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EVALUATION OF THE SUPERPAVE GYRATORY COMPACTOR FOR LOW VOLUME ROADS

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16 Abstract

There is evidence that some Kansas mixes, which have performed well in the past, will not meet the currently proposed design requirements for a Superpave level I mix. The major problem is low voids in the mineral aggregate (VMA). The major reasons for low VMA are the high amounts of natural sand currently used and the higher compactive effort required by Superpave compared to 50-blow Marshall compaction.

Cores, plant produced (field) mix, the original aggregates and asphalt cement were obtained from four low volume pavements. The cores established the in-place density of the pavements. The field mix was compacted in the Superpave Gyratory Compactor (SGC) to establish the number of gyrations required to reach the field density of the mix. The aggregates and asphalt cement were obtained and Superpave mix designs were performed. The void properties were evaluated at the original and revised N_{design} gyrations. The effect of reducing the ram pressure from 600 kPa to 400 kPa was evaluated as well.

Even the revised N_{design} gyrations produce samples with densities higher than both 50-blow Marshall compaction and what was found in–place. VMA was the void parameter that controlled Superpave mix designs. Converting from Marshall to Superpave mixes will require new designs. Implementing the revised N_{design} requirements will ease the burden of converting from Marshall to Superpave mixes.

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Aggregate, Asphalt Cement, Superpave, Superpave Gyratory Compactor

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Final Report

No. KS-00-2

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ABSTRACT

There is evidence that some Kansas mixes, which have performed well in the past, will not meet the currently proposed design requirements for a Superpave level I mix. The major problem is low voids in the mineral aggregate (VMA). The major reasons for low VMA are the high amounts of natural sand currently used and the higher compactive effort required by Superpave compared to 50-blow Marshall compaction.

Cores, plant produced (field) mix, the original aggregates and asphalt cement were obtained from four low volume pavements. The cores established the in-place density of the pavements. The field mix was compacted in the Superpave Gyratory Compactor (SGC) to establish the number of gyrations required to reach the field density of the mix. The aggregates and asphalt cement were obtained and Superpave mix designs were performed. The void properties were evaluated at the original and revised N_{design} gyrations. The effect of reducing the ram pressure from 600 kPa to 400 kPa was evaluated as well.

Even the revised N_{design} gyrations produce samples with densities higher than both 50-blow Marshall compaction and what was found in-place. VMA was the void parameter that controlled Superpave mix designs. Converting from Marshall to Superpave mixes will require new designs. Implementing the revised N_{design} requirements will ease the burden of converting from Marshall to Superpave mixes.

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CHAPTER 1
INTRODUCTION

PROBLEM STATEMENT

There is evidence that some Kansas mixes, which have performed well in the past, will not meet the currently proposed design requirements for a Superpave Level 1 mix. Preliminary experience with Kansas aggregates and Superpave Level 1 mixes has shown this to be true and importation of aggregates to meet mix requirements has been necessary. There is evidence, from the original development of Superpave, that it is difficult to meet the volumetric requirements with mixes containing more than 15% natural sand. However, Superpave Level 1 mix requirements allow more than 15% natural sand and uncrushed coarse aggregates in mixes with low traffic.

The Kansas Department of Transportation (KDOT) has been successfully utilizing sand gravel and sand limestone mixes in their bituminous pavements for years. Previous specifications typically allowed 50% uncrushed material on the majority of their low volume roads. The adoption of the AASHTO/Superpave Level 1 mix specifications will preclude the use of many locally available aggregates and mixes that have performed adequately, making its implementation difficult on the local level and for low volume pavements.

The initial Superpave gyratory compactor (SGC) design compactive efforts were developed based on 18 field mixes selected from nine Long-Term Pavement Performance (LTPP) sites in three climatic regions of the United States (1). The experimental plan was not completed as replicate samples were unavailable for the three hot climate pavements. What is more important, the sites sampled had higher traffic loadings and better quality aggregates than typical Kansas pavements. Therefore, the original $N_{initial}$, N_{design} and N_{final} gyrations are based on limited test data from mixes that have little in common with Kansas aggregates or traffic levels. The $N_{initial}$, N_{design} and N_{final} gyrations need to be established for Kansas aggregates and Kansas traffic levels. It is possible that with rounded aggregates and the lower traffic levels seen on most bituminous pavements in Kansas, lower compactive efforts would be required to allow the use of some Kansas mixes with a history of good performance.

The reasons for the difficulty in meeting Superpave Level 1 mix requirements are varied and somewhat subjective in nature. D'Angelo (2) showed that the SGC is a more efficient compactor, resulting in 2% fewer voids total mix (VTM) than Marshall compaction. Since that time many other researchers have reported similar results as well. The development of the SGC design gyration table (1), N_{design}, is proving to be inaccurate for all levels of traffic. In addition, N_{design} was developed with higher quality aggregates than typically found in Kansas and the Midwest.

Brown et al. (3), at the National Center for Asphalt Technology (NCAT), repeated the N_{design} experiment for six pavements and found that the original N_{design} gyrations were too high, especially for lower traffic levels. The researchers recommended a more detailed study to refine the N_{design} tables. NCAT conducted two more comprehensive studies evaluating the SGC. The first study (4) pointed out the problems with back calculating the mix volumetrics at N_{design} from the N_{final} bulk specific gravity using a single correction factor. The researchers reported that errors up to 0.5% VTM and 0.5% to 1.5% in relative density are possible between the actual values at N_{design} and the back calculated N_{design} values. The researchers recommended mixes be compacted to N_{design} rather than N_{final}. A second study by NCAT (5) focused on the N_{design} compaction tables. The researchers reported that the current N_{design} gyrations resulted in denser mixes than similar field mixes, with the same traffic intensity. The researchers reported that the N_{design} number of gyrations was approximately 30 revolutions too high at all traffic levels.

The N_{design} tables were recently redesigned by an AASHTO task force (6). The different gyrations for different pavement temperatures were eliminated, the traffic levels reduced and the number of gyrations was reduced. Void calculations are now made on samples compacted to N_{design} rather than N_{final}. No changes were made in voids in the mineral aggregate (VMA). Slight changes were made in the requirements for voids filled with asphalt (VFA), but these should not affect Kansas mixes. Table 1 shows the original Superpave requirements and the changes proposed by AASHTO (6).

Table 1. Proposed Major Changes by AASHTO to Superpave Design Requirements.

Original Recommendations				Proposed Changes			
Traffic Level (million ESALs)	N_{ini}/ N_{design}/ N_{final}	% Gmm at N_{ini}	Coarse Agg. Angularity ≤ 100 mm	Traffic Level (million ESALs)	N_{ini}/ N_{dsign}/ N_{final}	Coarse Agg. Angularity ≤ 100 mm	% Gmm at N_{ini}
<0.3	7/68/104	≤ 89.0	55/-	<0.3	6/50/75	55/-	≤ 91.5
0.3-1	7/76/117	≤ 89.0	65/-				
1-3	7/86/134	≤ 89.0	75/-	0.3-3	7/75/115	75/-	≤ 90.5
3-10	8/96/152	≤ 89.0	85/80	3-10	8/100/160	85/80	≤ 89.0
10-30	8/109/174	≤ 89.0	95/90	10-30	8/100/160	95/90	≤ 89.0
30-100	9/126/204	≤ 89.0	100/100	>30	9/125/212	100/100	≤ 89.0
> 100	9/143/235	≤ 89.0	100/100				

The primary problem in meeting Superpave Level 1 mix requirements has typically been VMA. VMA is a volumetric property and a function of compactive effort. Therefore, the only place mix volumetrics are meaningful is in the road after compaction by two to three years of traffic. After this time, the mix should reach an equilibrium condition and it is at this condition that mix volumetrics correlate to pavement performance. If the SGC artificially compacts high sand content mixes (greater than 15% natural sand) to a density exceeding the field density, then the mix design volumetrics would be misleading and would not be a good indicator of mix performance. Mallick (4) has reported that the SGC will compact a mix with 20% natural sand to approximately 1.5% less VMA than a comparable 100% limestone mix. The resulting lower VMA could also lead to the importation of higher quality, more expensive aggregates for low volume roads. Higher compactive efforts can also cause the design mix density to exceed the field density, resulting in an under asphalted mix that would be prone to durability failures.

PROJECT OBJECTIVES

The objectives of this project were to evaluate the recommendations for $N_{initial}$, N_{design} and N_{final} gyrations for Kansas mixes and traffic levels in the same manner the original recommendations were established. The work concentrated on mixes with traffic less than one million ESALs. The mixes were compacted to the SGC N_{design} number of gyrations and the performance of the mix evaluated using the Asphalt Pavement Analyzer (APA). This information will help KDOT evaluate N_{design} gyrations for low traffic pavements and evaluate the stability of their mixes.

CHAPTER 2
PLAN OF STUDY

WORK PLAN

To evaluate the effects of the changes to the N_{design} tables on KDOT mixes, the following tasks were performed:

Task 1. Evaluation of Pavement Cores: Cores from five pavements that were cored for maintenance overlays were provided by KDOT for compaction on the SGC. The location of the cores, estimated traffic and reason for overlay are shown in Table 2. The cores were sawed into their respective layers, heated, broken apart and recombined by layers by KDOT. The surface mix from each site was sent to the Bituminous Laboratory at the University of Kansas (KU) and was compacted in the SGC. The mixes were compacted to 114 gyrations at 600 kPa and at 400 kPa. The void properties versus compactive effort were determined and used to evaluate the N_{design} compactive effort.

Task 2. Evaluation of Field Mix: To evaluate how a current KDOT mix would compare to a Superpave mix, three projects were selected for evaluation. The three projects were KDOT BM-2A mixes placed on K-4, K-20 and K-116. Field mix was obtained from behind the paver by KDOT and supplied to KU for testing. The project numbers for the three mixes samples and estimated total 20 year traffic is shown in Table 3.

The field mix was heated to the compaction temperature and compacted in the SGC to 117 gyrations. To evaluate the Superpave mix void properties, the voids were determined at 50 and 75 gyrations at 600 kPa and at 75 gyrations at 400 kPa. The void properties evaluated at 400 kPa were used to evaluate the effect of a reduced ram pressure to simulate lower traffic levels.

Task 3. Superpave Mix Designs: One of the objectives of this study was to determine how difficult it would be to convert 50-blow Marshall mixes for low volume roads to Superpave mixes. To accomplish this Marshall mix designs and the original aggregates and asphalt cements from the projects sampled in Task 2 were obtained. Materials were available from a fourth project on US-281 from a previous study, so this site was included as

Table 2. Sample Information for Pavement Cores.

Site	Project Number	Major Distress	Age at Coring (years)	Daily ESALs	20 Year Design Traffic (10^6 ESALs)
42	96-41 K-6198-01	Cracking	6	100	0.730
43	73-3 K-6074-01	Cracking	5	64	0.467
46	96-51 K-6198-01	Cracking	6	78	0.569
47	73-3 K-6074-01	Cracking	7	64	0.467
48	156-5 K-5749-01	Rutting	3	158	1.153

Table 3. Sample Information for Field Mix.

Site	Project Number	Mix Type	AADT	Daily ESALs	20 Year Design Traffic (10^6 ESALs)
K-4	4-99 K-5677-01	BM-2A	245	17	0.124
K-20	106 K-5975-01	BM-2A	370	18	0.131
K-116	106 K-5649-01	BM-2A	275	13	0.095
US-281*	281-4 K-4051-01	BM-2	573	50	3.650

* Field mix not available.

well. Superpave mix designs were performed on the four mixes to determine if the mixes would meet the new Superpave requirements, or if new aggregate gradations would be required. The mix designs were performed using the procedures recommended in SP-2 by the Asphalt Institute (7). A two-hour cure time between mixing and compaction was utilized.

Task 4. Performance Testing: Mix samples made in Task 2 and 3 were evaluated for rutting potential using the APA to evaluate the stability of the mixes and generate typical APA rut depth values for good performing mixes.

CHAPTER 3
EVALUATION OF CORES

LOCATION

Cores from five projects that were cored during the design of maintenance overlays were provided by KDOT for compaction in the SGC. Table 2 showed the project information for each site and the primary distress. The 20 year design equivalent single axle loads (ESALs) were estimated from current daily ESALs, assuming no growth. Based on the estimated design ESALs, all of the sites except site 48 fell into the original Superpave traffic level II, 0.3 - 1 million ESALs. Site 28 fell in traffic level III, 1-3 million ESALs. Under the revised AASHTO recommendations (6), all five sites fall under traffic level II, 0.3 - 3 million ESALs.

PRELIMINARY TESTING

The surface mix was removed from each core and utilized for testing. The bulk specific gravity was determined in accordance with Kansas Test Method KT-15, Procedure III (8). Two cores from each site were heated, broken apart and tested for theoretical maximum specific gravity (Gmm) in accordance with KT-39 (8). The Gmm was used to determine the voids total mix using AASHTO T 269. The average density and VTM for the cores obtained in the wheel path and between the wheel path are shown in Table 4. Typically, VTMs in the wheel paths would be in the 3-5% range after several years of traffic due to further densification. The VTMs are within expected ranges for low volume pavements, 4-7%, as low volume pavements have been shown to densify only slightly with traffic (9).

After Gmm determination the asphalt content was determined using KT-57 (8). The gradation of the aggregate remaining after the ignition test was determined using KT-57 (8) as well. The results are shown in Table 5 and the gradations in Figures 1 and 2. Four of the sites, sites 42, 43, 46 and 48 were 12.5 mm nominal mixes. All mixes met the requirements for a Superpave 12.5-mm nominal mix except site 43 which was slightly finer, 0.8%, than the specification limit on the 2.36-mm sieve. Site 47 was a 9.5-mm nominal size mix. Site 47 met the requirements for a Superpave 9.5-mm mix on every sieve except the 12.5-mm sieve

Table 4. Wheel Path Density and VTM.

Site	Project #	Mix	Density (kg/m^3)		VTM	
			WP	IWP	WP	IWP
42	96-41 K-6198-01	BM-1B	2326	2273	5.5	7.7
43	73-3 K-6074-01	BM-2A	2311	2259	4.5	6.7
46	96-51 K-6198-01	BM-2A	2287	2271	6.2	6.9
47	73-3 K-6074-01	BM-1	2267	2233	7.1	8.4
48	156-5 K-5749-01	N/A	2364	2324	4.5	6.1

N/A = Mix information not available.
WP = In wheel path.
IWP = In between wheel paths.

Table 5. Gradations and Asphalt Content of Core Samples.

Sieve Size (mm)	Site 42	Site 43	Site 46	Site 47	Site 48	Superpave 12.5 mm Spec.	Superpave 9.5-mm Spec.
	Percent Retained						
19.0	0.0	0.0	0.0	0.0	0.0	0	
12.5	4.5	3.3	4.1	0.4	6.6	0-10	0
9.5	12.8	10.8	11.9	6.3	15.8	>10	0-10
4.75	40.3	25.8	31.5	31.3	40.6		>10
2.36	57.3	41.2	44.5	45.9	57.9	42-72	33-68
1.18	67.5	57.4	56.5	55.8	71.3		
0.600	75.9	70.0	69.6	64.5	78.7		
0.300	86.9	83.0	84.1	80.2	85.1		
0.150	91.2	91.5	90.8	88.5	90.3		
0.075	92.8	94.4	92.9	90.4	92.6	90-98	90-98
AC (%)	5.4	5.55	5.55	5.9	4.9		

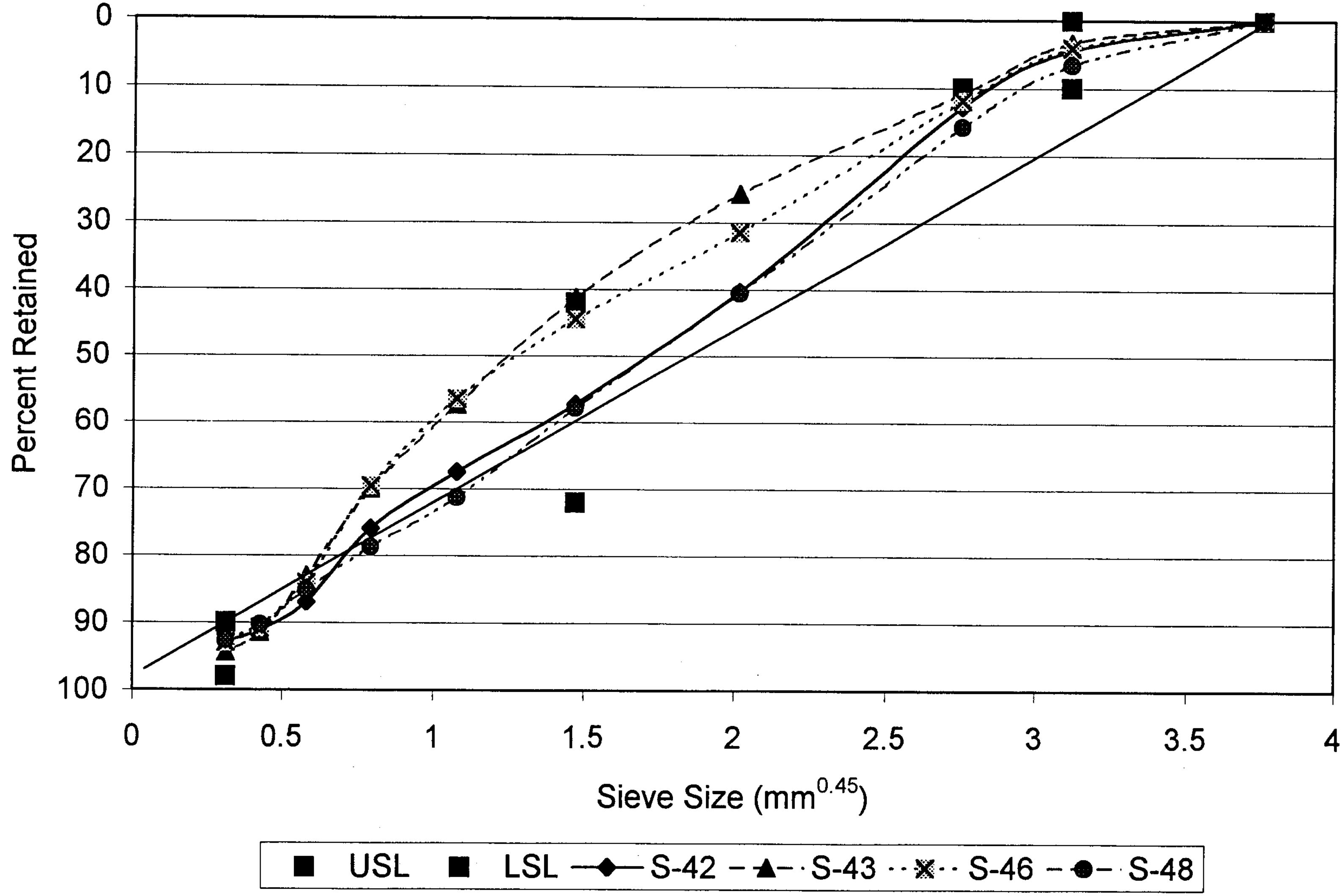

Figure 1. Gradations of 12.5 mm Mixes From Cores.

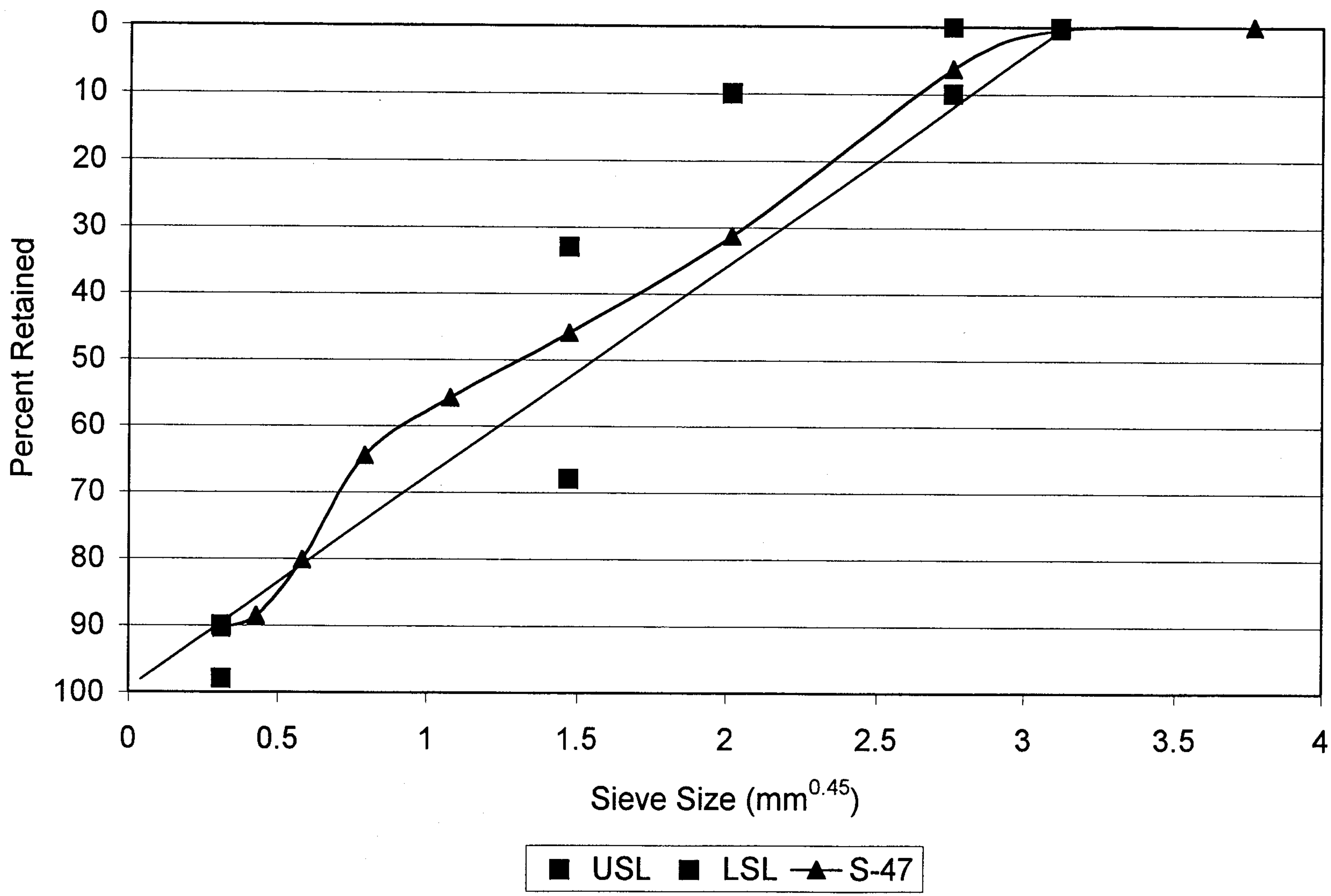

Figure 2. Gradation of 9.5 mm Mix From Site 47.

with 0.4% retained when the specification required 0% retained. The mixes are KDOT mixes and were not designed to be Superpave mixes.

COMPACTION

The remaining surface layer cores were heated, broken apart and combined by site. The mix was then brought up to compaction temperature (135°C) and compacted in the SGC. The recommended cure time between mixing and compaction was not used. Duplicate samples of the mix were compacted in the SGC using two different ram pressures. The first ram pressure was 600 kPa as specified. A second ram pressure of 400 kPa was used to see if a reduced ram pressure would give a more reasonable density for low volume mixes, closer to the field density, than the standard pressure. The results of the percent Gmm versus gyrations for the sites are shown in Table 6.

Table 7 shows the number of gyrations required to reach the average wheel path density for each site. This was performed by converting the VTMs to %Gmm by subtracting the VTM from 100 and comparing to the %Gmm versus gyrations shown in Table 6. In all instances the number of gyrations required to reach the field density is well below the N_{design} number of gyrations. This is expected as the mixes did not densify to 4% VTM (96% Gmm) in the field and both Superpave and Marshall mixes are designed at 4% VTM.

A more meaningful analysis is to compare the number of gyrations required to reach the design VTM of 4%. Brown et al. (5) have shown that reheated cores densify more than virgin mix, approximately 1%. Therefore, the number of gyrations required to reach 97% Gmm for recompacted mix would be equivalent to 96% Gmm for virgin mix. The number of gyrations required to reach both 96% and 97% Gmm at 600 and 400 kPa ram pressure are shown in Table 8.

The original N_{design} number of gyrations was 76 for all sites except site 48, which was 86 gyrations. The proposed revised N_{design} number of gyrations is 75 for all of the mixes. At 600 kPa ram pressure the number of gyrations to reach 97% Gmm is less than both the original and revised N_{design} number of gyrations. The number of gyrations to reach 97% Gmm ranged from 53 to 67 gyrations with an average of 59.4 gyrations. Reducing the SGC ram

Table 6. Results of Percent Gmm vs. Number of Gyrations for Core Samples.

Number Gyrations	Site 42		Site 43		Site 46		Site 47	Site 48	
	600 kPa	400 kPa	600 kPa	400 kPa	600 kPa	400 kPa	600 kPa	600 kPa	400 kPa
	Gmm (%)								
1	82.8	80.7	86.8	86.3	86.6	85.7	85.2	84.0	82.8
5	88.0	85.8	90.9	90.2	90.7	89.7	89.7	89.0	87.1
10	90.7	88.6	92.9	92.2	92.7	91.7	92.1	91.7	89.7
15	92.5	90.3	94.0	93.4	93.8	92.9	93.4	93.3	91.1
20	93.4	91.4	94.8	94.1	94.5	93.7	94.3	94.3	92.2
30	94.9	93.0	95.7	95.2	95.6	94.7	95.6	95.7	93.6
40	95.8	94.0	96.4	95.9	96.2	95.4	96.4	96.6	94.6
50	96.4	94.8	96.9	96.3	96.6	95.9	96.9	97.2	95.3
60	96.9	95.4	97.3	96.7	97.1	96.3	97.3	97.6	95.8
70	97.2	95.8	97.6	97.1	97.3	96.6	97.6	97.9	96.2
80	97.5	96.2	97.8	97.3	97.6	96.9	97.8	98.2	96.6
90	97.7	96.5	98.0	97.5	97.8	97.1	97.9	98.4	96.9
100	97.9	96.7	98.2	97.7	97.9	97.2	98.1	98.5	97.1
114	97.9	97.1	98.2	97.9	98.0	97.5	98.1	98.6	97.5

Table 7. Number of Gyrations to Wheel Path Density.

Site	Ram Pressure 600 kPa	400 kPa
42	27	46
43	28	35
46	17	20
47	13	N/T
48	29	56

N/T = Not tested, insufficient material.

Table 8. Number of Gyrations to Design %Gmm for Core Samples.

	600 kPa		400 kPa		Ndesign	
%Gmm	97	96	97	96	Original	Revised
Site 42	67	49	100	75	76	75
Site 43	56	37	69	46	76	75
Site 46	63	42	82	55	76	75
Site 47	59	41	N/T	N/T	76	75
Site 48	53	39	91	67	86	75
Average	59.4	41.6	85.4	60.9		

N/T = Not tested, insufficient material.

pressure from 600 kPa to 400 kPa is approximately equivalent to reducing N_{design} 25 gyrations at 600 kPa. Based on recompacted material from cores, the revised SGC compactive effort is still greater than 50-blow Marshall compaction.

CHAPTER 4
EVALUATION OF FIELD MIX

LOCATION

Field mix from three maintenance overlay projects were provided by KDOT for compaction in the SGC. Table 3 showed the project information provided by KDOT for each site. The daily ESALs and estimated 20 year design ESALs, assuming no growth, are shown as well. Based on the estimated design ESALs, all three sites fell into traffic level I, < 0.3 million ESALs, for both the original and revised Superpave traffic levels. The original and revised N_{design} number of gyrations for the three sites are 76 and 50 gyrations, respectively.

PRELIMINARY TESTING

Two 2,000 g samples were tested for theoretical maximum specific gravity (Gmm) in accordance with KT-39 (8). The Gmm was used to determine the voids total mix using AASHTO T 269. After Gmm determination the asphalt content and gradation of the recovered aggregate were determined using KT-57 (8). The results are shown in Table 9 and Figure 3. All three mixes met the requirements for a Superpave 12.5-mm nominal mix. The mixes are KDOT mixes and were not designed to be Superpave mixes.

KDOT supplied the Marshall mix designs for the three mixes. The mix properties at the design asphalt content are shown in Table 10 and the gradations in Table 11. The three field mixes were all KDOT BM-2A, 12.5 mm nominal aggregate size mixes. The mixes from K-4 and K-116 were not designed to give 4% VTM at optimum asphalt content, as is the case now. The mix design parameters at an asphalt content giving 4% VTM were estimated from the original mix designs and are shown in Table 10 as well.

COMPACTION

The field mix was heated to the compaction temperature (135°C) and compacted in the SGC. The recommended cure time between mixing and compaction was not used. Duplicate samples of the mix were compacted in the SGC using two different ram pressures. The first

Table 9. Gradations of Field Mix Samples.

Sieve Size (mm)	K-4	K-20	K-116	Superpave 12.5 mm Spec.
	Percent Retained			
19.0	0	0	0	0
12.5	6.2	9.7	6.7	0-10
9.5	18.0	17.8	13.9	>10
4.75	40.4	34.9	31.6	
2.36	51.6	46.2	48.8	42-72
1.18	60.5	55.0	64.6	
0.600	71.0	65.9	75.4	
0.300	89.0	87.3	88.7	
0.150	94.7	94.3	92.7	
0.075	95.9	95.1	93.6	90-98
AC (%)	5.4	6.0	5.0	

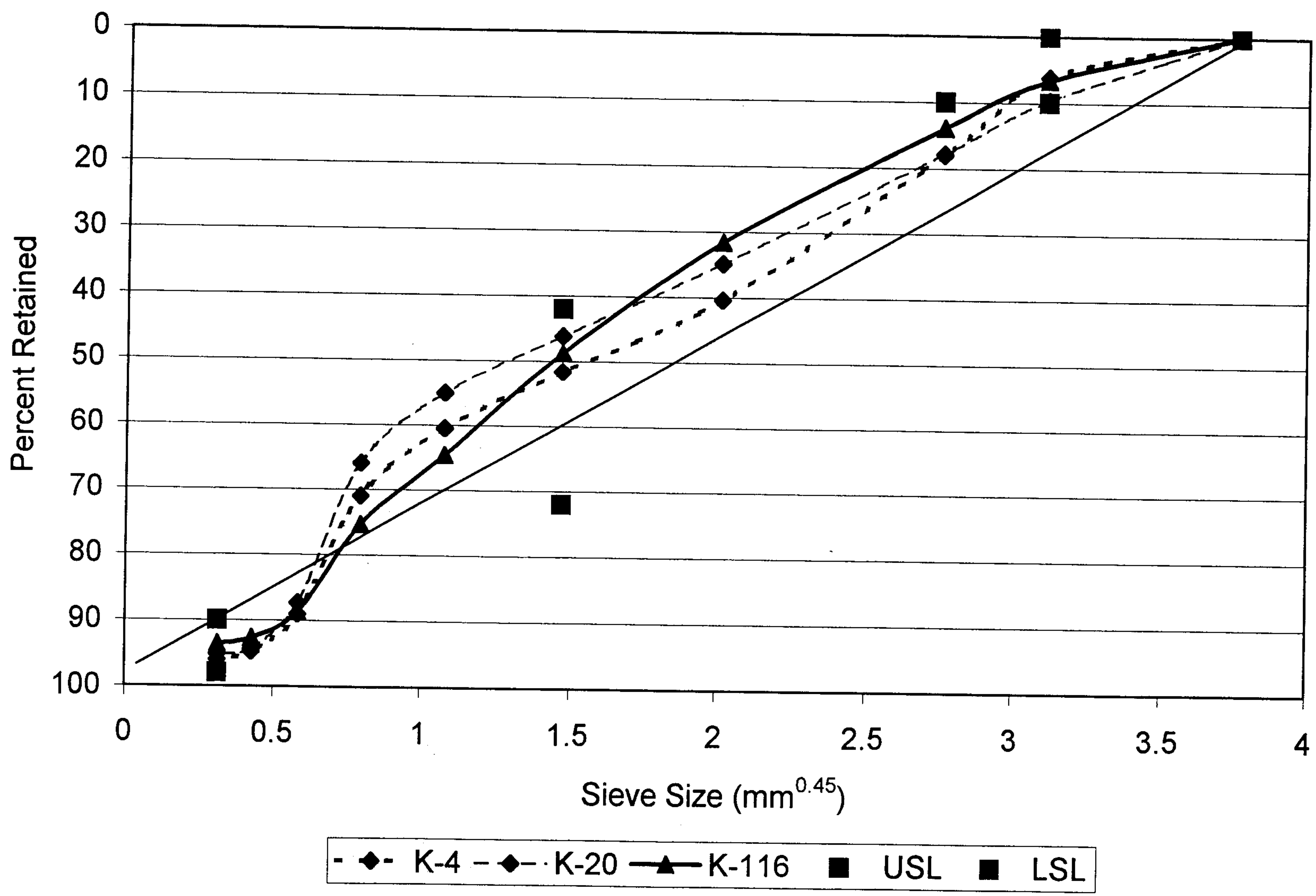

Figure 3. Gradation of Field Mix Samples.

Table 10. Marshall Mix Design Results.

Mix Parameter	K-4 Original	K-4 Adjusted	K-20 Original	K-116 Original	K-116 Adjusted	US-281* Original
Mix	BM-2A	BM-2A	BM-2A	BM-2A	BM-2A	BM-2
Blows	50	50	50	50	50	50
AC Grade	AC-10	AC-10	AC-10	AC-10	AC-10	AC-20
%AC	5.75	6.0	5.5	5.0	5.4	5.0
VTM (%)	5.70	4.00	4.03	5.29	4.00	4.36
VMA (%)	14.36	14.10	14.41	13.86	14.00	14.73
VFA (%)	60.1	71.6	72.1	61.8	71.4	70.4
Dust / AC Ratio	1.13	1.00	1.09	1.20	1.05	1.00
Film Thickness	5.40	6.21	6.68	5.93	6.96	8.07
Sand Equivalent	79	79	59	65	65	N/A
Coarse Aggregate % Crushed	100	100	100	100	100	77.6
% Natural Sand	35	35	35	25	25	50
% Natural Sand in Fine Aggregate	51.8	51.8	51.5	40.2	40.2	68.6

* Field mix not available.
N/A = Not available.

Table 11. Mix Design Gradations.

Sieve Size (mm)	K-4	K-20	K-116	US-281*
	Percent Retained			
19	0	0	0	0
12.5	5	7	7	8
9.5	16	15	14	22
4.75	33	32	31	40
2.36	44	44	48	49
1.18	54	52	62	61
0.600	67	65	72	73
0.300	86	86	88	88
0.150	91	92	92	94
0.075	93.5	94.0	94.0	95.0

* Field mix not available.

ram pressure was 600 kPa as specified. A second ram pressure of 400 kPa was used to evaluate the effects of reduced ram pressure on N_{design} for low volume mixes.

The results of the %Gmm versus gyrations for the field mix from the three sites are shown in Table 11. Table 12 shows the number of gyrations required to reach 96% Gmm and the void properties of VMA and VFA at 96% Gmm (4% VTM). Superpave specifications for these mixes require a minimum VMA of 14% and VFA between 70% and 80%.

K-20 and K-116 reached 96% Gmm at 48 and 41 gyrations, respectively, at 600 kPa ram pressure. This is slightly less than the revised N_{design} number of gyrations of 50. Both the VMA and VFA were within the specification limits, indicating that these mixes could be converted to Superpave mixes for the lowest traffic level, < 0.3 million ESALs. Reducing the SGC ram pressure from 600 kPa to 400 kPa is approximately equivalent to reducing N_{design} 20 gyrations at 600 kPa.

K-4 appears to be deficient in asphalt cement, requiring 102 gyrations to reach 96% Gmm. Table 10 shows that K-4 was designed at 5.7% VTM, not 4% VTM. It was estimated from the Marshall mix design provided that an additional 0.25% asphalt cement would be required to obtain 4% VTM. The VMA and VFA were below the Superpave requirements, indicating that it might be difficult to convert this mix to a Superpave mix.

The original N_{design} number of gyrations was 68 for all three sites. The proposed revised N_{design} number of gyrations is 50 for all of the mixes. These Marshall mixes could also be placed on slightly higher traffic level pavements, thus, the mixes were evaluated at 75 gyrations, the N_{design} value for the next higher traffic level, as well. The results are shown in Table 14.

At 50 gyrations for N_{design}, and using a 600 kPa ram pressure, K-20 and K-116 had slightly too much asphalt, as indicated by a percent Gmm of greater than 96%. The VMAs and VFAs were within the specification requirements. K-4 appears to be deficient in asphalt as indicated by a percent Gmm of less than 96% and a VFA of less than 70%. K-4 had adequate VMA. At 75 gyrations, traffic of 0.3 to three million ESALs, none of the three mixes

Table 12. Summary of Field Mix Properties vs. Number of Gyrations.

Number	K-4 Field Mix				K-20 Field Mix				K-116 Field Mix			
Gyrations	%Gmm	% VTM	% VMA	% VFA	%Gmm	% VTM	% VMA	% VFA	%Gmm	% VTM	% VMA	% VFA
1	84.7	15.3	23.2	34.1	87.0	13.0	22.8	43.0	84.8	15.2	25.4	40.0
5	88.4	11.6	19.9	41.7	90.6	9.4	19.6	52.0	89.4	10.6	21.3	50.1
7	89.3	10.7	19.1	44.0	91.5	8.5	18.8	54.8	90.3	9.7	20.5	52.7
10	90.3	9.7	18.2	46.7	92.4	7.6	18.0	57.8	91.8	8.2	19.2	57.2
20	92.0	8.0	16.5	51.5	94.2	5.8	16.4	64.6	94.1	5.9	17.2	65.6
30	93.1	6.9	15.6	55.8	95.2	4.8	15.6	69.2	95.3	4.7	16.1	70.8
40	93.8	6.2	14.9	58.4	95.8	4.2	15.0	72.0	96.2	3.8	15.4	75.0
50	94.3	5.7	14.5	60.7	96.2	3.8	14.6	74.0	96.8	3.2	14.8	78.4
60	94.8	5.2	14.1	63.1	96.6	3.4	14.3	76.2	97.2	2.8	14.4	80.6
70	95.1	4.9	13.7	64.2	96.8	3.2	14.1	77.3	97.6	2.4	14.1	82.9
75	95.3	4.7	13.6	65.4	97.0	3.0	13.9	78.4	97.8	2.2	13.9	84.1
80	95.4	4.6	13.5	65.9	97.1	2.9	13.8	79.0	97.9	2.1	13.8	84.8
90	95.6	4.4	13.3	66.9	97.3	2.7	13.6	80.1	98.2	1.8	13.6	86.7
100	95.9	4.1	13.1	68.7	97.4	2.6	13.6	80.9	98.4	1.6	13.4	88.0
117	96.2	3.8	12.8	70.3	97.7	2.3	13.3	82.7	98.7	1.3	13.1	90.2

Table 13. Number of Gyrations to 96% Gmm.

Site	N=96% Gmm 600 kPa	400 kPa	VMA (%)	VFA (%)
K-4	102	158*	13.1	69.5
K-20	48	65	14.7	72.8
K-116	41	62	15.5	74.2

* Estimated.

Table 14. Summary of Mix Properties from Field Mix Samples.

	% Gmm		VMA (%)		VFA (%)		% Gmm
Ndesign	50	75	50	75	50	75	@ Nini
			600 kPa				
K-4	94.3	95.3	14.5	13.6	60.7	65.4	89.3
K-20	96.2	97.0	14.6	13.9	74.0	78.4	91.5
K-116	96.8	97.8	14.8	13.9	78.4	84.1	90.3
			400 kPa				
K-4	93.3	94.1	15.4	14.7	56.5	59.9	88.2
K-20	95.6	96.3	15.2	14.5	71.0	74.6	90.8
K-116	95.6	96.6	15.9	15.0	72.3	77.3	89.2

had adequate VMA. Only K-4 had adequate VFA, however, it appeared to be slightly deficient in asphalt with a percent Gmm of 95.3%. All three mixes met the requirements for $N_{initial}$ for 0.3 to three million ESALs, except K-20. All mixes met the $N_{initial}$ requirement for < 0.3 million ESALs.

The effect of reducing the ram pressure from 600 kPa to 400 kPa was evaluated as well. The results are shown in Table 14. Reducing the ram pressure from 600 kPa to 400 kPa at 75 gyrations is approximately equal to reducing the number of gyrations from 75 to 50 at 600 kPa.

CHAPTER 5
SUPERPAVE MIX DESIGNS
and
PERFORMANCE TESTING

MATERIALS

The aggregates and asphalt cement from K-4, K-20 and K-116 were provided by KDOT for use in performing Superpave mix designs. Aggregates and asphalt cement were available from a forth site, US-281, from a previous K-TRAN project, which was included as well. The material designation and gradation of the aggregates, and percent of each used for the mix designs are shown in Tables 15-18 for each of the four sites.

MIX DESIGNS

Compaction

To perform the mix design, 4,500 g of aggregate were batched to the desired gradation. The mixes were batched to match more closely the gradations of the field mix and cores, and not necessarily the Marshall mix design gradations. The gradations of the mixes were shown in Table 9. The mix design was performed in general accordance with AASHTO TP4. A two-hour cure time at 135°C between mixing and compaction was used rather than the recommended four-hour cure. The three K routes were all traffic level I mixes according to the revised specification, requiring 50 gyrations for N_{design}. US-281 has a 20-year traffic of greater than 0.3 million ESALs and requires 75 design gyrations. All mixes were compacted to 117 gyrations and the void properties determined at 50 and 75 gyrations. To evaluate the effects of a reduced ram pressure for low volume roads, the samples were compacted at 400 kPa as well as 600 kPa. The results are presented in the Appendix in Tables A1-A7.

As shown in the tables in the Appendix, complete mix designs were not performed, samples were compacted to try and bracket 4% VTM. If it became obvious that it would not be possible to make a Superpave mix with the given aggregate blend by adjusting the asphalt

Table 15. Gradation of Individual Aggregates for K-4.

Material	CS-1	CS-2	SSG	Blend
Percent in Blend	25	40	35	100
Sieve Size (mm)	Percent Retained			
19	0			0.0
12.5	20			5.0
9.5	62	0		15.5
4.75	93	23	0	32.5
2.36	94	48	4	44.1
1.18	95	63	15	54.2
0.600	95	72	40	66.6
0.300	95	78	87	85.4
0.150	95	82	99	91.2
0.075	96	86	100	93.4

Table 16. Gradation of Individual Aggregates for K-20.

Material	CS-1	CS-2	SSG	Blend
Percent in Blend	20	45	35	100
Sieve Size (mm)	Percent Retained			
19	0			0.0
12.5	36			7.2
9.5	76	0		15.2
4.75	97	28	0	32.0
2.36	98	53	1	43.8
1.18	98	69	5	52.4
0.600	98	77	30	64.8
0.300	98	82	85	86.3
0.150	98	86	97	92.3
0.075	98	88	99	93.9

Table 17. Gradation of Individual Aggregates for K-116.

Material	CS-1	CS-2	M'Sand	SSG	Blend
Percent in Blend	18	42	15	25	100
Sieve Size (mm)	Percent Retained				
19	0				0.0
12.5	38	0			6.8
9.5	73	2	0		14.0
4.75	93	33	1	0	30.8
2.36	95	55	42	5	47.8
1.18	95	68	82	16	62.0
0.600	96	75	94	38	72.4
0.300	96	80	96	90	87.8
0.150	96	85	96	99	92.1
0.075	97	87	97	100	93.6

Table 18. Gradation of Individual Aggregates for US-281.

Material	SSG-1	CS-1	CS-2A	CS-2	Blend
Percent in Blend	48	25	18	9	100
Sieve Size (mm)	Percent Retained				
19	0	0			0.0
12.5	3	25	0		7.7
9.5	8	60	8		20.3
4.75	18	90	40	0	38.3
2.36	25	97	61	2	47.4
1.18	43	98	72	21	60.0
0.600	63	98	78	40	72.4
0.300	89	98	83	55	87.1
0.150	99	98	86	63	93.2
0.075	99	98	89	70	94.3

content, testing was terminated and it was assumed a new blend of the aggregate would be required.

Mixture Analysis

The four mixtures were analyzed to determine the optimum asphalt content and the mix properties of %Gmm at $N_{initial}$, VMA and VFA at the optimum asphalt content. The mixes were analyzed using the 600 kPa ram pressure with N_{design} of 50 and 75 gyrations and at 400 kPa ram pressure at 75 gyrations. The results are shown in Table 19 and presented graphically in Figures A1-A16 in the Appendix. The data from KDOT's Marshall mix designs are shown on the plots as well.

As shown in Table 19, three of the four Marshall mix designs met the Superpave mix requirements of VTM, VMA and VFA. K-116 had a VMA of 13.9%, less than the required 14.0% minimum. None of the SGC compacted mixes had sufficient VMA. K-4 met all the other mix requirements at all three compaction levels. K-20 met the VFA requirement but failed the %Gmm at $N_{initial}$ requirement. Both K-116 and US-281 passed all other requirements for a level II mix but failed VFA for a level I mix.

The effects of the different compaction energies on the mix properties of optimum asphalt content and VMA are shown in Table 20. Changing from 50-blow Marshall compaction to the original level I requirements or the revised level II requirements resulted in a 0.5% to a 0.95% reduction in asphalt with an average reduction of 0.8%. VMA was reduced from between 1.2% and 3.0% with an average reduction of 1.9%.

Three of the four mixes fall under the new mix requirements for traffic level I. Comparing the new level I requirements (50 gyrations) to Marshall mixes resulted in a reduction of 0.4% to 0.65% in optimum asphalt content with an average reduction of 0.5%. VMA was reduced from between 0.7% and 2.5% with an average reduction of 1.2%. There were no strong relationships between these percent reductions and mix properties such as fine aggregate angularity or percent natural sand in the mix. Reducing the ram pressure from 600 kPa to 400 kPa had the same effect on mix properties as reducing the number of gyrations from 75 to 50.

Table 19. Mix Design Volumetrics at Optimum Asphalt Content.

Compaction	SGC			50-Blow	AASHTO	
Ram Pressure	600 kPa	600 kPa	400 kPa	Marshall	Orig.	Revised
Ndes	75	50	75		Spec.	Spec.
			K-4			
Optimum AC (%)	5.25	5.6	5.5	6.0		
VMA (%)	12.6	13.5	13.2	14.2	14 min	14 min
VFA (%)	68.3	70.3	69.7	71.7	70-80	70-80
%Gmm @ Nini	90.4	91.0	90.7	N/A	< 89	< 91.5
			K-20			
Optimum AC (%)	4.7	4.8	N/T	5.2		
VMA (%)	13.2	13.6	N/T	14.4	14 min	14 min
VFA (%)	69.6	70.6	N/T	72.2	70-80	70-80
%Gmm @ Nini	90.8	91.6	N/T	N/A	< 89	< 91.5
			K-116			
Optimum AC (%)	4.5	4.8	4.8	5.35		
VMA (%)	12.2	13.0	13.0	13.9	14 min	14 min
VFA (%)	67.2	69.2	69.2	71.2	70-80	70-80
%Gmm @ Nini	88.8	90.1	89.2	N/A	< 89	< 91.5
			US-281			
Optimum AC (%)	4.0	4.3	4.0	4.95		
VMA (%)	11.9	12.4	12.8	14.9	14 min	14 min
VFA (%)	66.4	67.7	68.8	73.1	70-80	70-80
%Gmm @ Nini	89.6	90.9	89.6	N/A	< 89	< 90.5

N/T = Not tested, insufficient materials.
N/A = Not applicable.

Table 20. Effect of Compaction on Mix Parameters.

Site	Difference Between 50-Blow Marshall and 600 kPa 75 rev.	50-Blow Marshall and 600 kPa 50 rev.	600 kPa 75 rev. and 600 kPa 50 rev.	400 kPa 75 rev. and 600 kPa 50 rev.
	Optimum Asphalt (%)			
K-4	0.75	0.40	0.35	0.10
K-20	0.50	0.40	0.10	N/T
K-116	0.85	0.55	0.30	0.00
US-281	0.95	0.65	0.30	0.30
Average	0.76	0.50	0.26	0.13
	VMA (%)			
K-4	1.60	0.70	0.90	0.30
K-20	1.20	0.80	0.40	N/T
K-116	1.70	0.90	0.80	0.00
US-281	3.00	2.50	0.50	0.40
Average	1.88	1.23	0.65	0.23

N/T = Not tested, insufficient materials.

PERFORMANCE TESTING

To evaluate the effect of compaction methods and energy on performance, the mixes were evaluated for rutting potential using the Asphalt Pavement Analyzer (APA). Field mix samples from the three K routes were compacted to 7±1% VTM using the SGC at 400 kPa and 600 kPa ram pressure. Mix design samples were compacted to 7±1% VTM using the SGC at 400 kPa and 600 kPa ram pressure. The samples were compacted at the optimum asphalt contents determined using 75 gyrations at 600 kPa ram pressure and 75 gyrations at 400 kPa ram pressure. The mix design samples underwent a two-hour oven aging at 135°C prior to compaction. The field mix samples were heated to the compaction temperature and immediately compacted.

Duplicate samples were tested in the APA in the dry mode in general accordance with Georgia Department of Transportation Test Method GDT 115 Method A (10). The samples were tested at 40°C using a 0.44 kN loaded wheel traveling across a 690 kPa pressurized hose. The samples were tested to 8,000 load cycles and the average maximum rut depths are reported in Table 21.

Figure 4 shows the results for the field mix samples compacted using 400 kPa and 600 kPa ram pressure. There is little difference in rut depth, as would be expected. The samples are compacted to the same density, and the reduced ram pressure simply requires more compaction gyrations to reach this level. Based on the field mix samples, all mixes appear to be stable.

Figure 5 shows the results of the APA testing on the mix design samples using 75 gyrations at 400 kPa and 600 kPa. The asphalt contents ranged from zero to 0.3% lower for the 600 kPa designs. The lower asphalt content resulted in slightly less rutting, as expected. Site K-20 was unstable with rut depths over 6-mm and K-4 was marginal with rut depths at 6-mm. K-116 and US-281 appear to be stable mixtures. Figure 6 compares the field mix samples to the mix design samples. The field mix samples had less rutting than the mix design samples. Generally speaking, mixes with more asphalt cement rut more. However, the asphalt contents of the mix design samples were approximately 0.5% less than the Marshall designed field mix samples. The increased rutting is probably a function of the aging of the asphalt cement. The two-hour oven cure at 135°C did not result in the same aging as the field mix samples received in the field.

Table 21. Maximum Dry Rut Depths from APA Testing.

Mix Type	Ram Pressure	Ndesign Rev.	K-4	K-20	K-116	US-281
			Maximum Rut Depth (mm)			
Field	400 kPa	N/A	4.9	6.9	2.8	N/T
Field	600 kPa	N/A	4.9	5.0	2.3	N/T
Mix Design	400 kPa	75	6.5	9.1	3.5	3.5
Mix Design	600 kPa	75	6.1	6.7	3.2	3.1

N/T = Not tested, material not available.

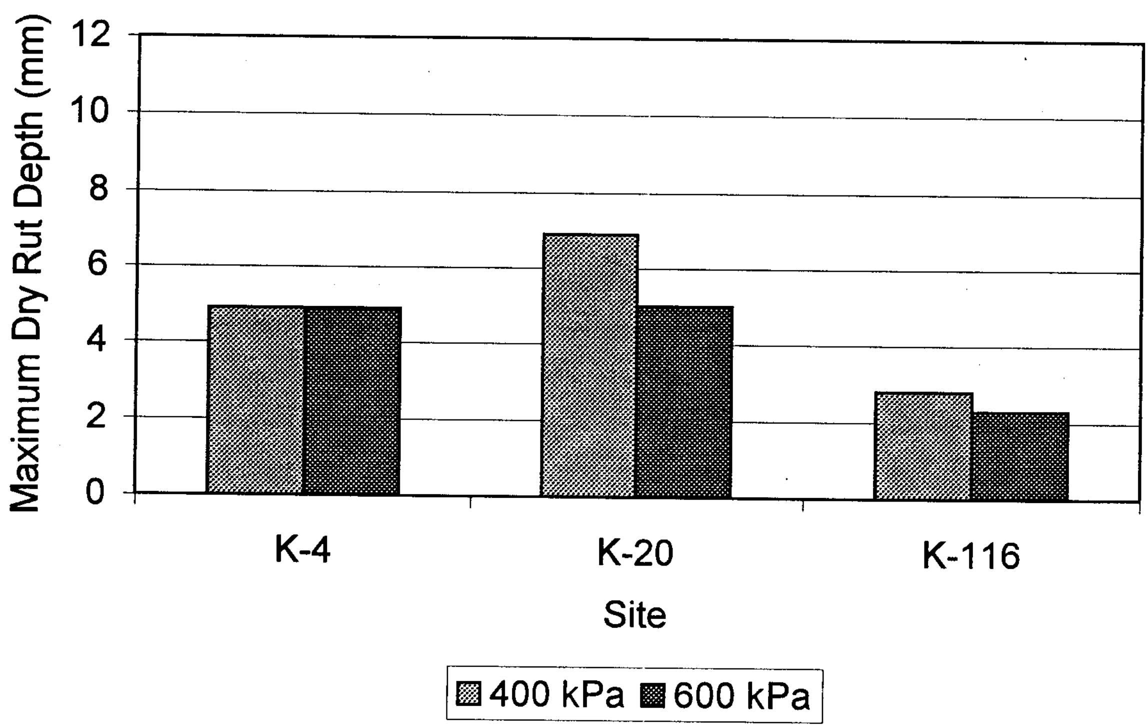

Figure 4. Results of APA Dry Rut Test on Field Mix.

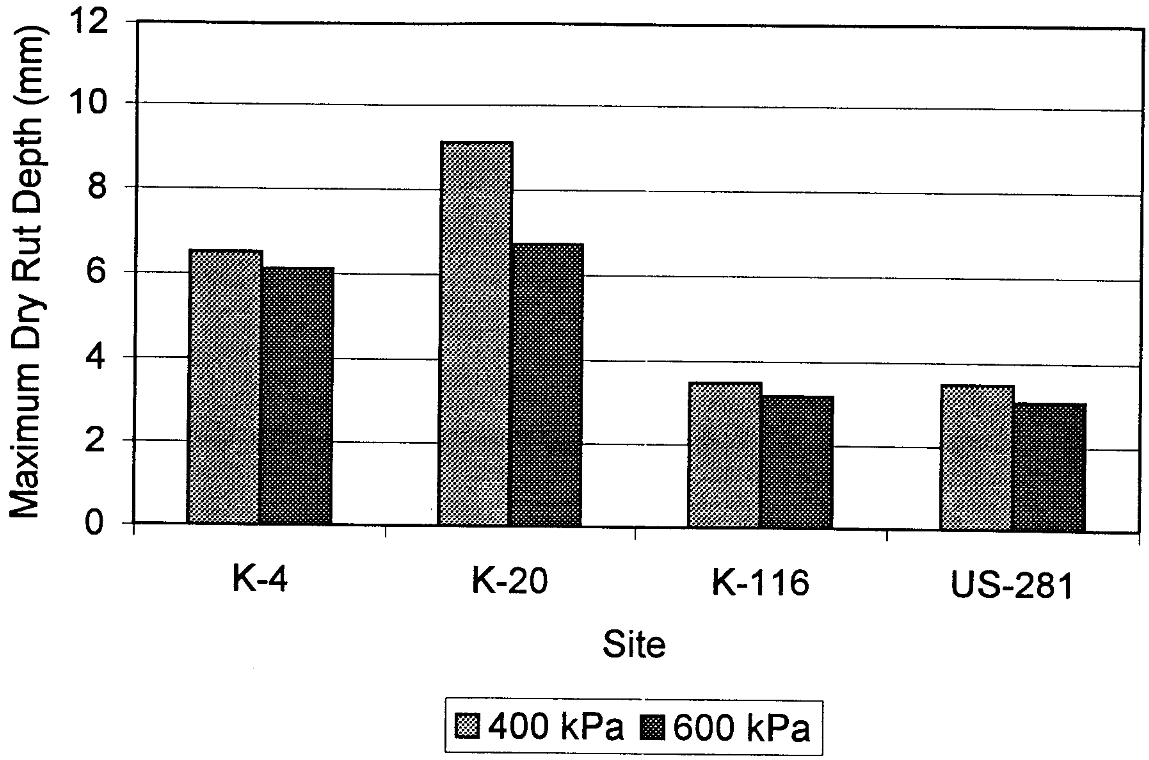

Figure 5. Results of APA Dry Rut Test on Mix Design Samples.

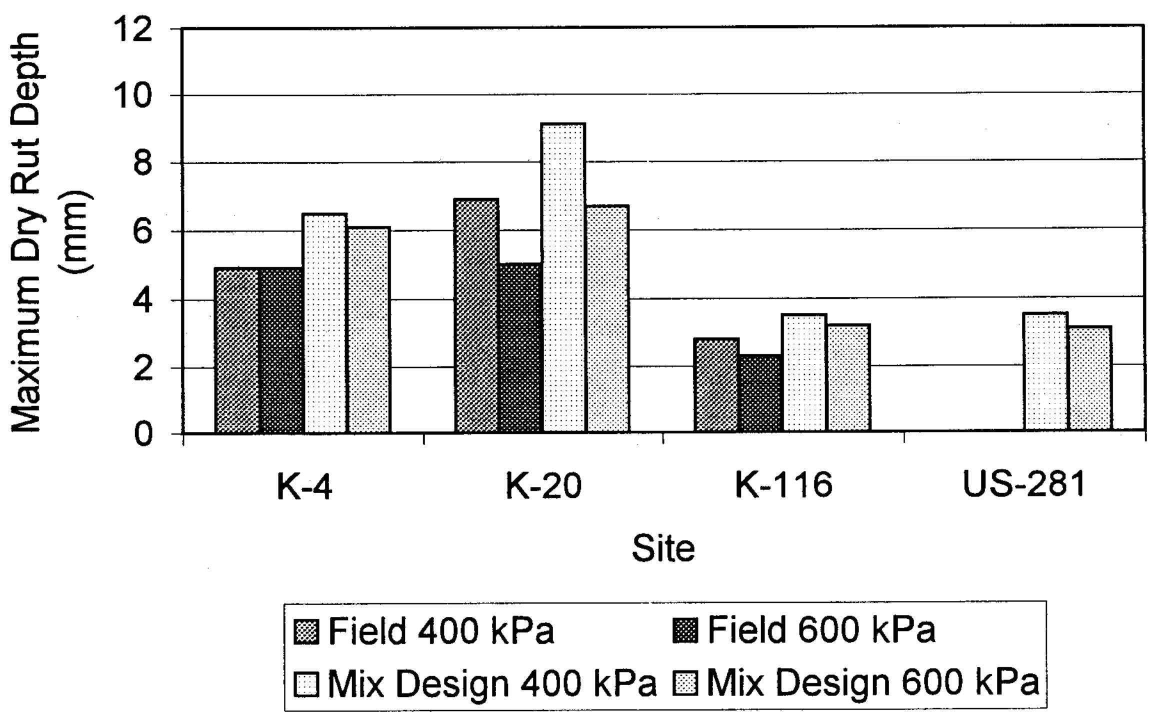

Figure 6. Comparison of Field and Mix Design APA Dry Rut Depths.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Based on the mixes and materials evaluated, the following conclusions are warranted:

1. The SGC compactive efforts evaluated are higher than 50-blow Marshall compaction.
2. It was not possible to easily convert the Marshall mixes to Superpave mixes, regardless of the SGC compactive effort used.
3. The use of the SGC resulted in an average reduction in VMA of 1.2% to 1.9%, when compared to 50-blow Marshall compaction.
4. The use of the SGC resulted in an average reduction in optimum asphalt content of 0.5% to 0.8%, when compared to 50-blow Marshall compaction.
5. Reducing the ram pressure from 600 kPa to 400 kPa had the same effect on mix properties as reducing the gyrations at 600 kPa from 75 to 50.
6. A two-hour oven cure at 135°C did not produce the same amount of aging as field mix samples.

RECOMMENDATIONS

Based on the mixes and materials evaluated, the following conclusions are warranted:

1. Adopt the revised Superpave mix requirements and traffic levels. The reduced SGC compactive effort at the lowest traffic level is closer to 50-blow Marshall compaction and increases the probability that satisfactory mixes can be made with local aggregates.
2. The major problem meeting the Superpave mix requirements is meeting the minimum VMA requirement. The effect of reducing the minimum VMA requirement on durability of bituminous mixes should be evaluated. It may be possible to reduce the VMA requirement 1/2% to 1% without sacrificing the performance of low volume pavements. This could reduce the need to import sweeteners to enhance VMA.

3. The use of the APA to evaluate the stability of Superpave mixtures should be investigated for use as a proof test during mix design.

IMPLEMENTATION

AASHTO's revised Superpave mix requirements should be implemented through the Bureau of Materials and Research. The suitability of using the APA as a proof test during mix design should be evaluated. There is no test currently available to evaluate the stability or durability of mixes being designed and placed. The K-TRAN research program would be a logical mechanism to implement the study. Finally, the major problem that will be encountered in Superpave mix design will be meeting the minimum VMA requirement. Contractors will evaluate the use of sweeteners to artificially enhance VMA. Guidelines are needed to evaluate the effects of aggregate angularity on VMA and mixture performance. Again, the existing K-TRAN program would be a logical mechanism to implement the study.

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Table A-1. Results of Mix Design at 600 kPa Ram Pressure, K-4.

Number	5.35% AC				5.75% AC			
Gyrations	%Gmm	% VTM	% VMA	% VFA	%Gmm	% VTM	% VMA	% VFA
1	86.2	13.8	21.8	36.7	86.9	13.1	21.9	40.2
5	89.8	10.2	18.6	45.2	90.7	9.3	18.5	49.7
7	90.6	9.4	17.8	47.2	91.5	8.5	17.8	52.2
10	91.5	8.5	17.0	50.0	92.4	7.6	17.0	55.3
20	93.3	6.7	15.4	56.5	94.2	5.8	15.4	62.3
30	94.3	5.7	14.5	60.7	95.2	4.8	14.5	66.9
40	95.0	5.0	13.8	63.8	95.8	4.2	13.9	69.8
50	95.5	4.5	13.4	66.4	96.3	3.7	13.5	72.6
60	95.8	4.2	13.1	67.9	96.7	3.3	13.1	74.8
70	96.2	3.8	12.7	70.1	97.0	3.0	12.9	76.7
75	96.3	3.7	12.6	70.6	97.2	2.8	12.7	78.0
80	96.5	3.5	12.5	72.0	97.3	2.7	12.6	78.6
90	96.7	3.3	12.3	73.2	97.4	2.6	12.5	79.2
100	96.9	3.1	12.1	74.4	97.6	2.4	12.3	80.5
117	97.2	2.8	11.9	76.5	97.9	2.1	12.0	82.5

Table A-2. Results of Mix Design at 400 kPa Ram Pressure, K-4.

Number	5.42% AC				5.58% AC				5.82% AC			
Gyrations	%Gmm	% VTM	% VMA	% VFA	%Gmm	% VTM	% VMA	% VFA	%Gmm	% VTM	% VMA	% VFA
1	85.8	14.2	22.3	36.3	86.5	13.5	22.0	38.6	86.8	13.2	22.1	40.3
5	89.4	10.6	19.0	44.2	90.2	9.8	18.6	47.3	90.5	9.5	18.9	49.7
7	90.2	9.8	18.3	46.4	91.0	9.0	17.9	49.7	91.3	8.7	18.1	51.9
10	91.1	8.9	17.5	49.1	92.0	8.0	17.0	52.9	92.3	7.7	17.2	55.2
20	92.8	7.2	16.0	55.0	93.7	6.3	15.4	59.1	94.1	5.9	15.6	62.2
30	93.7	6.3	15.1	58.3	94.6	5.4	14.6	63.0	95.0	5.0	14.8	66.2
40	94.4	5.6	14.5	61.4	95.2	4.8	14.1	66.0	95.6	4.4	14.2	69.0
50	94.8	5.2	14.1	63.1	95.7	4.3	13.6	68.4	96.1	3.9	13.8	71.7
60	95.2	4.8	13.8	65.2	96.1	3.9	13.3	70.7	96.5	3.5	13.5	74.1
70	95.5	4.5	13.5	66.7	96.4	3.6	13.1	72.5	96.7	3.3	13.2	75.0
75	95.6	4.4	13.5	67.4	96.5	3.5	13.0	73.1	96.8	3.2	13.1	75.6
80	95.7	4.3	13.3	67.7	96.6	3.4	12.8	73.4	96.9	3.1	13.1	76.3
90	95.9	4.1	13.1	68.7	96.8	3.2	12.6	74.6	97.1	2.9	13.0	77.7
100	96.1	3.9	12.9	69.8	97.0	3.0	12.5	76.0	97.3	2.7	12.8	78.9
117	96.4	3.6	12.6	71.4	97.2	2.8	12.3	77.2	97.6	2.4	12.5	80.8

Table A-3. Results of Mix Design at 600 kPa Ram Pressure, K-20.

Number	4.54% AC				4.90% AC			
Gyrations	%Gmm	% VTM	% VMA	% VFA	%Gmm	% VTM	% VMA	% VFA
1	85.9	14.1	21.9	35.6	88.0	12.1	21.2	43.0
5	89.3	10.7	18.8	43.1	91.4	8.6	18.1	52.4
7	90.1	9.9	18.1	45.3	92.3	7.8	17.3	55.1
10	90.9	9.1	17.3	47.4	93.3	6.7	16.4	59.0
20	92.6	7.4	15.8	53.2	94.7	5.3	15.1	64.6
30	93.6	6.4	15.0	57.3	95.6	4.5	14.3	68.9
40	94.1	5.9	14.5	59.3	96.1	3.9	13.9	71.8
50	94.6	5.4	14.0	61.4	96.6	3.5	13.5	74.3
60	94.9	5.1	13.8	63.0	96.9	3.2	13.2	76.1
70	95.2	4.8	13.5	64.4	97.2	2.8	12.9	77.9
75	95.4	4.6	13.3	65.4	97.3	2.7	12.8	78.9
80	95.4	4.6	13.3	65.4	97.4	2.6	12.7	79.5
90	95.6	4.4	13.1	66.4	97.6	2.5	12.6	80.5
100	95.8	4.2	12.9	67.4	97.7	2.3	12.5	81.5
117	96.0	4.0	12.7	68.5	98.0	2.1	12.2	83.2

Table A-4. Results of Mix Design at 600 kPa Ram Pressure, K-116

Number	4.56% AC				4.80% AC			
Gyrations	%Gmm	% VTM	% VMA	% VFA	%Gmm	% VTM	% VMA	% VFA
1	83.7	16.3	23.7	31.2	84.7	15.3	23.2	34.1
5	88.1	11.9	19.7	39.6	89.0	11.0	19.3	43.0
7	89.2	10.8	18.7	42.2	90.1	9.9	18.3	45.9
10	90.3	9.7	17.6	44.9	91.3	8.7	17.3	49.7
20	92.5	7.5	15.6	51.9	93.4	6.6	15.4	57.1
30	93.8	6.2	14.5	57.2	94.5	5.5	14.3	61.5
40	94.6	5.4	13.7	60.6	95.4	4.6	13.6	66.2
50	95.3	4.7	13.1	64.1	96.0	4.0	13.0	69.2
60	95.7	4.3	12.7	66.1	96.5	3.5	12.5	72.0
70	96.1	3.9	12.4	68.5	96.8	3.2	12.3	74.0
75	96.3	3.7	12.2	69.7	97.0	3.0	12.1	75.2
80	96.5	3.5	12.0	70.8	97.1	2.9	11.9	75.6
90	96.7	3.3	11.8	72.0	97.3	2.7	11.8	77.1
100	97.0	3.0	11.6	74.1	97.6	2.4	11.5	79.1
117	97.3	2.7	11.3	76.1	97.9	2.1	11.2	81.3

Table A-5. Results of Mix Design at 400 kPa Ram Pressure, K-116

Number	4.56% AC				4.76% AC				4.92% AC			
Gyrations	%Gmm	% VTM	% VMA	% VFA	%Gmm	% VTM	% VMA	% VFA	%Gmm	% VTM	% VMA	% VFA
1	81.7	18.3	25.5	28.2	83.5	16.5	24.2	31.8	84.6	15.4	23.5	34.5
5	86.1	13.9	21.5	35.3	87.9	12.1	20.2	40.1	89.0	11.0	19.5	43.6
7	87.2	12.8	20.5	37.6	88.9	11.1	19.3	42.5	90.1	9.9	18.6	46.8
10	88.3	11.7	19.4	39.7	90.1	9.9	18.3	45.9	91.2	8.8	17.5	49.7
20	90.6	9.4	17.4	46.0	92.2	7.8	16.3	52.1	93.4	6.6	15.6	57.7
30	91.8	8.2	16.3	49.7	93.4	6.6	15.2	56.6	94.6	5.4	14.5	62.8
40	92.6	7.4	15.5	52.3	94.2	5.8	14.6	60.3	95.4	4.6	13.8	66.7
50	93.2	6.8	15.1	55.0	94.8	5.2	14.0	62.9	96.0	4.0	13.3	69.9
60	93.7	6.3	14.6	56.8	95.3	4.7	13.6	65.4	96.4	3.6	12.8	71.9
70	94.0	6.0	14.2	57.7	95.6	4.4	13.2	66.7	96.8	3.2	12.5	74.4
75	94.1	5.9	14.2	58.5	95.8	4.2	13.1	67.9	97.0	3.0	12.3	75.6
80	94.3	5.7	14.0	59.3	95.9	4.1	13.0	68.5	97.1	2.9	12.2	76.2
90	94.6	5.4	13.7	60.6	96.2	3.8	12.7	70.1	97.4	2.6	12.0	78.3
100	94.8	5.2	13.6	61.8	96.5	3.5	12.5	72.0	97.6	2.4	11.8	79.7
117	95.1	4.9	13.2	62.9	96.8	3.2	12.2	73.8	98.0	2.0	11.4	82.5

Table A-6. Results of Mix Design at 600 kPa Ram Pressure, US-281.

Number	3.80% AC				4.24% AC				4.80% AC			
Gyrations	%Gmm	% VTM	% VMA	% VFA	%Gmm	% VTM	% VMA	% VFA	%Gmm	% VTM	% VMA	% VFA
1	83.6	16.4	22.7	27.8	85.4	14.6	22.0	33.6	87.5	12.5	21.2	41.0
5	87.7	12.3	18.9	34.9	89.5	10.5	18.2	42.3	91.7	8.3	17.4	52.3
7	88.7	11.3	18.1	37.6	90.6	9.4	17.3	45.7	92.7	7.3	16.4	55.5
10	89.7	10.3	17.1	39.8	91.6	8.4	16.3	48.5	93.8	6.2	15.5	60.0
20	91.7	8.3	15.3	45.8	93.5	6.5	14.5	55.2	95.9	4.1	13.6	69.9
30	92.8	7.2	14.3	49.7	94.6	5.4	13.6	60.3	96.9	3.1	12.7	75.6
40	93.5	6.5	13.6	52.2	95.3	4.7	12.9	63.6	97.6	2.4	12.1	80.2
50	94.1	5.9	13.0	54.6	95.8	4.2	12.5	66.4	98.0	2.0	11.7	82.9
60	94.6	5.4	12.6	57.1	96.3	3.7	12.0	69.2	98.3	1.7	11.5	85.2
70	94.9	5.1	12.3	58.5	96.6	3.4	11.7	70.9	98.5	1.5	11.3	86.7
75	95.1	4.9	12.2	59.8	96.7	3.3	11.6	71.6	98.6	1.4	11.2	87.5
80	95.2	4.8	12.1	60.3	96.9	3.1	11.5	73.0	98.7	1.3	11.1	88.3
90	95.5	4.5	11.8	61.9	97.1	2.9	11.3	74.3	98.8	1.2	11.0	89.1
100	95.7	4.3	11.6	62.9	97.3	2.7	11.1	75.7	98.9	1.1	10.9	89.9
117	96.1	3.9	11.3	65.5	97.5	2.5	10.9	77.1	99.0	1.0	10.8	90.7

Table A-7. Results of Mix Design at 400 kPa Ram Pressure, US-281.

Number	4.12% AC				4.80% AC			
Gyrations	%Gmm	% VTM	% VMA	% VFA	%Gmm	% VTM	% VMA	% VFA
1	84.9	15.1	22.2	32.0	86.8	13.2	21.8	39.4
5	88.9	11.1	18.5	40.0	90.9	9.1	18.1	49.7
7	89.9	10.1	17.5	42.3	91.8	8.2	17.2	52.3
10	91.0	9.0	16.6	45.8	92.9	7.1	16.3	56.4
20	93.0	7.0	14.8	52.7	94.8	5.2	14.5	64.1
30	94.1	5.9	13.7	56.9	95.9	4.1	13.6	69.9
40	94.8	5.2	13.0	60.0	96.7	3.3	12.9	74.4
50	95.4	4.6	12.5	63.2	97.2	2.8	12.4	77.4
60	95.8	4.2	12.2	65.6	97.5	2.5	12.2	79.5
70	96.1	3.9	11.9	67.2	97.8	2.2	11.9	81.5
75	96.3	3.7	11.7	68.4	97.9	2.1	11.8	82.2
80	96.4	3.6	11.6	69.0	98.0	2.0	11.7	82.9
90	96.7	3.3	11.3	70.8	98.2	1.8	11.5	84.3
100	96.9	3.1	11.2	72.3	98.3	1.7	11.4	85.1
117	97.2	2.8	10.9	74.3	98.5	1.5	11.3	86.7

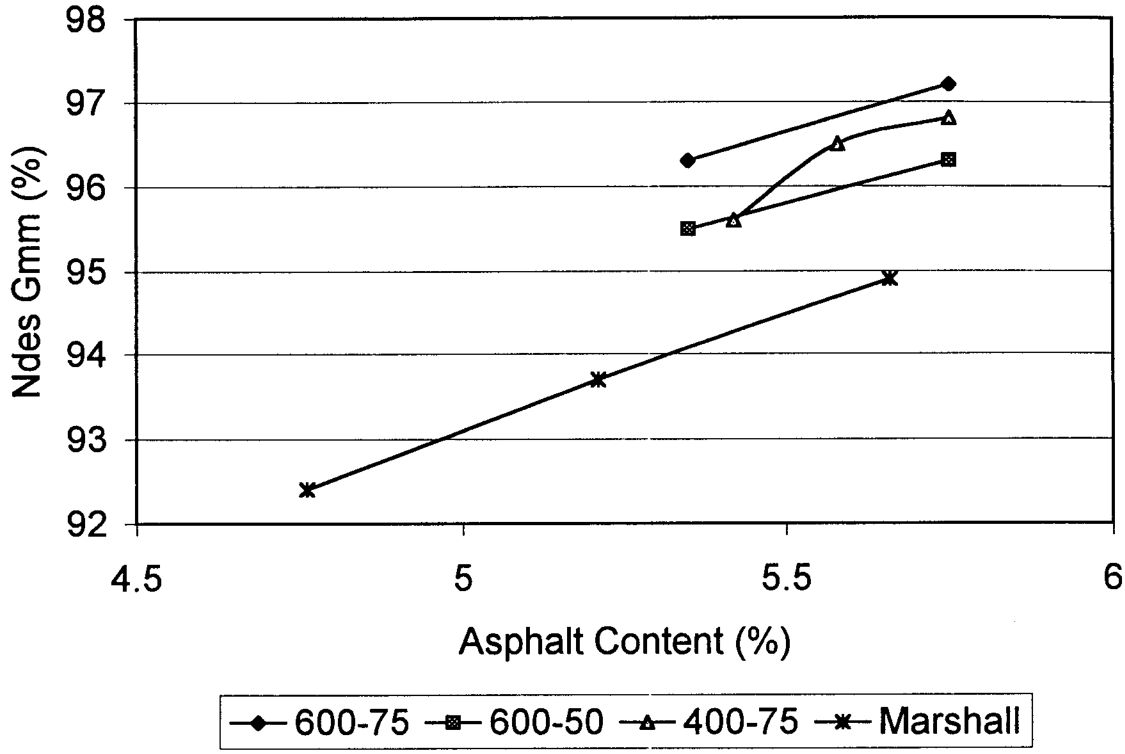

Figure A-1. %Gmm @ N_{design} vs. Asphalt Content, K-4.

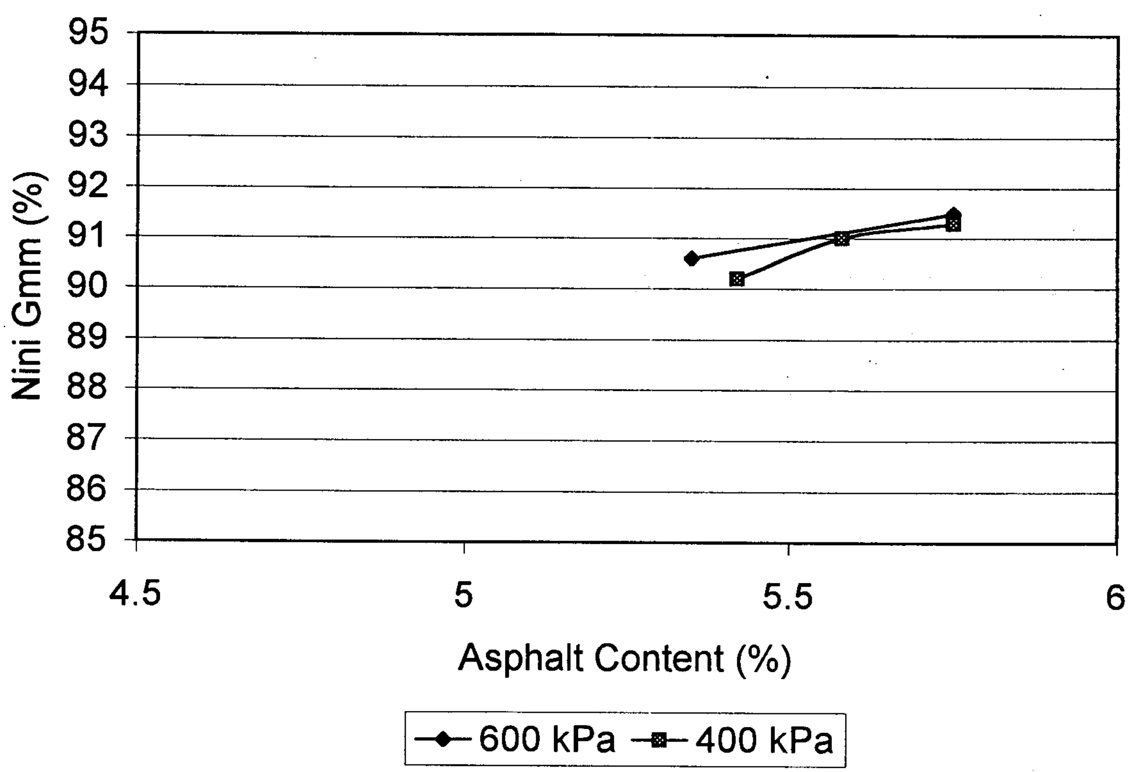

Figure A-2. %Gmm @ N_{ini} vs. Asphalt Content, K-4.

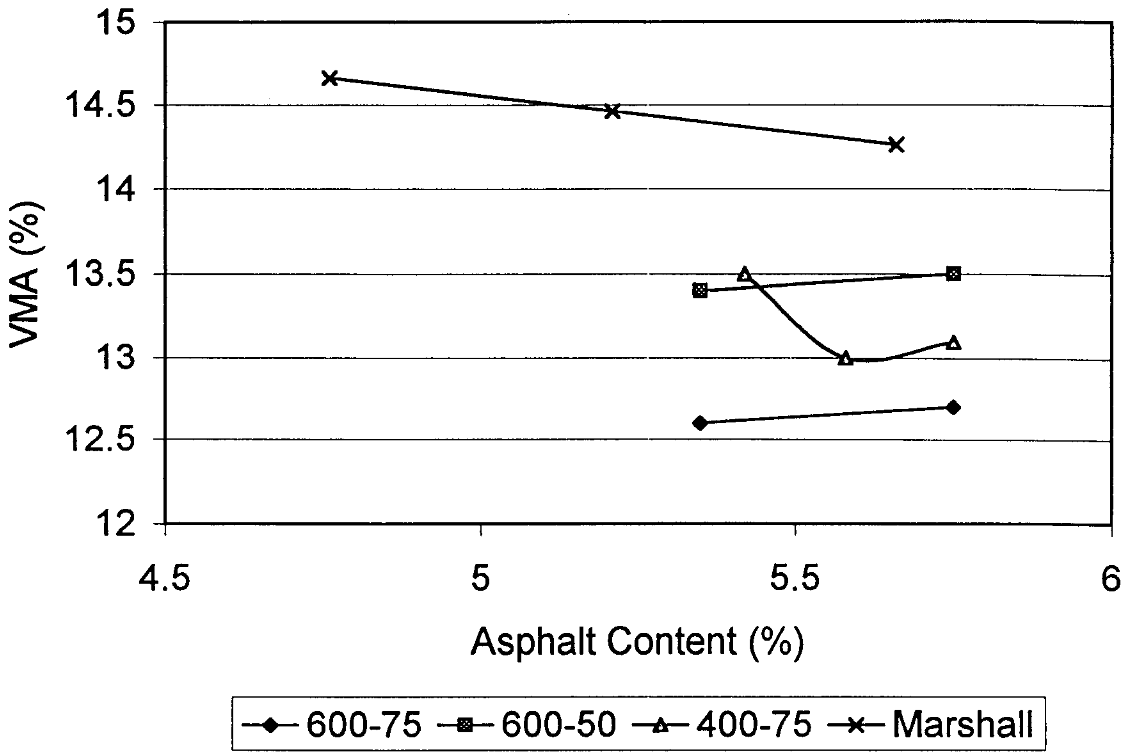

Figure A-3. VMA vs. Asphalt Content, K-4.

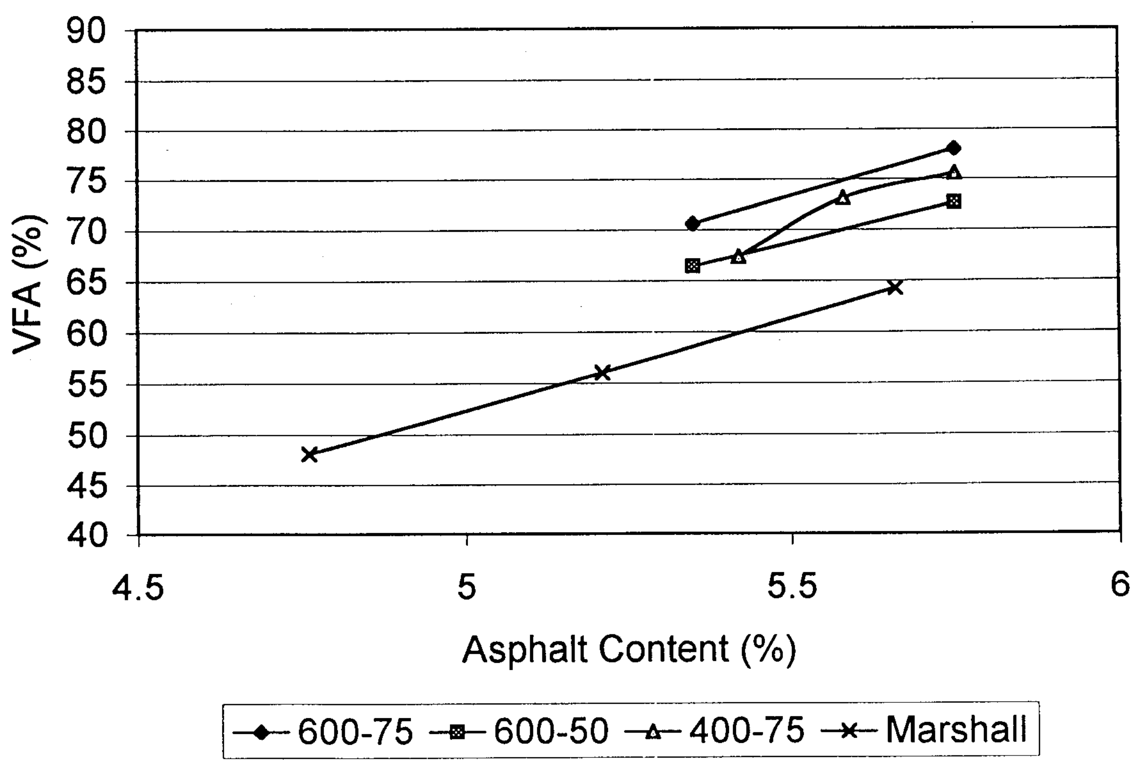

Figure A-4. VFA vs. Asphalt Content, K-4.

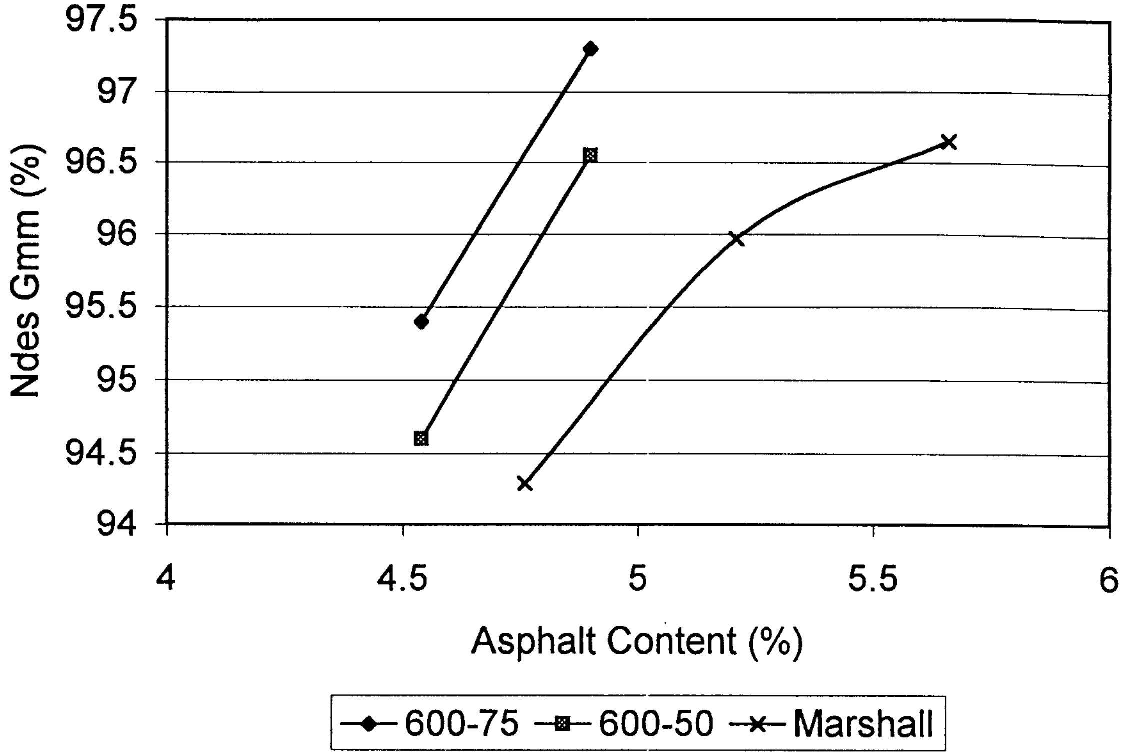

Figure A-5. %Gmm @ N_{design} vs. Asphalt Content, K-20.

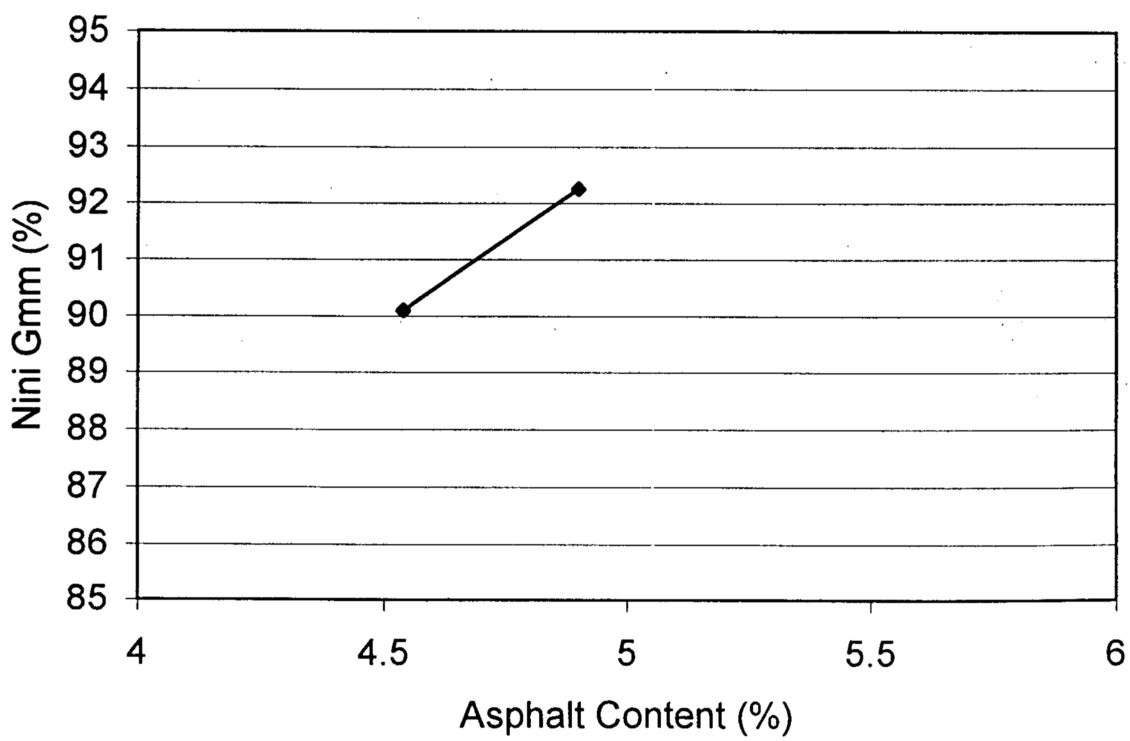

Figure A-6. %Gmm @ N_{ini} vs. Asphalt Content, K-20.

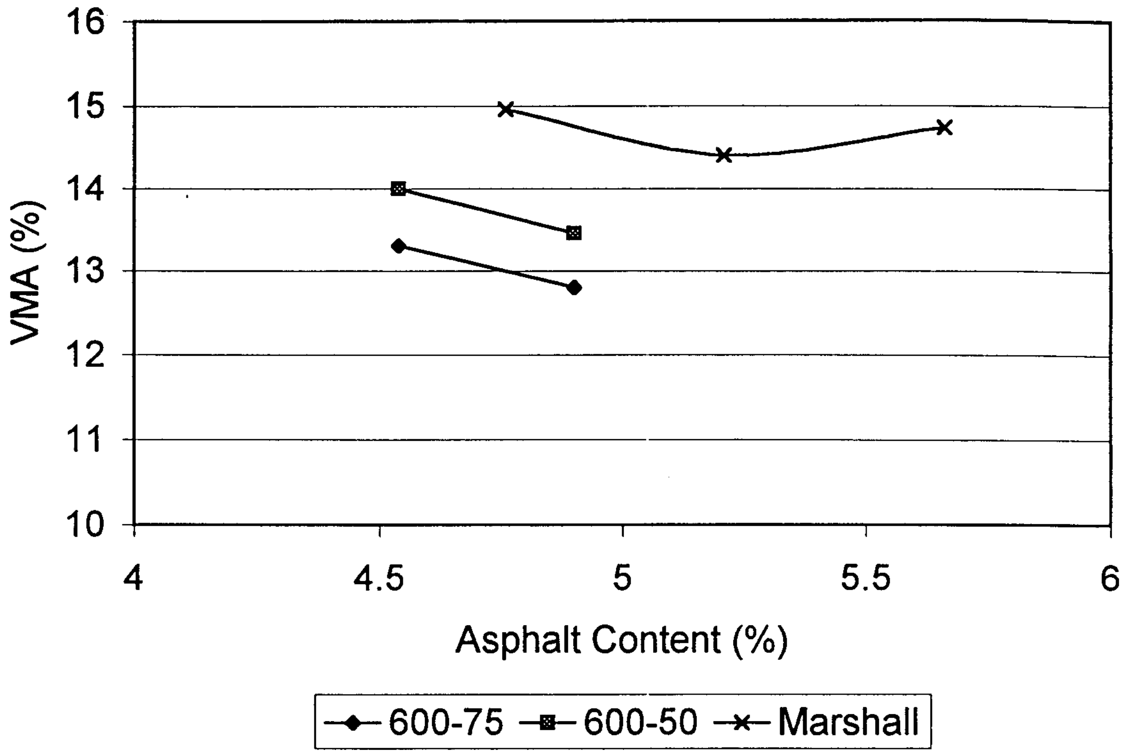

Figure A-7. VMA vs. Asphalt Content, K-20.

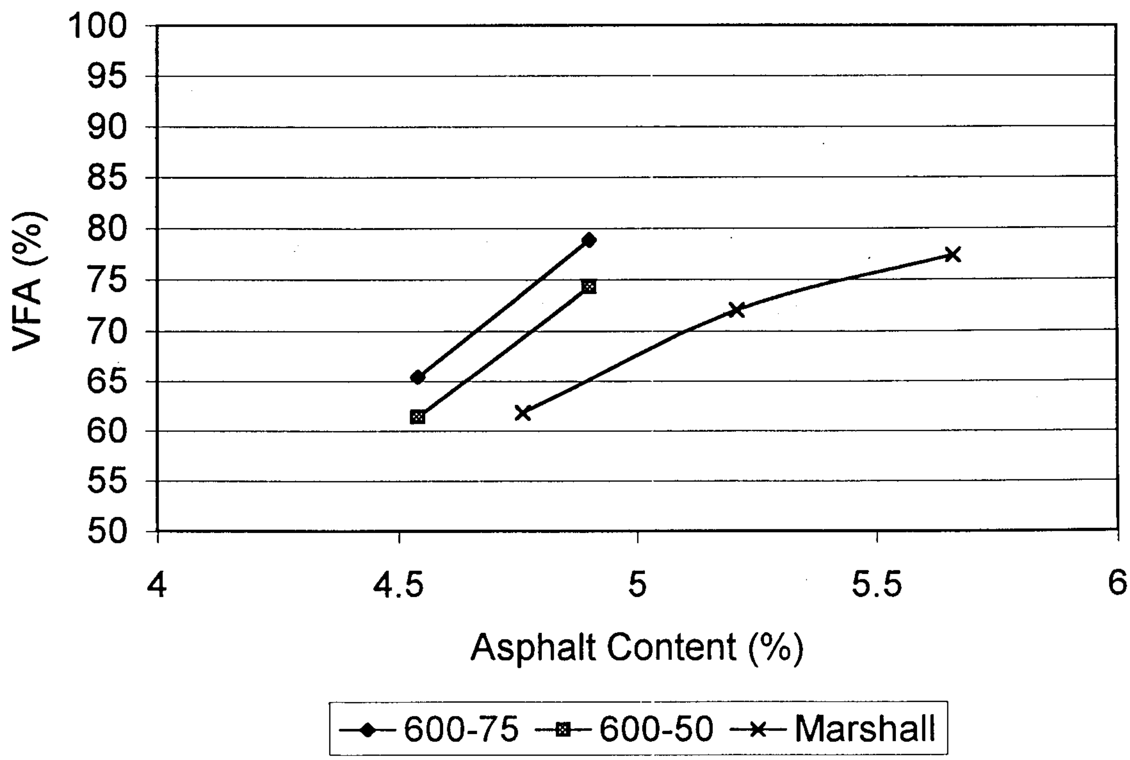

Figure A-8. VFA vs. Asphalt Content, K-20.

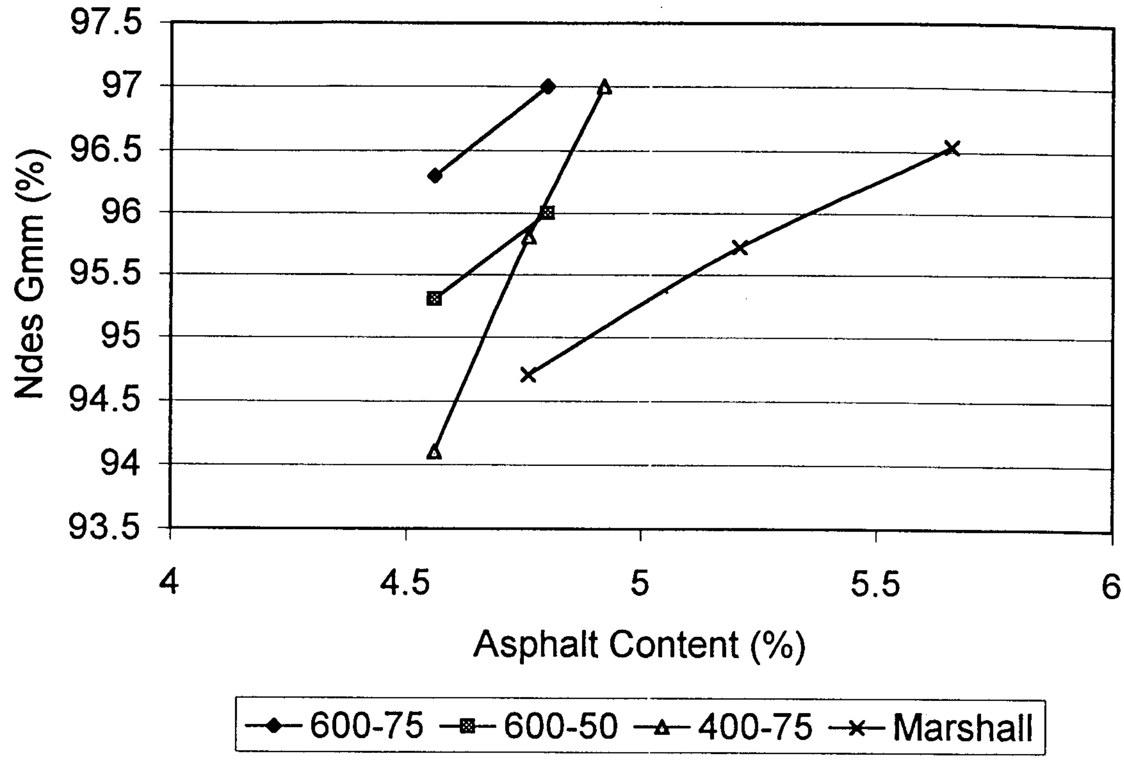

Figure A-9. %Gmm @ N_{design} vs. Asphalt Content, K-116.

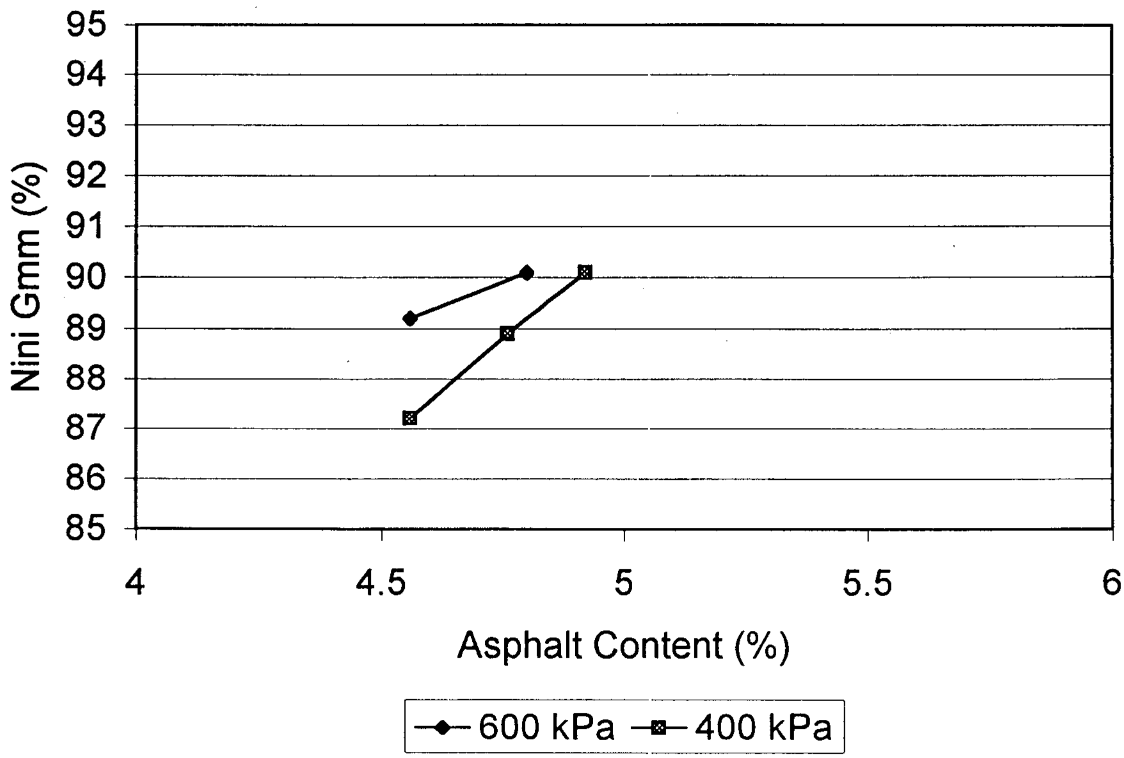

Figure A-10. %Gmm @ N_{ini} vs. Asphalt Content, K-116.

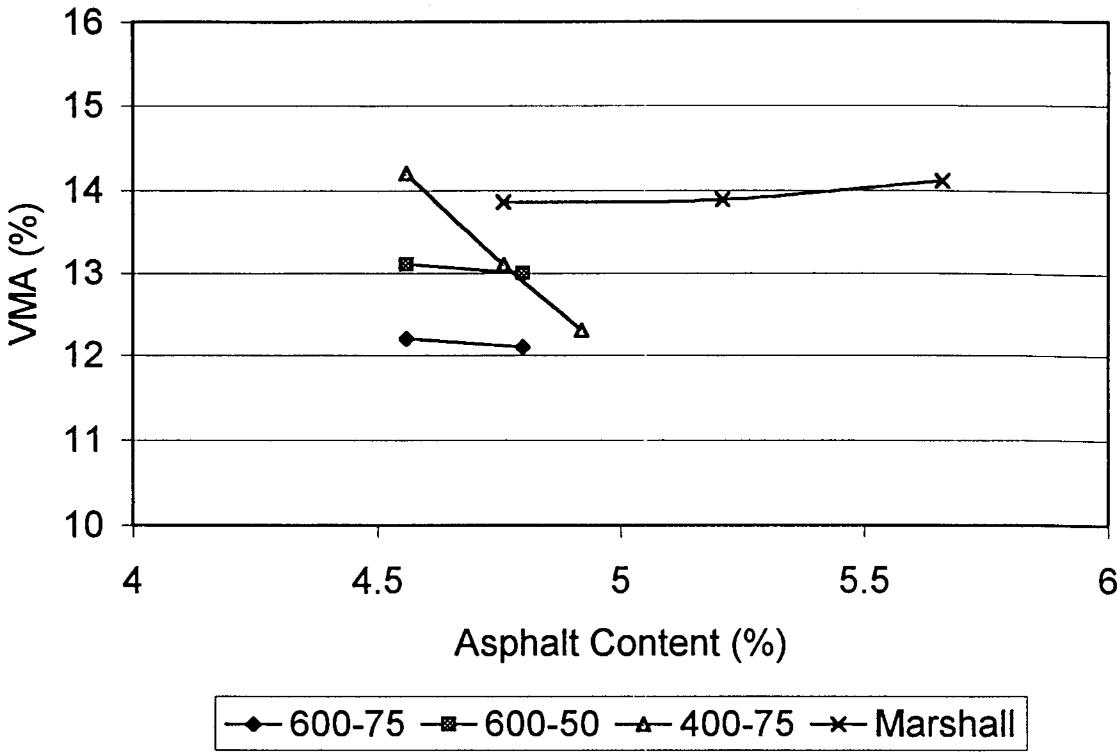

Figure A-11. VMA vs. Asphalt Content, K-116.

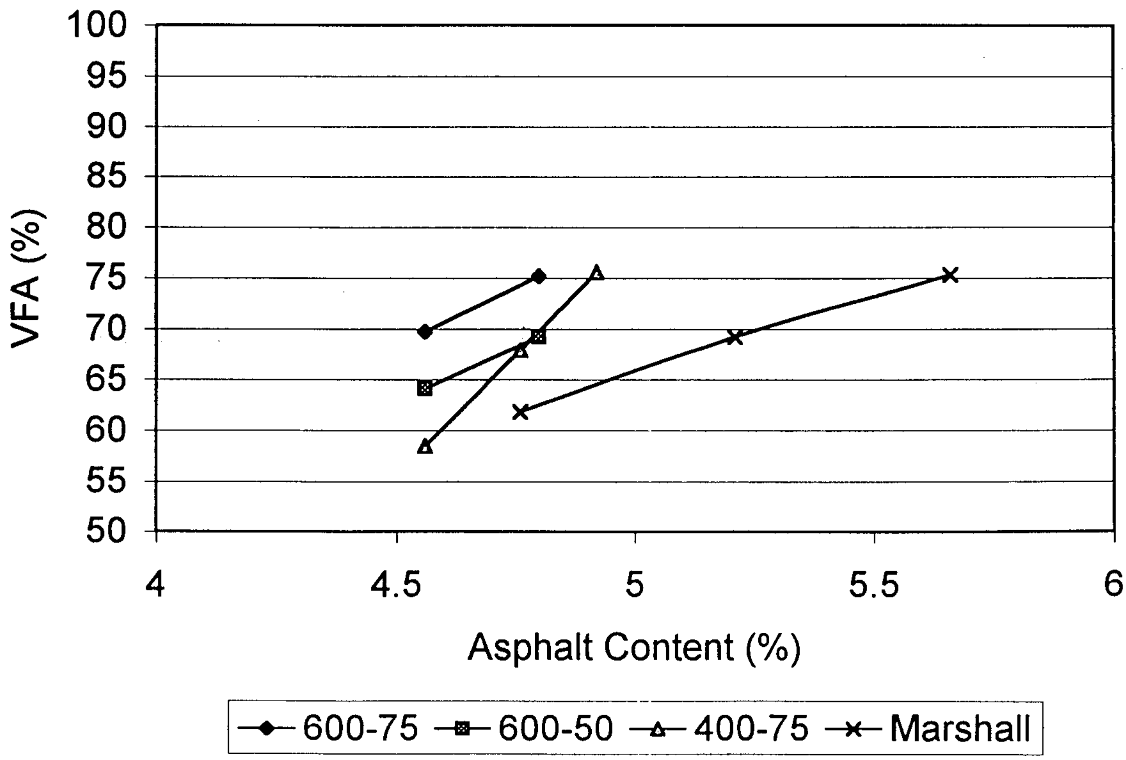

Figure A-12. VFA vs. Asphalt Content, K-116.

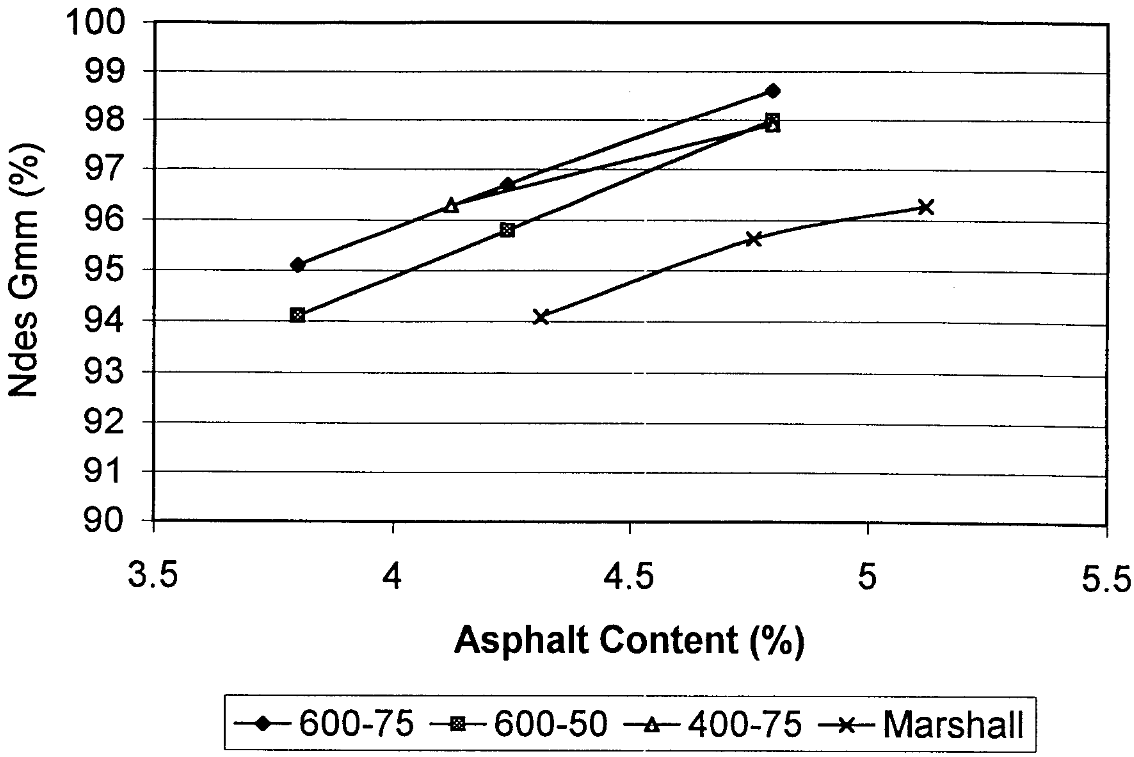

Figure A-13. %Gmm @ N_{design} vs. Asphalt Content, US-281.

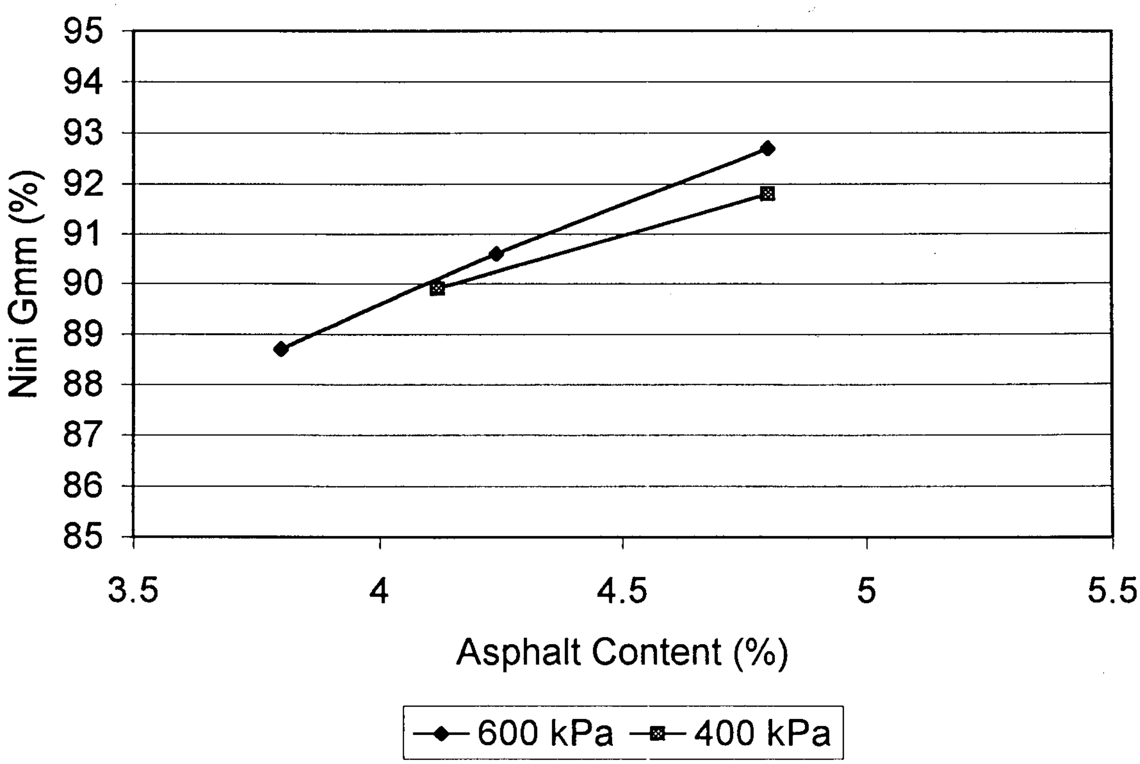

Figure A-14. %Gmm @ N_{ini} vs. Asphalt Content, US-281.

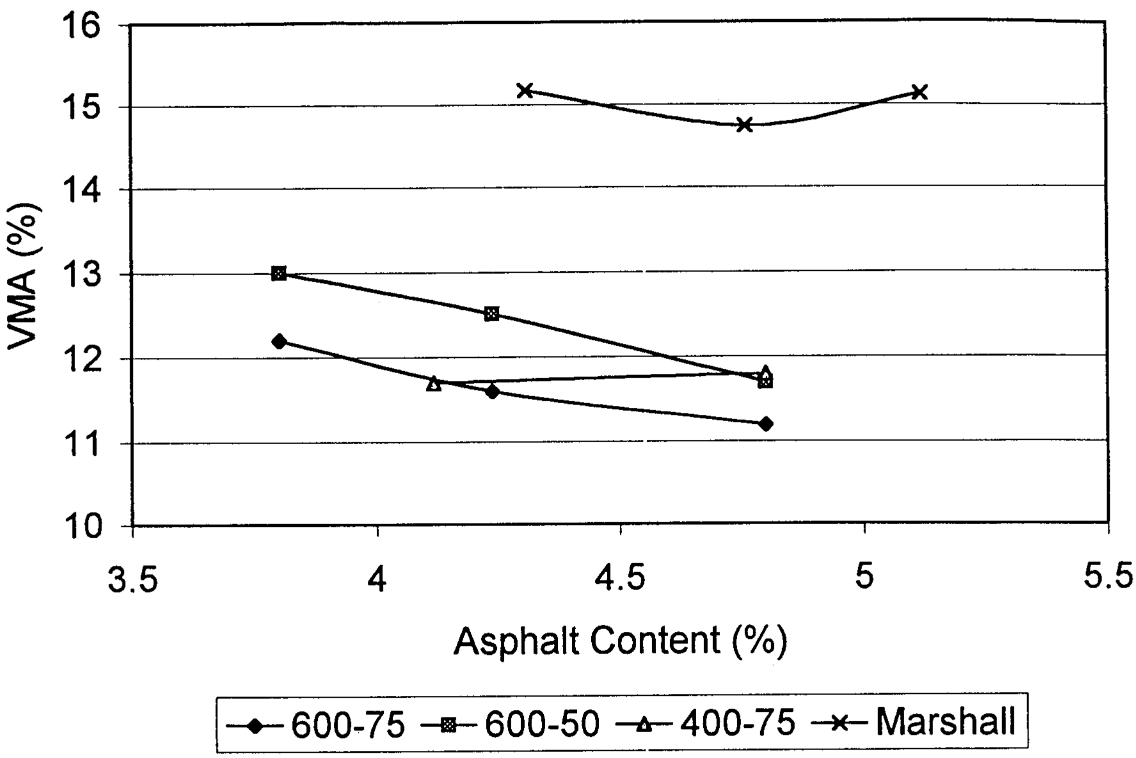

Figure A-15. VMA vs. Asphalt Content, US-281.

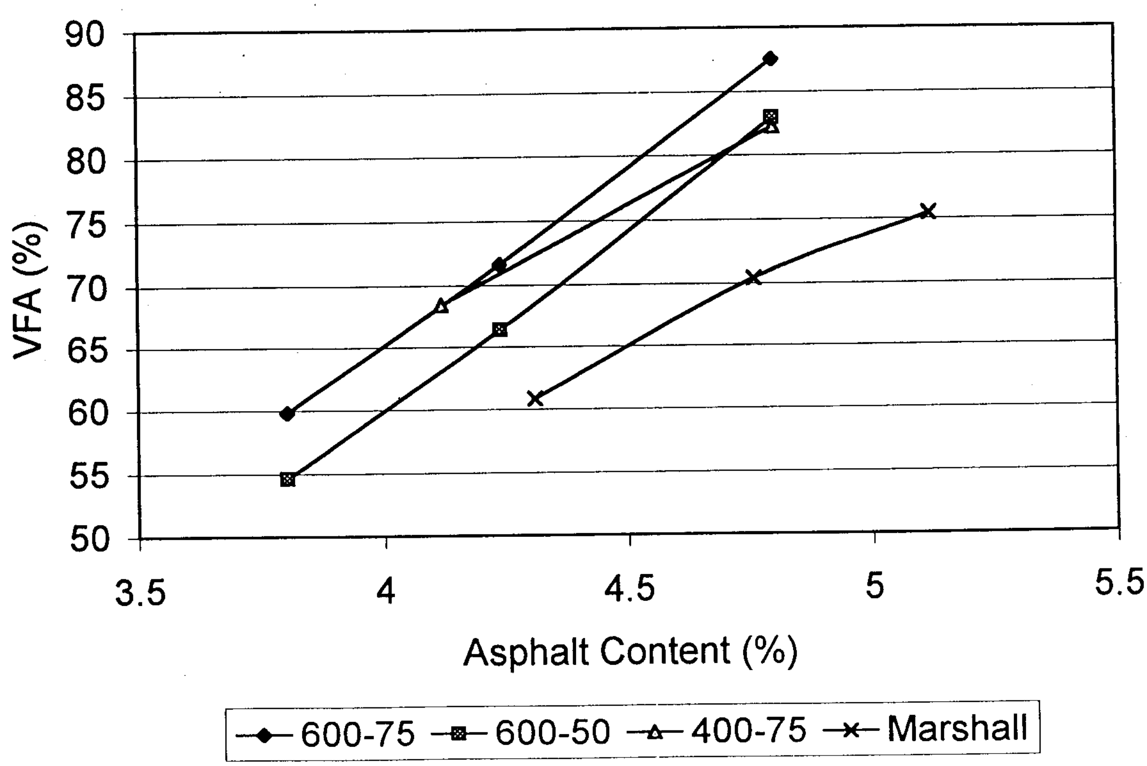

Figure A-16. VFA vs. Asphalt Content, US-281.