1	66.2	5,610	1.9
5.5	2.320	2.408	3.67	14.2	74.3	5,460	2.1
6.0	2.345	2.391	1.94	13.8	86.0	6,720	2.4
6.5	2.329	2.374	1.91	14.8	87.2	5,220	2.6

Table 4.52. Mix design data for leveling mix made with gravel coarse aggregate and 50/50% sand blend; Mechanical Marshall compaction (not aged mix).

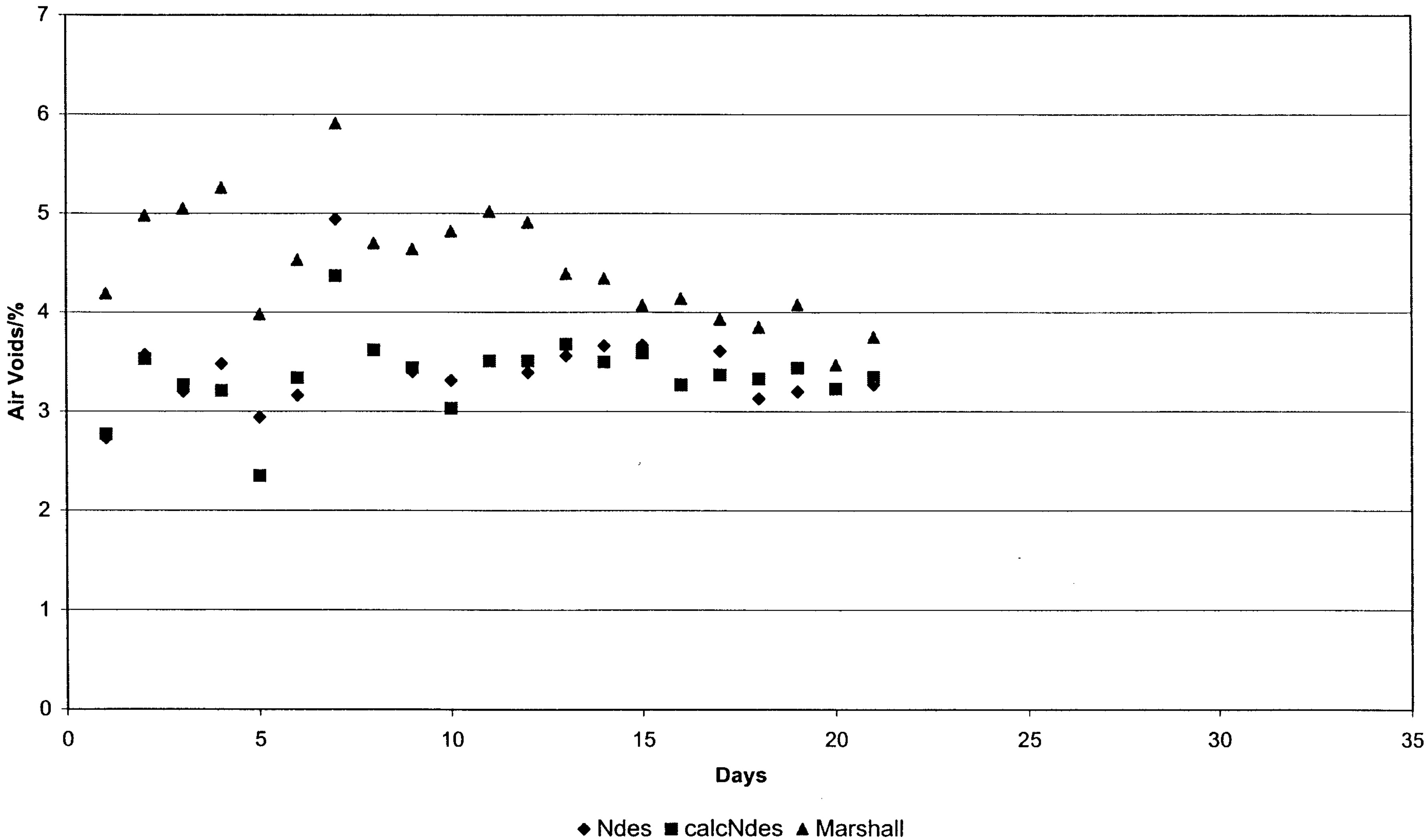
% Total Asphalt	Bulk Mix S.G.	Max Mix S.G.	% Air Voids	% VMA	% VFA	Stability (N)	Flow (mm)
4.5	2.273	2.458	7.52	14.3	47.3	8,030	2.2
5.0	2.298	2.440	5.82	13.8	57.8	8,980	2.2
5.5	2.322	2.422	4.14	13.3	69.0	10,300	2.3
6.0	2.325	2.404	3.28	13.7	76.0	8,850	2.7
6.5	2.336	2.387	2.15	13.7	84.4	9,500	2.7

APPENDIX B

Air Voids in Superpave Mix 9.5mm. Marshall Compaction. Days 1-5 75 blows; Days 6-15 100 blows; Days 16-22 125 blows; Days 23-33 150 blows.



Air Voids in Superpave Mix 12.5mm. Marshall Compaction. Days 1-12 75 blows; Days 13-21 100 blows.



Air Voids in Superpave Mix 19mm. Marshall Compaction. Days1-4 75 blows; Days 5-9 100 blows; Days 10-14 125 blows.