Influence of Hot Mix Asphalt Macrotexture on Skid Resistance

Prepared by:

Mary Stroup-Gardiner
Brandy Studdard
Christopher Wagner

Auburn University
Civil Engineering Department
238 Harbert
Auburn, Alabama 36849

(334) 844-6280

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ABSTRACT

Macrotexture is considered the primary factor in skid resistance at speeds over 65 kph (40 mph). A total of 18 projects (9 Superpave and 9 Marshall mix designs) were evaluated to determine if the macrotexture of the pavement surface was influenced by gradation changes associated with the move to Superpave mix designs. The Federal Highway Administration (FHWA) ROSAN high frequency laser system was used to measure macrotexture. Changes in microtexture, also a factor in skid resistance, were evaluated using a British Pendulum (BP) tester to determine the BP number of laboratory compacted samples.

Results indicated that the macrotexture did not change as a result of changes in mix design practices. The nominal maximum size of aggregate seemed to be the key factor in change in pavement surface macrotexture. Mixes, either Superpave or Marshall, with a nominal maximum size 9.5 or 12.5 mm have macrotextures of less than 0.5 mm. Based on information in the literature and an evaluation of the Long Term Pavement Performance (LLTPP) database, the skid resistance for these Alabama pavements was estimated at 40 or higher.

Keywords: Macrotexture, skid resistance

INTRODUCTION

Driver control of vehicles is strongly dependent upon pavement surface characteristics, geometrics, driver speed, and vehicle variables such as tire pressure, type of tread, and wheel loads. Important surface characteristics include pavement microtexture, macrotexture, and drainage attributes. Changes in microtexture, which refers to the texture of the aggregate particle surface and small sand-sized particles in the exposed asphalt mortar, and macrotexture, which is defined by the shape, size, and overall particle arrangement, significantly affect the skid resistance.

Skid resistance is defined as the frictional force that opposes the sliding of tires on the surface when the tires are prevented from rotating. Several methods are available for measuring this force and results are commonly reported as skid numbers (SN) (Balmer, 1978; Balmer and Hegmon, 1980). Skid numbers at low speeds are primarily a function of the pavement microtexture; at higher speeds, the macrotexture dominates the skid resistance. Changes in the aggregate structure and gradation can affect one or both of these parameters.

Implementation of the new Superpave mix design procedure has led to changes in the coarseness of the asphalt concrete gradation, along with a potential decrease in fines content. These changes can alter both the macro- and microtexture characteristics of the pavement surface thereby changing the skid resistance. Since the use of Superpave mixtures is relatively new, little information is available on the affect of hot mix asphalt (HMA) design changes on skid resistance. This research effort was designed to evaluate the affect of mix design changes on skid resistance.

BACKGROUND

Macrotexture has historically been measured with the sand patch test (ASTM E965, 2000) to determine the volume of voids on surface of the pavement. More recently, high frequency lasers have been employed to measure the mean profile depth (ASTM E1845, 2000). The mean profile depth, MPD, is empirically related to the estimated sand patch texture depth, ETD, by:

$$ETD = 0.2 + 0.8MPD \quad \text{for units in inches}$$

or

$$ETD = 0.008 + 0.8MPD \quad \text{for units in mm.}$$

Typical macrotexture depths range from about 0.2 to 3.0 mm according to Roe, et al. (TRRL RR296, 1991). Balmer and Hegmon (1980) define macro texture as beginning at about 0.5 mm.

Microtexture of the coarse aggregate source is commonly defined by determining the polishing value using the British Pendulum Test (ASTM E1393, 2000). The contribution of the sand-sized aggregate mortar on microtexture has also been estimated using the British Pendulum Test (ASTM D303, 2000), however in this case the pavement surface or cores are tested (Forster, 1989; Balmer and Hegmon, 1980). Microtexture is considered to dominate the surface characteristics between 0 and either 0.2 or 0.5 mm (TRRL 296, ; Balmer and Hegmon, 1980, respectively).

Forster (1989) found that the microtexture can be characterized by a single shape factor parameter than combines measurements of the average height and average spacing of the microtexture asperities. There is a fair correlation between this shape factor and the British Pendulum Test as used on pavement surfaces.

Safety Considerations

Experiments conducted by Balmer (1978) showed that changes in surface textures from about 0.5 to over 3 mm resulted in a difference of 16 km/hr (10 mph) in the speed for the initiation of hydroplaning. A combination of the pavement cross slope and the macrotexture have been linked to the prevention of significant water depths. Data presented by Balmer (1978) showed that for a design rainfall intensity of 25 mm/hr (1in/hr), the texture depth required to keep the water depth below the macrotexture asperities increases with increasing pavement width. Conversely, the needed texture depth decreased with increasing slope. Using the data presented by Balmer, the following regression equations can be used to estimate a critical minimum texture, y (in mm), for a given cross slope, x, and pavement width:

$y = -0.27x + 1.402$ for 3.6 meter (12 foot) pavement widths, and

$y = -0.53x + 2.172$ for 7.6 meter (24 foot) pavement widths.

The first equation suggests that a minimum texture depth of 0.86 mm is needed for a cross slope of 2 percent and a lane width of 3.3 meters to keep the water depth below the top of the aggregate tips. The texture needs to be increased to about 1.1 mm for the same cross slope but a pavement width of 7.6 meters.

Skid resistance is most commonly determined in the field using a wet locked wheel skid test. A power law relationship exists between the macrotexture and the skid number at 65 kph (40 mph) (Balmer and Hegmon, 1980). This relationship is also affected by the microtexture as measured using the British Pendulum Test (Figure 1).

Figure 1 indicates that small changes in macrotextures (less than about 0.5 mm) are related to large changes in skid resistance. Increasing macrotextures above about 0.5 mm has less of an impact on skid resistance than does increasing the BPN values. That is, when the macrotexture is greater than 0.5 mm, the microtexture becomes a major factor in increasing skid resistance. Balmer (1978) reported that accident rates decreased with increasing skid numbers up to an SN40 of about 44. Skid numbers above this threshold value did not have a significant affect on the accident rates, regardless of traffic levels.

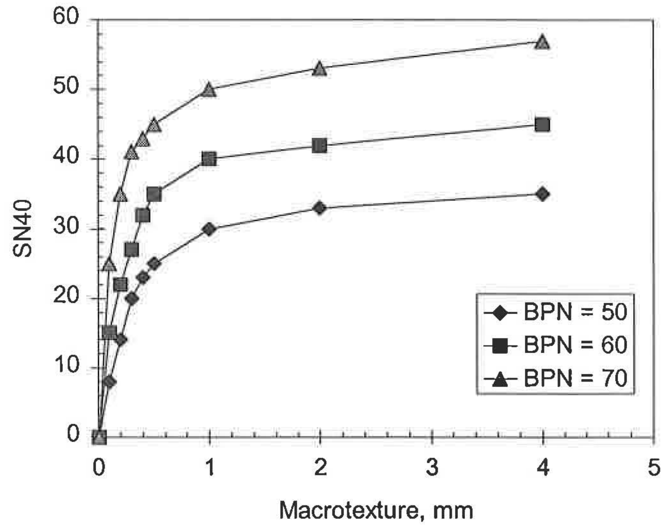

FIGURE 1. Effect of micro- and macrotexture on skid resistance (after Balmer, 1978).

Forster (1989) also presented data that confirmed the relationship between microtexture, macrotexture and the skid numbers for a large number of actual in-service pavements.

RESEARCH PROGRAM

Objective

The objectives of this study were to:

- Evaluate the affect of HMA mix design choices on in-service pavement surface macrotexture.
- Conduct a laboratory study on the affect of HMA mix design changes on microtexture as defined by using the British Pendulum Test.
- Assess the potential for macrotexture changes to affect skid numbers.

Scope

A set of two projects (one Superpave and one Marshall mix design) from each of the nine Alabama Divisions were identified for investigation of their macrotexture using the Federal Highway Administration's ROSAN high frequency laser system. A total of 17 projects were surveyed using this technology; one Superpave mix design project was eliminated from the testing program due to equipment difficulties. Average macrotextures were obtained for three consecutive 100-meter sections for each mile of each project. Testing was conducted for each wheel path as well.

Originally, corresponding skid numbers were to be obtained by the Alabama Department of Transportation (ALDOT) but recurring equipment problems made it impossible to collect a complete set of data within a reasonable time frame after construction. Therefore, skid numbers were estimated from relationships presented in the literature and from an analysis of the Long Term Pavement Performance (LTPP) database.

Six of the 17 Alabama projects (3 Superpave and 3 Marshall), were selected for a laboratory study. For this portion of the research, the project aggregate gradations were used to prepare gyratory-compacted samples. One asphalt cement source and a single aggregate source were used to prepare the samples so that all factors affecting microtexture other than gradation could be eliminated from the experiment. The British Pendulum Test was used to evaluate the effect of gradation changes on Alabama mix microtexture.

PROJECT DESCRIPTIONS

Figure 2 shows the general location of the field projects used for the evaluation of macrotexture changes due to changes in mix design practices. Table 1 summarizes information on contract number, county, contractor, and general project location. Table 2 presents the material and mix properties reported by each division for the mix designs.

FIGURE 2. General Project Locations.

Gradations included 3 nominal maximum size aggregate gradations: 9.5 mm (9 projects), 12.5 mm (4 projects), and 19 mm (4 projects). All of the projects reported at least 85 percent of the coarse aggregates with two or more crushed faces. Only one project reported fine aggregate angularity of less than 45 percent.

Twelve of the 17 projects used a PG 64-22 binder. The one PG 67-22 binder actually graded as a PG 64-22. Two binders were polymer modified and one project specified the binder using the old viscosity grade designation of AC30.

Seven of the projects used reclaimed asphalt pavement (RAP) with 6 of the 7 using 15 percent RAP and the seventh project using only 10 percent. Seven projects also indicated that a liquid antistripping additive was used. None of the reported tensile strength ratios (TSR) used to assess moisture sensitivity were lower than 80 percent.

TABLE 1. Project Identification and Location.

Division	Project No.	County	Project Length, miles	Section
1	99-301-452-002-702	Madison	6	Governor's Dr.
	STPNU-3600 (20)	Jackson	5	Co. Rd. 17
2	99-302-673-074-711	Winston	6	AL Highway 278
	99-302-391-020-715	Lauderdale	7	AL Highway 20
3	99-303-644-005-718	Walker	6	US Highway 78
	99-303-052-053-711	Blount	6	US 231 / AL 53
4	99-304-615-038-701	Talladega	5	US Highway 280
	99-304-615-077-706	Talladega	19	AL Highway 77
5	99-305-632-013-702	Tuscaloosa	14	US Highway 43
6	99-306-513-008-701	Montgomery	2	AL Highway 9
	99-306-513-009-701	Montgomery	14	US Highway 80
7	99-307-351-210-701	Houston	3	AL Highway 210
	99-307-555-010-701	Pike	6	US Highway 231
8	99-308-601-008-713	Sumter	5	SU 80 / St. Rd. 8
	99-308-663-028-714	Wilcox	4	St. Rd. 28
9	99-309—22-003-707	Baldwin	9	I-10
	99-309-273-015-709	Escambia	6	US 29 / 41

Table 2. Project Aggregate and HMA Information.

Properties	Division 1		Division 2		Division 3		Division 4		Division 5	
	Superpave	Marshall	Superpave	Marshall	Superpave	Marshall	Superpave	Marshall		Marshall
	8-106-169	50 Blow	8-95-150	50 Blow	9-121-195	50 Blow	8-106-169	50 Blow		75 Blow
Aggregate Properties										
Cumulative Percent Passing, %										
37.5 mm										
25 mm		100				100				
19 mm		99	100			91				
12.5 mm	100	73	99	100	100	70	100	100		100
9.5 mm	95	52	87	92	94	56	94	93	NA	97
4.75 mm	63	33	63	72	63	36	62	73		76
2.36 mm	40	23	45	52	40	24	38	50		52
1.18 mm	30	17	33	42	29	17	26	38		41
0.60 mm	22	13	27	32	21	13	16	28		33
0.30 mm	12	9	16	19	14	9	9	19		19
0.15 mm	8	6	7	9	8	6	5	10		9
0.075 mm	6	4.8	5	5.5	5.6	4.6	4	5.8		5.3
Coarse Agg. Angularity, %	98/97	100/100	100/99	99/95	100/97	100/100	97/94	95/88		100/100
Fine Aggregate Angularity, %	46	45	45	45	46	43	48	48		45
Aggregate Bulk Specific Gravity	2.605	2.675	2.816	2.602	2.779	2.701	2.618	2.658		2.793
HMA Properties										
Asphalt Cement Grade	PG 64-22	PG 64-22	PG 67-22	PG 64-22	PG 76-22 (Poly)	PG 64-22	PG 64-22	PG 64-22		PG 64-22
Asphalt Cement Content, %	4.66/0.9	3.75/0.90	5.2	5.9	5.65	3.78/0.82	5.7	5.95		6.1
Additives RAP, %	15	15	None	None	None	None	None	None		None
Antistrip Additives	0.5	None	None	None	None	None	None	0.5		None

NA: Not available

Table 2 (Continued). Project Aggregate and HMA Information.

Properties	Division 6		Division 7		Division 8		Division 9	
	Superpave	Marshall	Superpave	Marshall	Superpave	Marshall	Superpave	Marshall
	8-106-168	75 Blow	9-121-195	75 Blow	8-106-169	75 Blow	8-106-169	50 Blow
Aggregate Properties								
Cumulative Percent Passing, %								
37.5 mm								
25 mm	100			100				
19 mm	99		100	97		100		
12.5 mm	88	100	98	80	100	94	100	100
9.5 mm	76	94	85	71	89	85	96	93
4.75 mm	52	76	46	46	76	72	68	67
2.36 mm	40	56	31	30	53	56	44	44
1.18 mm	30	38	21	19	39	41	31	31
0.60 mm	21	28	16	13	28	29	22	22
0.30 mm	14	19	9	7	16	16	14	12
0.15 mm	6	11	6	5	10	7	7	7
0.075 mm	4	5.9	4	3.9	5.3	4.6	4.5	4
Coarse Agg. Angularity, %	95/89	98/95	99/98	96/97	96/93	93/80	89/86	99/97
Fine Aggregate Angularity, %	46	45	46	45	45	45	45	46
Aggregate Bulk Specific Gravity	2.654	2.680	2.71	2.746	2.732	2.639	2.641	2.664
HMA Properties								
Asphalt Cement Grade	PG 64-22	PG 64-22	PG 76-22	PG 76-22 (SBS)	PG 64-22	AC-30	PG 64-22	PG 64-22
Asphalt Cement Content, %	3.64/0.86	5.0/0.55	3.90/0.90	3.63/0.62	5.6	5.85	5	5.9
Additives RAP, %	15	10	15	15	None	None	None	None
Antistrip Additives	0.5	0.5	None	0.5	None	None	0.5	0.5

NA: not available

TESTING PROGRAM

Federal Highway Administration ROSAN

The Road Surface Analyzer (ROSAN) consists of a small high frequency laser that is capable of acquiring vertical measurements at least every 1 mm of profile length, signal conditioning hardware, and a computer data acquisition system. The software is capable of reporting the mean profile depth over base lengths of 100 mm that are then averaged so that an average mean profile depth is reported for each 100-meter section surveyed. The minimum requirements for this testing are described in ASTM E1845 (2000). The entire system is easily attached to the bumper of any vehicle (Figure 3).

FIGURE 3. ROSAN laser (FHWA, 1998)

British Pendulum Testing

Testing was conducted as described in ASTM E303 for evaluating the frictional resistance of flat surfaces. A frame was fabricated to firmly hold a standard 150 mm diameter gyratory-compacted sample under the pendulum's rubber padded foot (Figure 4.) Samples were first tested dry and then wet.

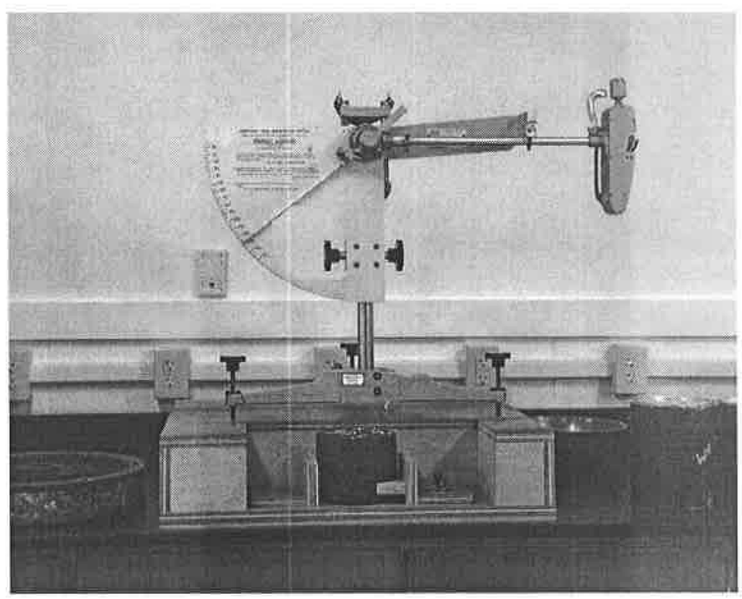

FIGURE 4. British Pendulum Tester on Frame.

RESULTS

Macrotexture Measurements for Field Projects

All of the average estimated texture depth as calculated from the mean profile depth measurements for each of the consecutive three 100 meter sections for each project are shown in Appendix A. Figure 5 shows examples of the various features observed in the general database. Observations that can be made about the data include:

- Macrotexture measurements are reasonably consistent within a set of three 100-meter values for each mile of the projects.
- There are occasional statistical differences between the wheel paths for the same lane of highway. When there was a difference, the inside (left) wheel path typically had the statistically higher macrotexture.
- Macrotextures were typically consistent throughout a given project for each wheel path in each direction.

Consecutive 100 Meter Measurements

The within-set variability was determined for each project, each direction and within each wheel path. Data was separated by the type of mix design and the average within sample set standard deviation was calculated. An F-test with a confidence level of 95 percent was used to determine that there was a statistical difference in variability between the textures associated with each mix design method. The within-set standard deviation for the Superpave projects was 0.086 mm (n = 196) and 0.051 mm for the Marshall mix design projects (n = 242). These statistics were used to determine any outliers prior to calculating the average per-wheel path per-mile macrotexture (i.e., the average of the three 100-meter averages). Overall, the three 100–meter average texture measurements within each mile were very consistent.

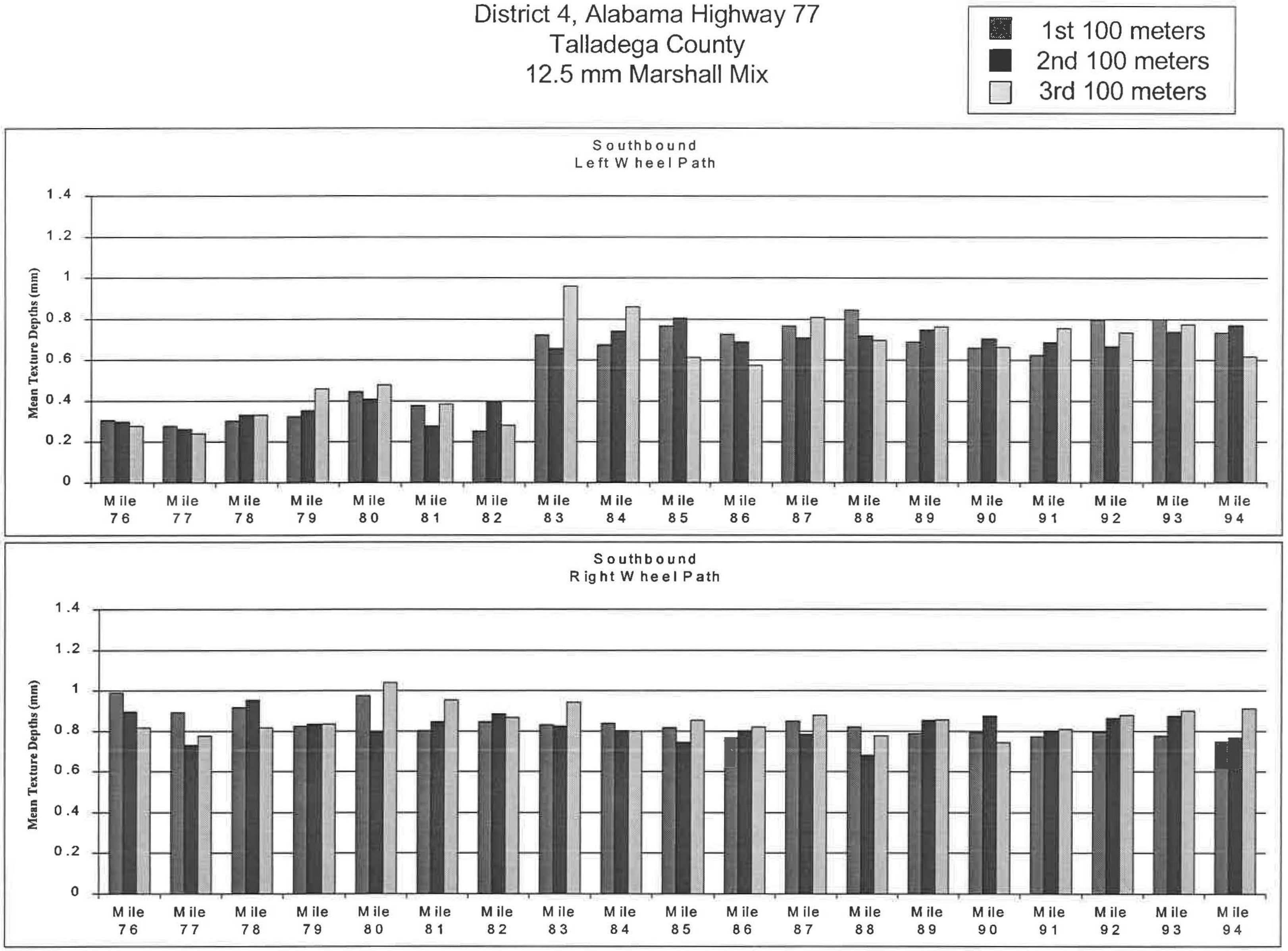

FIGURE 5. Typical results for macrotexture measurements for each mile of highway and each wheel path.

Statistical Differences Between Wheel Paths

The average per-mile texture for each wheel path for each project was reported as the average of the three consecutive 100-meter measurements. A paired t-test was conducted using these average per-mile data to determine if there was a statistical difference in the macrotexture between the wheel paths at a confidence level of 95 percent.

Table 3 shows the means, standard deviations, number of data points (i.e., number of miles for which data was collected), the calculated t-value and whether there was a statistical difference between the wheel paths. For the Superpave mixtures, only the Division 2 project had consistently higher macrotextures in the inside wheel path. The inside wheel path, southbound, for Division 3 (Superpave) and the outside wheel path, northbound, for Division 9 (Superpave) showed statistically higher macrotexture values. For the Marshall mix designs, eight of the 16 pavement lanes (2 per project) evaluated showed higher textures in the inside wheel path. Only two showed higher macrotextures in the outside lane.

The standard deviation for the reported project macrotexture per lane per wheel path was 0.05 mm. This standard deviation was used to determine if there is a statistical difference as a result of changes in mix design practices. An F-test for variances was used to determine if the mix design method (i.e., gradation selection method) affected the overall project macrotexture variability. At the 95 percent confidence level, there was no statistical difference in macrotexture variability due to mix design procedures.

TABLE 3. Statistics for Mean Texture Depth for All Projects.

Lane	Superpave					Marshall				
	Mean Texture	Std. Dev.	n	T-value	Statistically Different?	Mean Texture	Std. Dev.	n	T-value	Statistically Different?
Division 1										
Northbound Inside	0.53	0.09	6	0.56	No	0.81	0.06	5	3.26	Yes
Outside	0.49	0.08	6			0.46	0.05	5		
Southbound Inside	0.50	0.09	6	1.82	No	0.93	0.05	5	9.99	Yes
Outside	0.42	0.06	6			0.38	0.02	5		
Division 2										
East / Northbound Inside	0.98	0.03	6	0.04	Yes	0.26	0.02	7	-7.24	Yes
Outside	0.70	0.09	6			0.41	0.01	7		
West / Southbound Inside	1.13	0.02	6	0.02	Yes	0.27	0.01	7	4.69	Yes
Outside	0.88	0.07	6			0.19	0.01	7		
Division 3										
East / Northbound Inside	0.36	0.05	6	0.35	No	0.40	0.02	6	-0.13	No
Outside	0.31	0.03	6			0.40	0.05	6		
West / Southbound Inside	0.32	0.02	6	3.32	Yes	0.50	0.04	6	6.35	Yes
Outside	0.24	0.01	6			0.37	0.02	6		
Division 4										
Northbound Inside	0.39	0.01	5	1.62	No	0.78	0.01	19	0.78	No
Outside	0.35	0.02	5			0.76	0.01	19		
Southbound Inside	0.43	0.02	5	0.71	No	0.73	0.05	12	-8.39	Yes
Outside	0.42	0.02	5			0.82	0.01	12		
Division 5										
Northbound Inside	No Superpave Mix					0.73	0.06	15	7.37	Yes
Outside						0.18	0.05	15		
Southbound Inside						Only One Lane				
Outside										
Division 6										
Northbound Inside										
Outside										
Southbound Inside										
Outside										
Division 7										
Northbound Inside	0.40	0.04	3	2.61	No	0.54	0.10	5	3.59	Yes
Outside	0.36	0.04	3			0.40	0.11	5		
Southbound Inside	0.39	0.06	3	1.18	No	0.45	0.04	4	0.58	No
Outside	0.27	0.06	3			0.40	0.12	4		
Division 8										
Northbound Inside	0.27	0.02	5	-1.22	No	0.29	0.03	4	-1.82	No
Outside	0.30	0.01	5			0.33	0.01	4		
Southbound Inside	0.23	0.01	5	-0.73	No	0.25	0.05	4	0	No
Outside	0.24	0.02	5			0.25	0.05	4		
Division 9										
Northbound Inside	0.33	0.02	9	-3.24	Yes	0.97	0.06	6	8.82	Yes
Outside	0.43	0.03	9			0.46	0.01	6		
Southbound Inside	0.47	0.01	6	-1.32	No	0.97	0.06	6	8.82	Yes
Outside	0.51	0.02	6			0.46	0.01	6		

Comparison of Mix Design Practices

Table 4 presents relevant aggregate size and gradation characteristics for all of the mixtures evaluated. When the macrotexture was not statistically different between the wheel paths, the grand average macrotexture for the project is shown in this table. If there were statistical differences, it was felt that the differences represented segregation of the mix at some point during construction. Therefore, no single representative macrotexture could be obtained for most of the projects; the individual projects are identified in the table with the designation "seg".

Superpave mixes had one of two nominal maximum size aggregates: 12.5 (4 projects), and 19.0 mm (4 projects). Division 6 Superpave gradation was a nominal maximum size of 25 but only two miles of data were available; it was felt that this was not a sufficient representation of the entire project and therefore eliminated from the evaluation. A Duncan's comparison of means test was conducted to determine if there was a statistical difference in the macrotexture as a function of the nominal maximum size aggregate or the associated gradations. The overall mean texture for either the 9.5 or 12.5 mm Superpave mixes, regardless of the nominal maximum size, was 0.36 mm.

A direct comparison between the Superpave and Marshall mixes could not be made due to the large number of Marshall mix design project lanes with between-wheel path statistical differences.

TABLE 4. Gradation Characteristics, Estimated Texture Depth and Actual Texture Depth for Non-Segregated Projects.

Superpave									
Parameters	Divisions								
	1	2	3	4	5	6	7	8	9
% Pass. No. 4.75 mm	63	63	76	62		52	46	76	68
D10	0.2	0.19	0.2	0.3		0.2	0.35	0.15	0.2
D30	1.1	0.9	1.1	1.15		1.1	2.1	0.70	1.1
D60	4	4	4	4.4		6	6	3.00	4
Cu	20.0	21.1	20.0	14.7		30.0	17.1	20.0	20.0
Cc	1.5	1.1	1.5	1.0		1.0	2.1	1.1	1.5
Max Agg	12.5	19.0	12.5	12.5		25.0	19.0	12.5	12.5
Estimated Texture	0.30	0.38	0.30	0.28		0.45	0.51	0.26	0.30
Actual Texture	0.48	Seg.	0.34	0.40		0.51/0.31*	0.36	0.26	0.49
Marshall Mixes									
Parameters	Divisions								
	1	2	3	4	5	6	7	8	9
% Pass. No. 4.75 mm	33	72	36	73	76	76	46	72	67
D10	0.3	0.20	0.3	0.2	0.2	0.15	0.4	0.18	0.12
D30	4	0.5	4	0.7	0.6	0.7	2.3	0.60	1.05
D60	10	3	10	3	2.8	2.7	7	2.80	4
Cu	33.3	15.0	33.3	15.0	14.0	18.0	17.5	15.6	33.3
Cc	5.3	0.4	5.3	0.8	0.6	1.2	1.9	0.7	2.3
Max Agg	25.0	12.5	25	12.5	12.5	12.5	25.0	19.0	12.5
Estimated Texture	0.88	0.21	0.88	0.26	0.24	0.53	0.60	0.37	0.32
Actual Texture	Seg.	Seg.	0.40	0.35	Seg.	0.60	0.43	0.27	Seg.

* First number = North bound or east bound, second number = south bound or west bound

Shaded value indicates that this was the initial texture for the first 3-4 miles of project

Laboratory Study Using the British Pendulum Tester

Six of the Alabama projects (3 Superpave, 3 Marshall) were selected for evaluation in the laboratory study. Table 5 shows the gradations and optimum asphalt contents used to prepare gyratory-compacted samples. All samples were fabricated using the same aggregate source and same PG 64-22 asphalt cement. The number of gyrations used to compact the samples was adjusted each mix so that 4 percent air voids (plus/minus 1 percent) were obtained. A set of 3 samples was prepared for each mix.

TABLE 5. Aggregate Gradations Used for BPN Laboratory Study.

Properties	Division 2	Division 4	Division 6	Division 3	Division 7	Division 9
	Superpave	Superpave	Superpave	Marshall	Marshall	Marshall
	8-95-150	8-106-169	8-106-168	50 Blow	75 Blow	50 Blow
Cumulative Percent Passing, %						
25 mm			100	100	100	
19 mm	100		99	91	97	
12.5 mm	99	100	88	70	80	100
9.5 mm	87	94	76	56	71	93
4.75 mm	63	62	52	36	46	67
2.36 mm	45	38	40	24	30	44
1.18 mm	33	26	30	17	19	31
0.60 mm	27	16	21	13	13	22
0.30 mm	16	9	14	9	7	12
0.15 mm	7	5	6	6	5	7
0.075 mm	5	4	4	4.6	3.9	4
Asphalt Cement Content, %	5.2	5.7	4.5	4.6	4.25	5.9

The British Pendulum Test was used to determine the surface friction characteristics of each mix under both dry and wet conditions. Table 6 presents the data obtained for this testing. A Duncan's comparison of means was used to determine if there was a statistical difference between the six gradations. The results of this analysis are also shown in Table 6. Mixes that are statistically different have different letter designations. The Duncan rankings indicate that there was no consistent trend due to the changes in mix design methods. This conclusion is the same, regardless of whether the samples were tested wet or dry. Table 6 does show that there were statistical differences between several of the gradations.

TABLE 6. Results from the British Pendulum Tester Using Laboratory-Compacted Samples.

Division	Mean BPN	Std. Dev.	Duncan Ranking		
Samples Tested Dry					
Division 7 Marshall	91.3	0.6	A		
Division 2 Superpave	90.3	3.5	A	B	
Division 6 Superpave	88.0	3.0	A	B	
Division 3 Marshall	86.3	1.5		B	
Division 9 Marshall	80.3	3.2			C
Division 4 Superpave	78.3	2.1			C
Samples Tested Wet					
Division 6 Superpave	68.7	3.1	A		
Division 3 Marshall	67.0	3.0	A	B	
Division 2 Superpave	66.7	0.6	A	B	
Division 4 Superpave	64.0	1.0		B	
Division 7 Marshall	63.7	0.6		B	
Division 9 Marshall	61.0	1.0			C

Figure 6a shows the three gradations that were most clearly statistically different (A and C rankings). It appears from this figure that for the dry testing condition, the overall coarseness of the gradation affected the BPN number. That is, the coarser the gradation, the higher the BPN. In this figure one Superpave and one Marshall mix (both 9.5 mm nominal maximum size) had the same Duncan ranking; they had the lowest two BPN values. One of the 19 mm Marshall mixes had the highest BPN value.

Figure 6b shows the two gradations that were statistically different using the wet testing condition. In this case, it appears that the coarseness of the coarse aggregate fraction is responsible for the statistical differences; the coarser the coarse fraction, the higher the BPN value. Note that in this case, the traditional Marshall mix design (9.5 nominal maximum aggregate) is the one with the lower BPN value and the Superpave mix (19 mm nominal maximum aggregate) had the highest value.

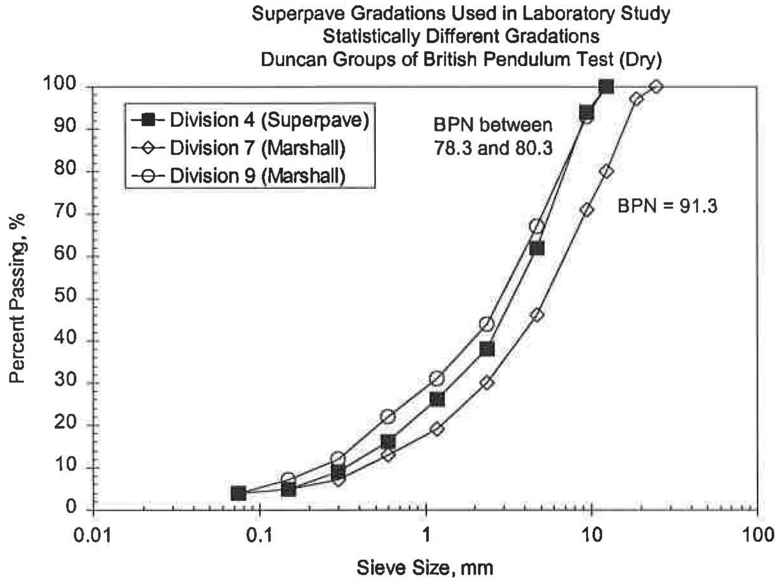

FIGURE 6a. Gradations that produced significantly different BPN (dry) values.

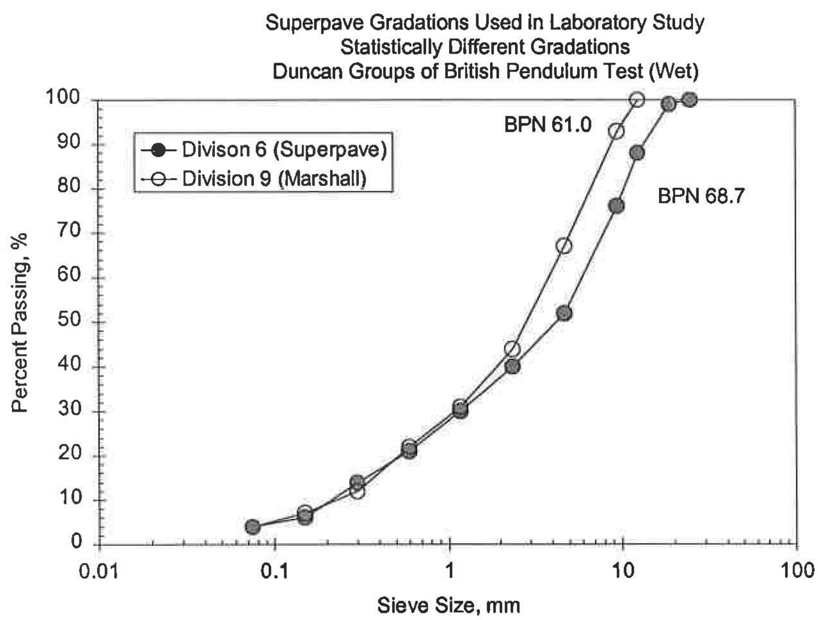

FIGURE 6b. Gradations that produced significantly different BPN (wet) values.

LTPP Database Analysis

A total of 62 projects were selected from the General Pavement Sections (GPS) Long Term Pavement Performance (LTPP) database. While the macrotexture was not measured for the LTPP sections, previous research provided an equation for estimating the macrotexture for a mixture based on the percent passing the 4.75 mm (No.4) sieve, the coefficients of curvature and uniformity, and the maximum size of aggregate (Stroup-Gardiner and Brown, 2000):

$$ETD = 0.0198\,(\text{Max aggregate size}) - 0.004984\,(\%\text{ passing 4.75 mm}) + 0.1038\,C_c - 0.004861\,C_u.$$

where:

ETD = estimated mean texture depth, mm

Max aggregate size = smallest sieve size that has 100 percent passing, mm

% passing 4.75 mm = the percent passing the 4.75 mm sieve in decimal form

$C_c = D_{60} / D_{10}$

$C_u = D_{30}^2 / (D_{60}\,D_{10})$

Data extracted for each of the 62 LTPP projects included the measured skid numbers, date of skid testing, the original date the section was opened to traffic, and the aggregate gradation information needed to estimate the macrotexture. The beginning and ending skid numbers for each section were averaged so that one skid number was obtained. Each gradation was graphed and the percent passing, and C_u and C_c parameters were determined.

Figure 7 shows the relationship between the estimated macrotexture and the reported skid numbers. The data scatter most likely reflects a number of factors. The first is the range of time between opening the sections to traffic and the reported friction testing which was from 1 to 16 years. Projects with less than 5 years between opening and testing were separated out and identified on this figure. There was little change in the power law relationship for either database. The second factor likely influencing the data scatter is that the SN40 is a function of not only macrotexture but of the microtexture (i.e., BPN) (Forster, 1989). This data is not available in the LTPP database so there is no way to sort the data by this parameter. The third factor is that aggregates prone to polishing will have unusually low SN40 values. Forster (1989) indicated that the limestone aggregates in his study all showed unusually low values and were therefore eliminated from his analysis. Since it is impossible to sort out polishing versus non-polishing limestone from the LTPP database, all values were left in the analysis. While there is a low correlation coefficient, the best-fit power law curve is similar to the curves developed by other researchers (Figure 1) using experimental data. The only conclusions that can be drawn about the potential skid resistance of the Alabama projects are that there is a reasonable expectation that the SN40 number should be above 40.

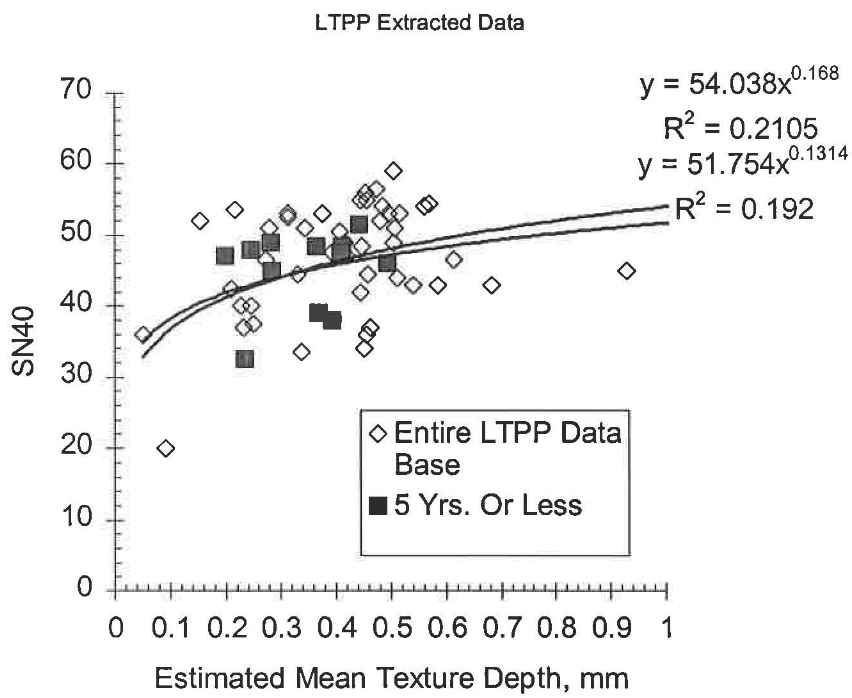

FIGURE 7. LTPP data used to develop a relationship between the estimated texture depth and the skid resistance.

CONCLUSIONS

The following conclusions can be drawn from this research:

1. The macrotexture is a function of the nominal maximum size of aggregates. The macrotexture is less than 0.37 mm for nominal maximum aggregate sizes of 9.5 and 12.5 mm, regardless of the type of mix design method used to select the target gradation and asphalt content. The macrotexture for 25 mm nominal maximum size aggregate gradations are typically greater than 0.5 mm.
2. The BPN determined for laboratory-compacted samples indicates that this value is also a function of the nominal maximum size aggregate. When tested with the surface of the sample dry, the coarser overall gradation with a 12.5 nominal maximum size aggregate had a higher BPN (around 91) than a finer gradation with a 9.5 mm nominal maximum size. When the same samples were tested with a wet surface, only the coarseness of the aggregate fraction above 1.18 mm (no. 16) sieve size seemed to influence the laboratory BPN.
3. An attempt to use the LTPP database to develop a predictive equation for estimating skid number (SN40) from a macrotexture estimated from gradation characteristics (i.e., maximum aggregate size, % passing the 0.075 mm (no. 200) sieve), C_c, C_u) was not successful. This is most likely due to key information about aggregate types and properties that are not readily available.

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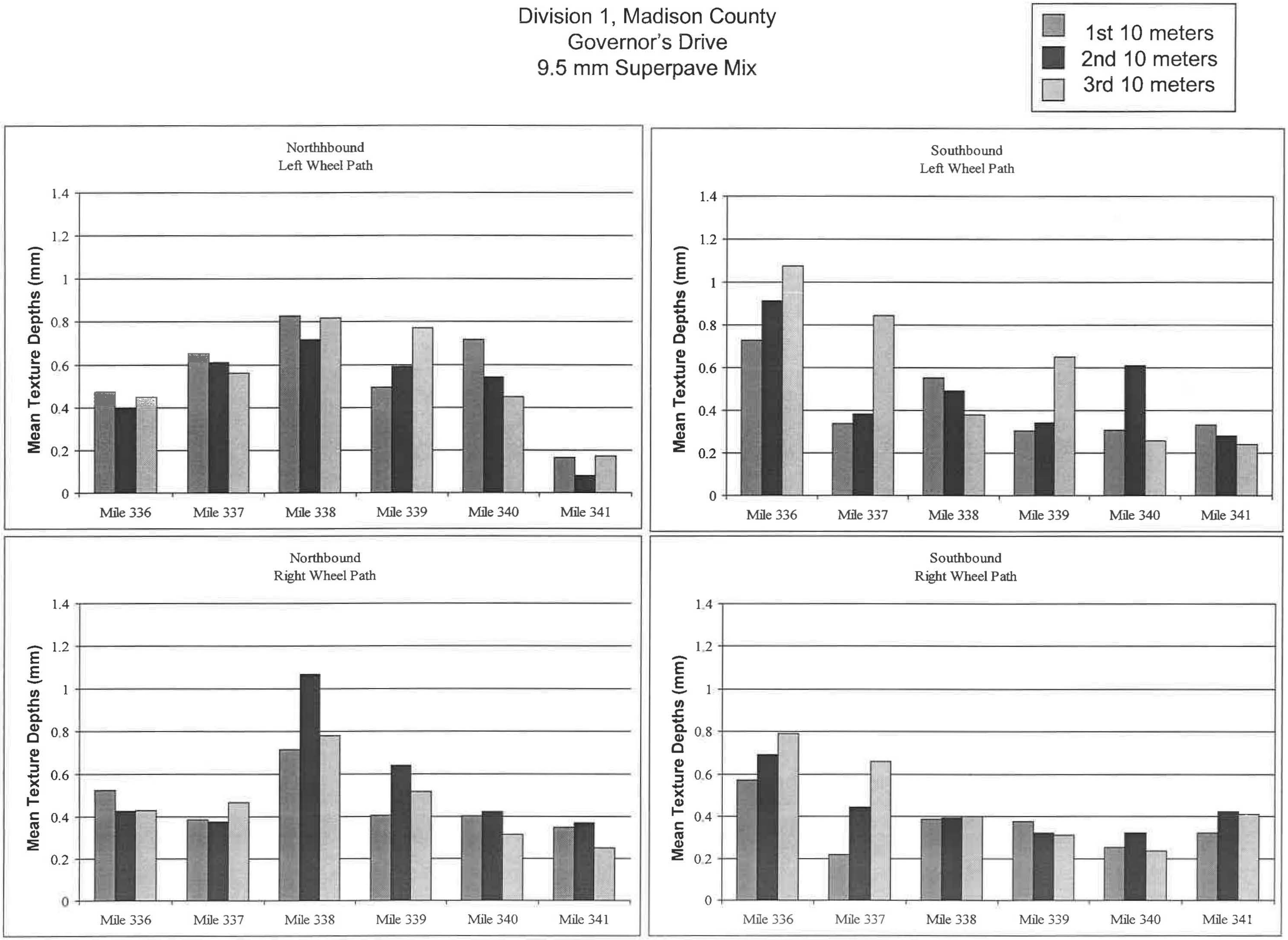
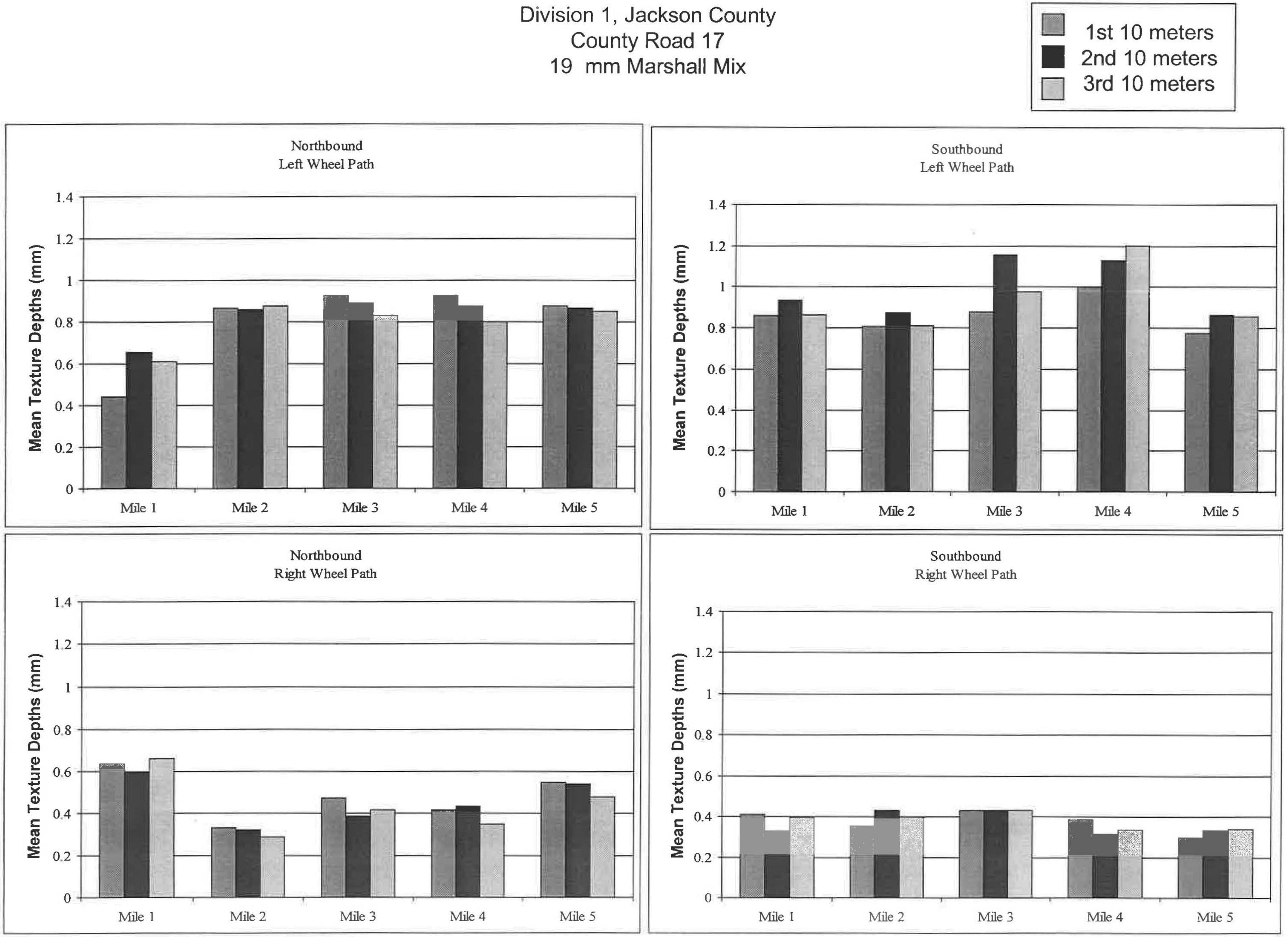
APPENDIX A

Macrotexture for Each 100 Meters for Each Lane for Each Project

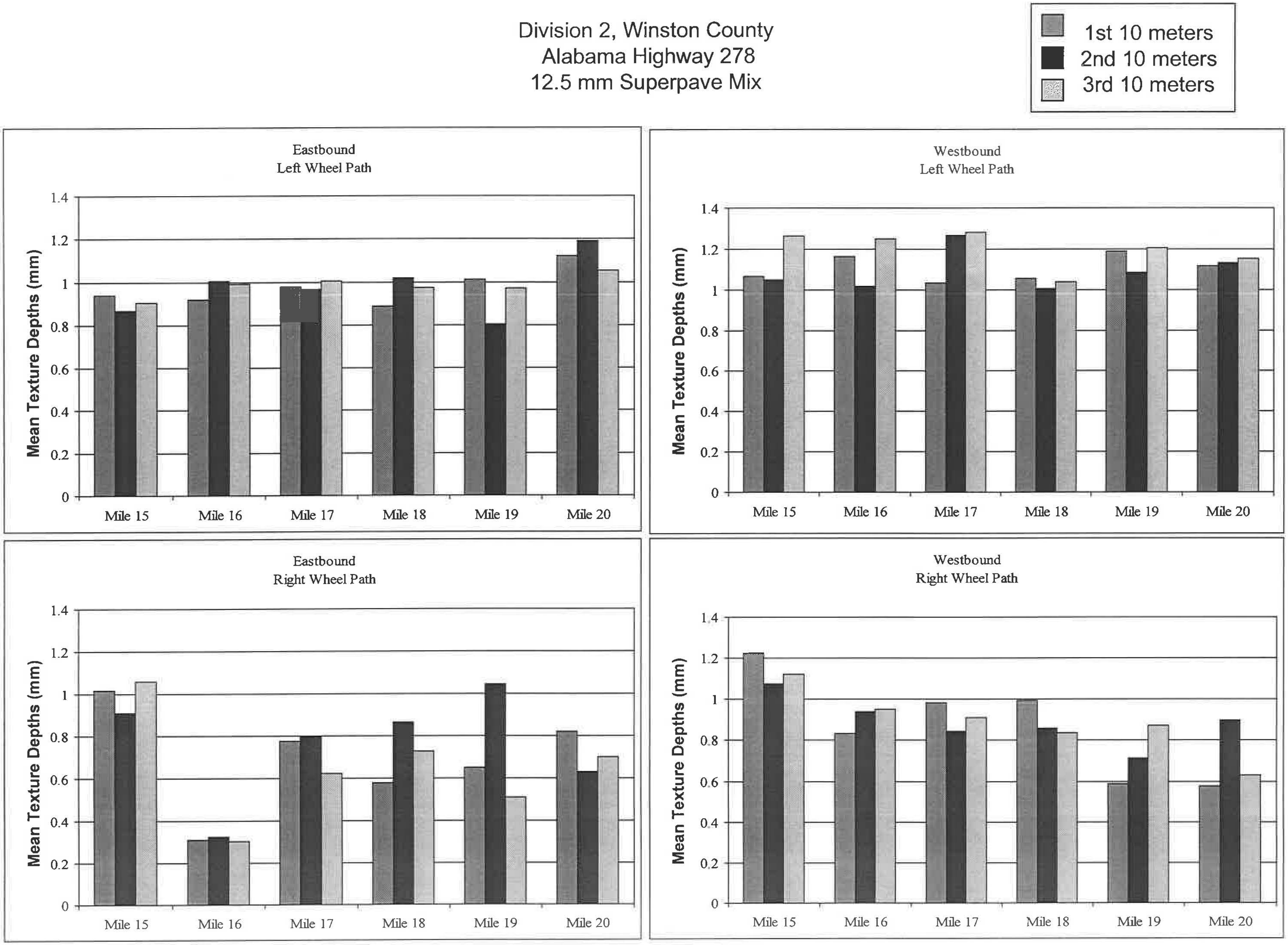
Division 1, Madison County
Governor's Drive
9.5 mm Superpave Mix

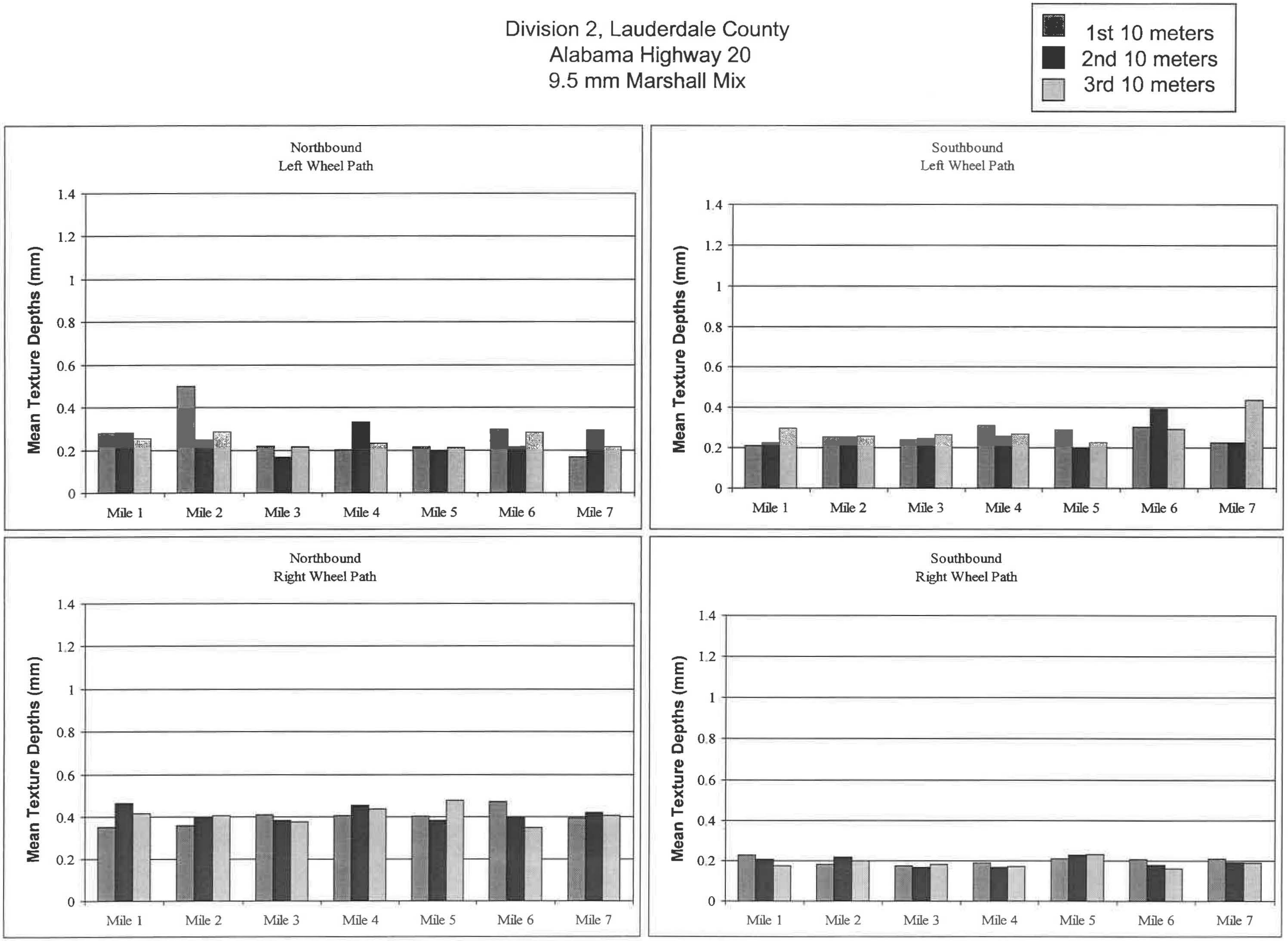


Division 1, Jackson County
County Road 17
19 mm Marshall Mix



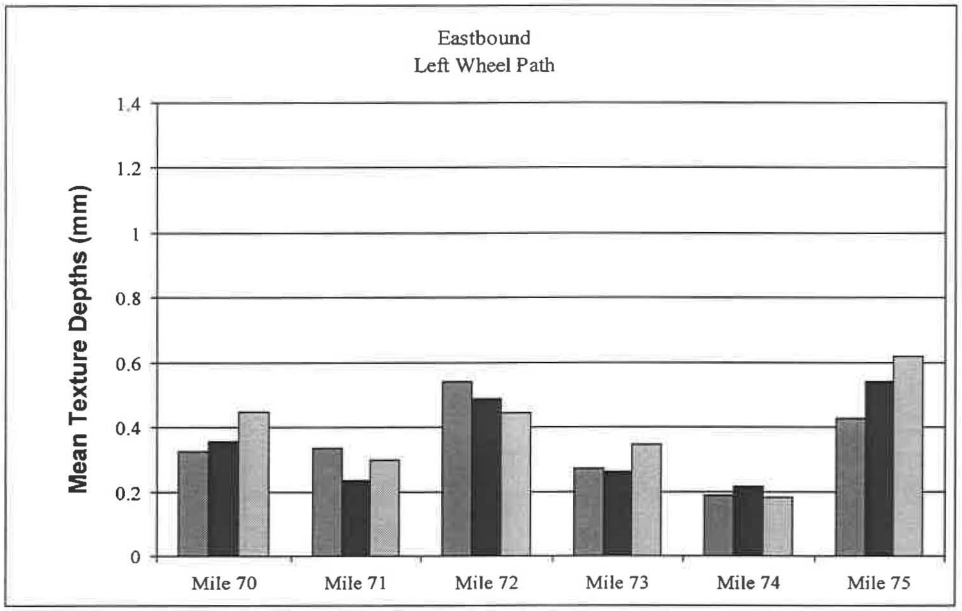
Division 2, Winston County
Alabama Highway 278
12.5 mm Superpave Mix

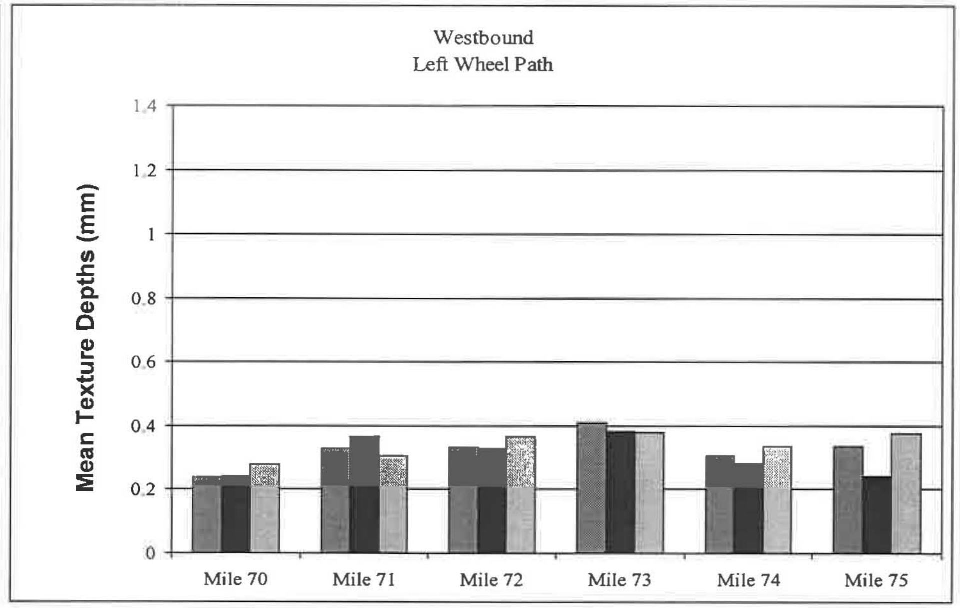


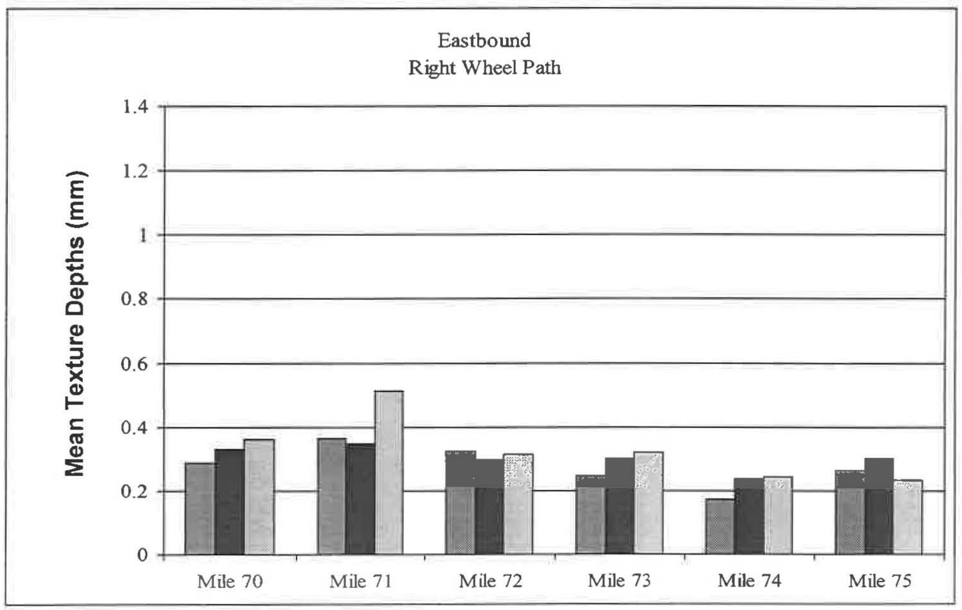

Division 2, Lauderdale County
Alabama Highway 20
9.5 mm Marshall Mix
1st 10 meters
2nd 10 meters
3rd 10 meters
Northbound
Left Wheel Path
Southbound
Left Wheel Path
Northbound
Right Wheel Path
Southbound
Right Wheel Path
Mean Texture Depths (mm)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Mile 1
Mile 2
Mile 3
Mile 4
Mile 5
Mile 6
Mile 7

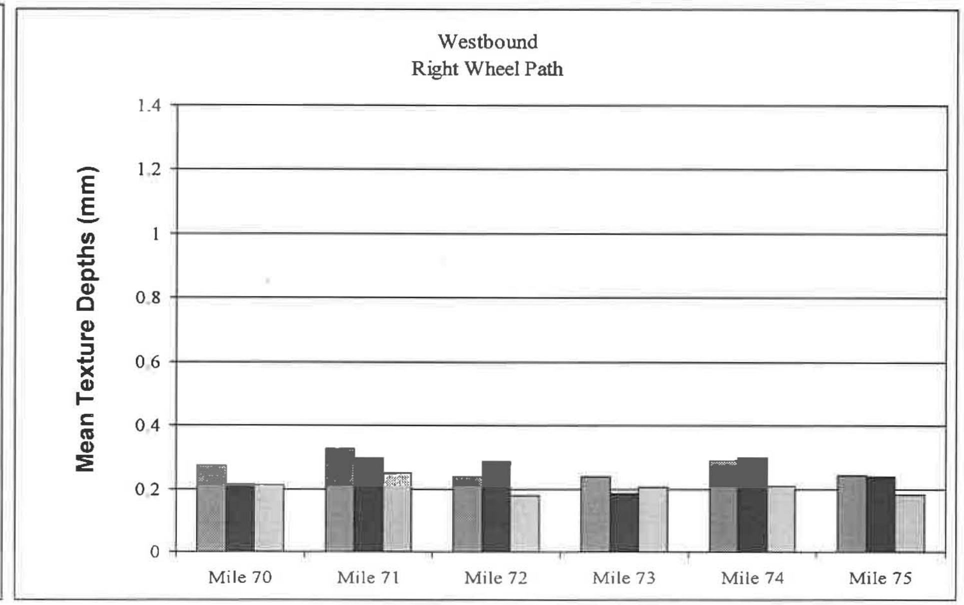
Division 3, Walker County
US Highway 78
9.5 mm Superpave Mix

1st 10 meters
2nd 10 meters
3rd 10 meters

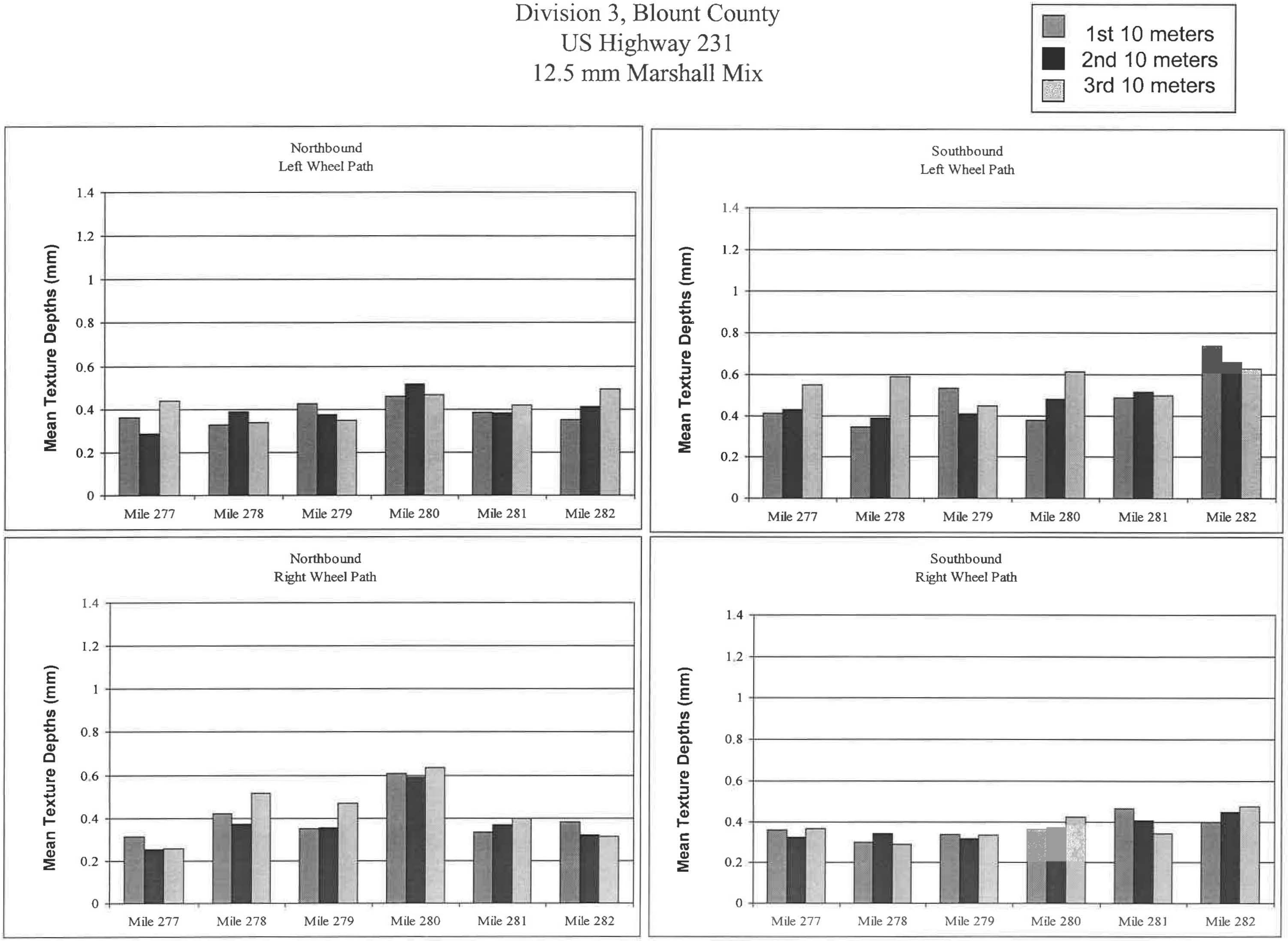


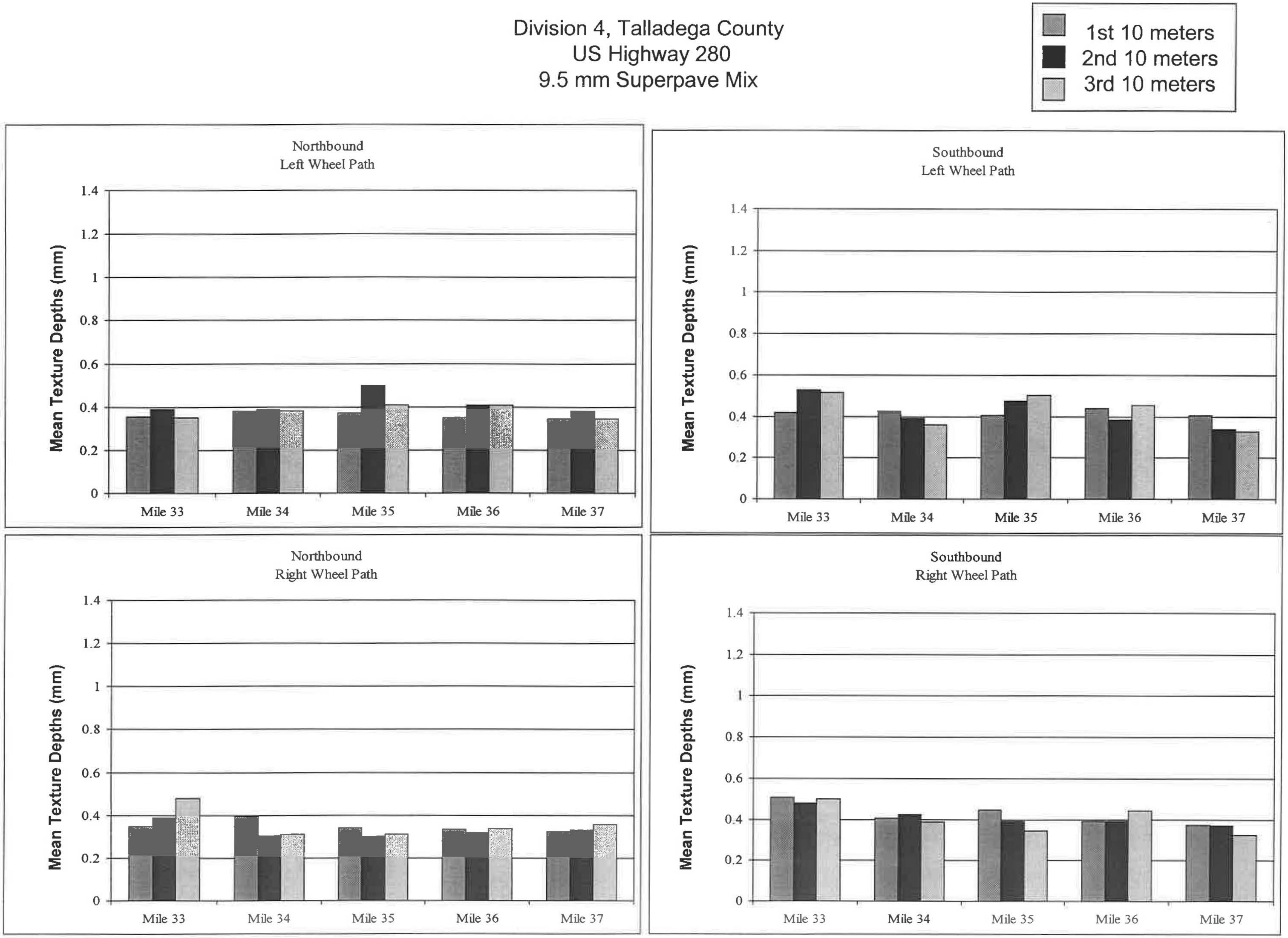


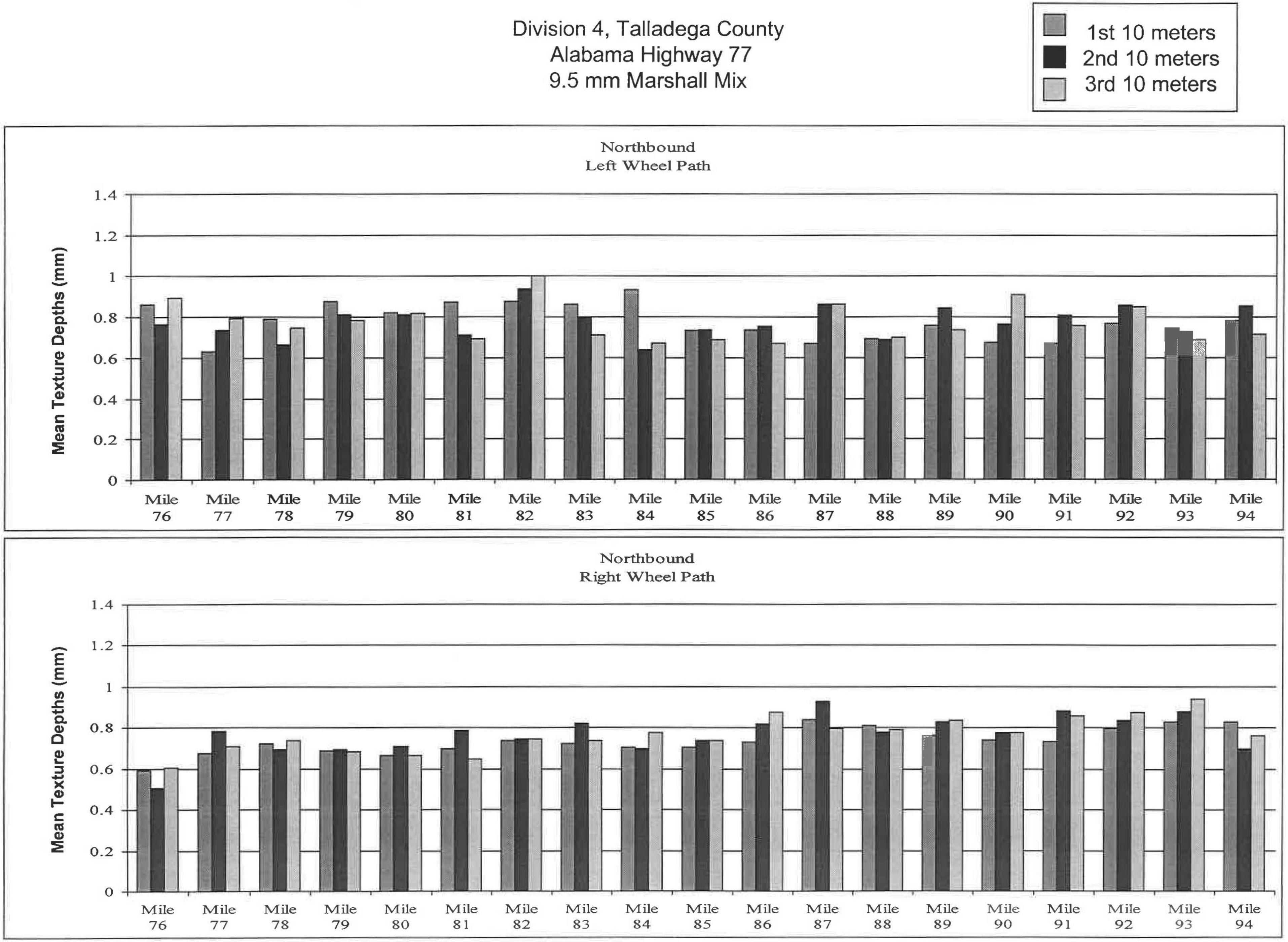




Division 3, Blount County
US Highway 231
12.5 mm Marshall Mix

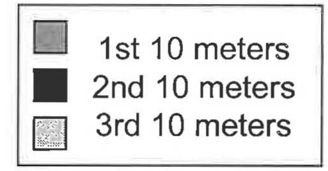


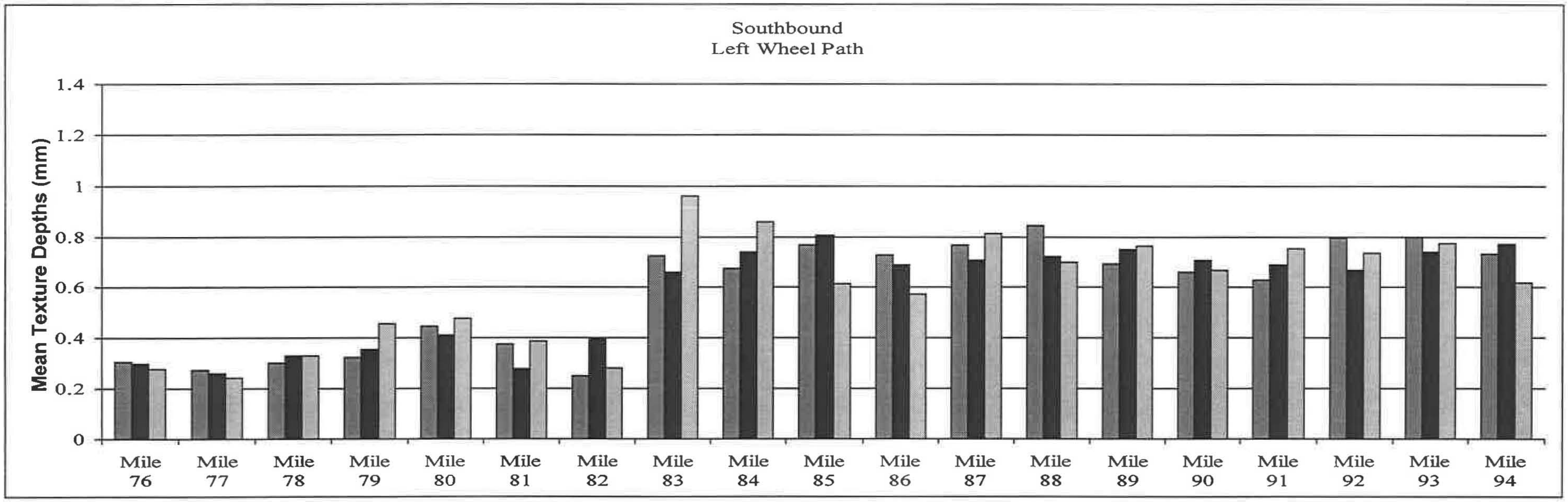

Division 4, Talladega County
US Highway 280
9.5 mm Superpave Mix
1st 10 meters
2nd 10 meters
3rd 10 meters
Northbound
Left Wheel Path
Southbound
Left Wheel Path
Northbound
Right Wheel Path
Southbound
Right Wheel Path
Mean Texture Depths (mm)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Mile 33
Mile 34
Mile 35
Mile 36
Mile 37

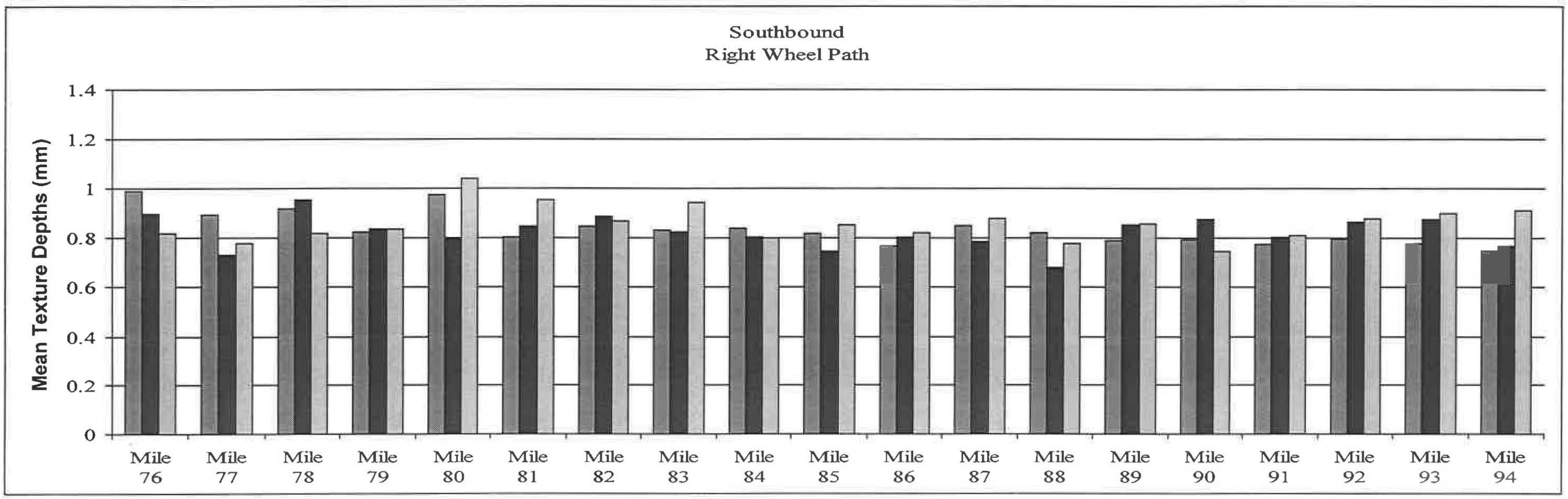


Division 4, Talladega County
Alabama Highway 77
9.5 mm Marshall Mix
1st 10 meters
2nd 10 meters
3rd 10 meters
Northbound
Left Wheel Path
Mean Texture Depths (mm)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Mile 76
Mile 77
Mile 78
Mile 79
Mile 80
Mile 81
Mile 82
Mile 83
Mile 84
Mile 85
Mile 86
Mile 87
Mile 88
Mile 89
Mile 90
Mile 91
Mile 92
Mile 93
Mile 94
Northbound
Right Wheel Path
Mean Texture Depths (mm)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Mile 76
Mile 77
Mile 78
Mile 79
Mile 80
Mile 81
Mile 82
Mile 83
Mile 84
Mile 85
Mile 86
Mile 87
Mile 88
Mile 89
Mile 90
Mile 91
Mile 92
Mile 93
Mile 94

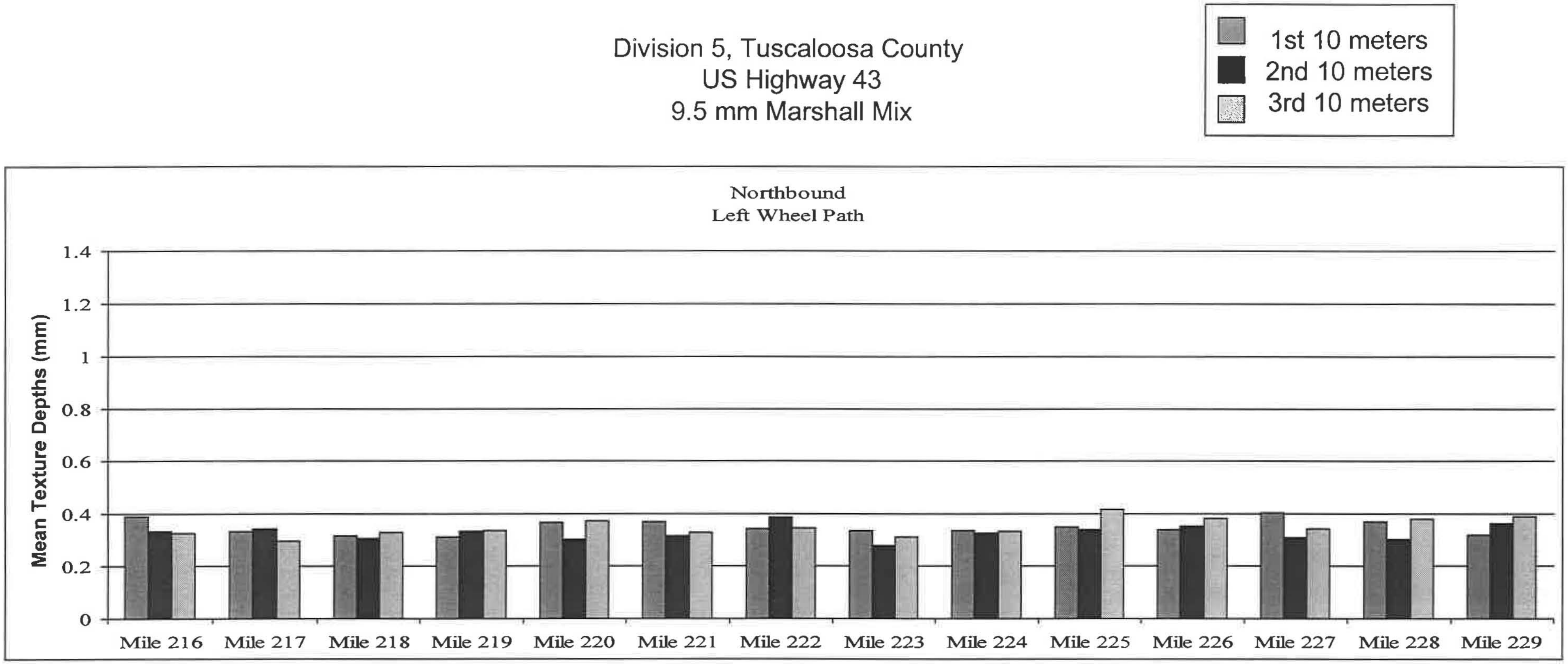
Division 4, Alabama Highway 77
Talladega County
9.5 mm Marshall Mix

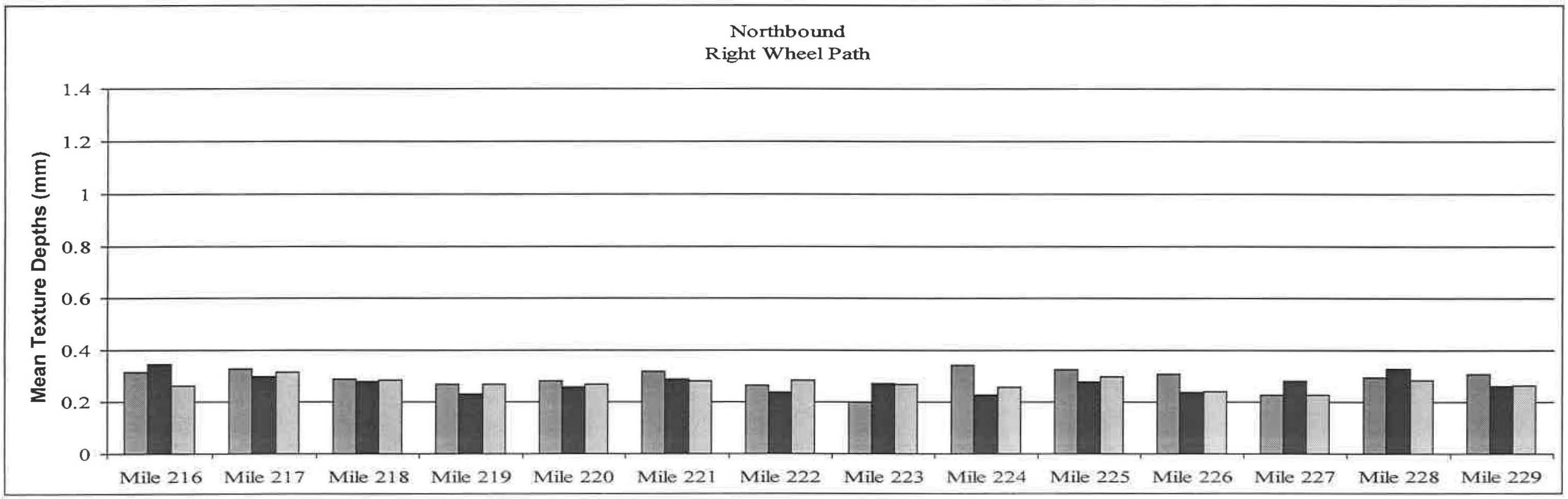


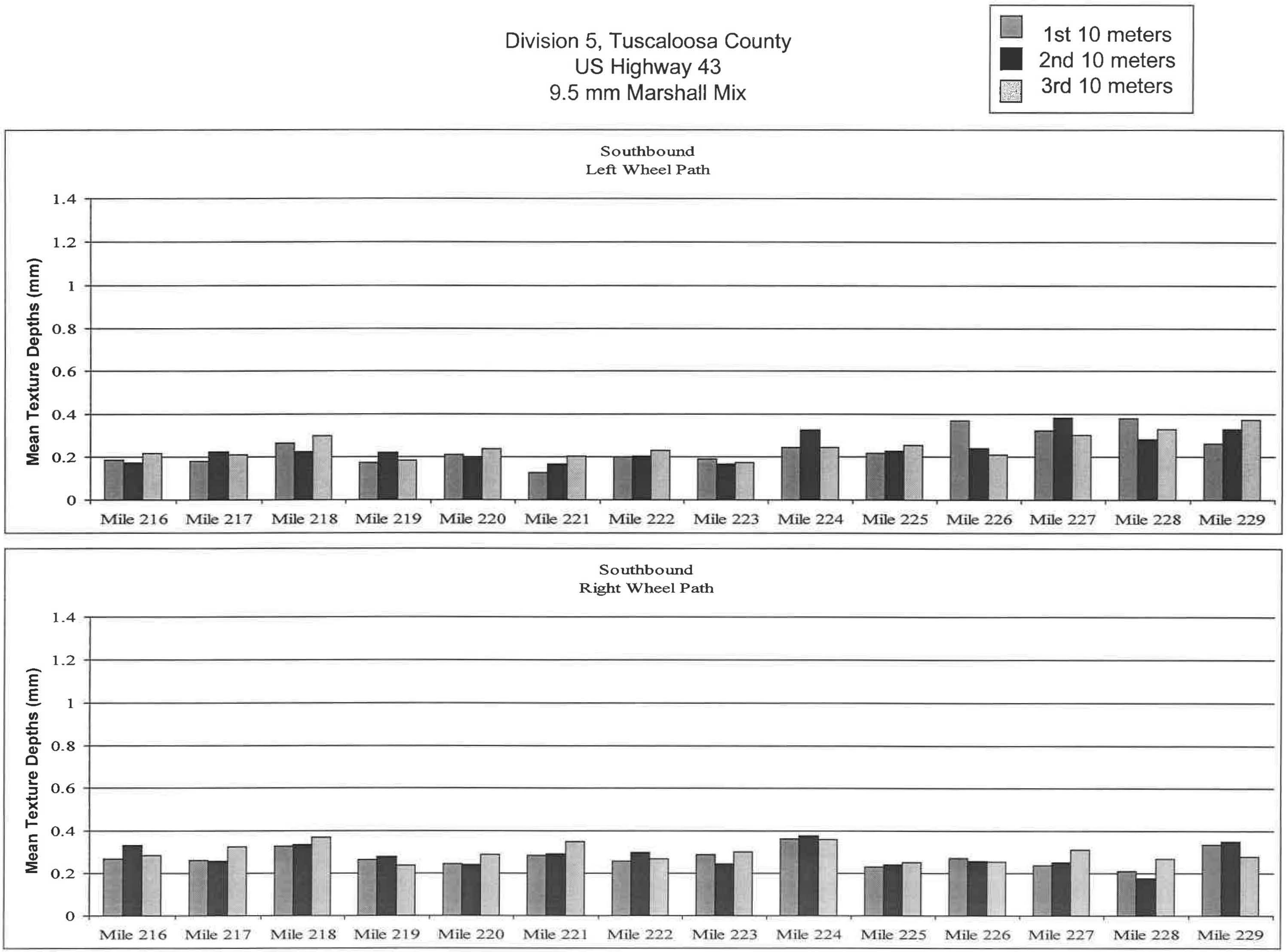




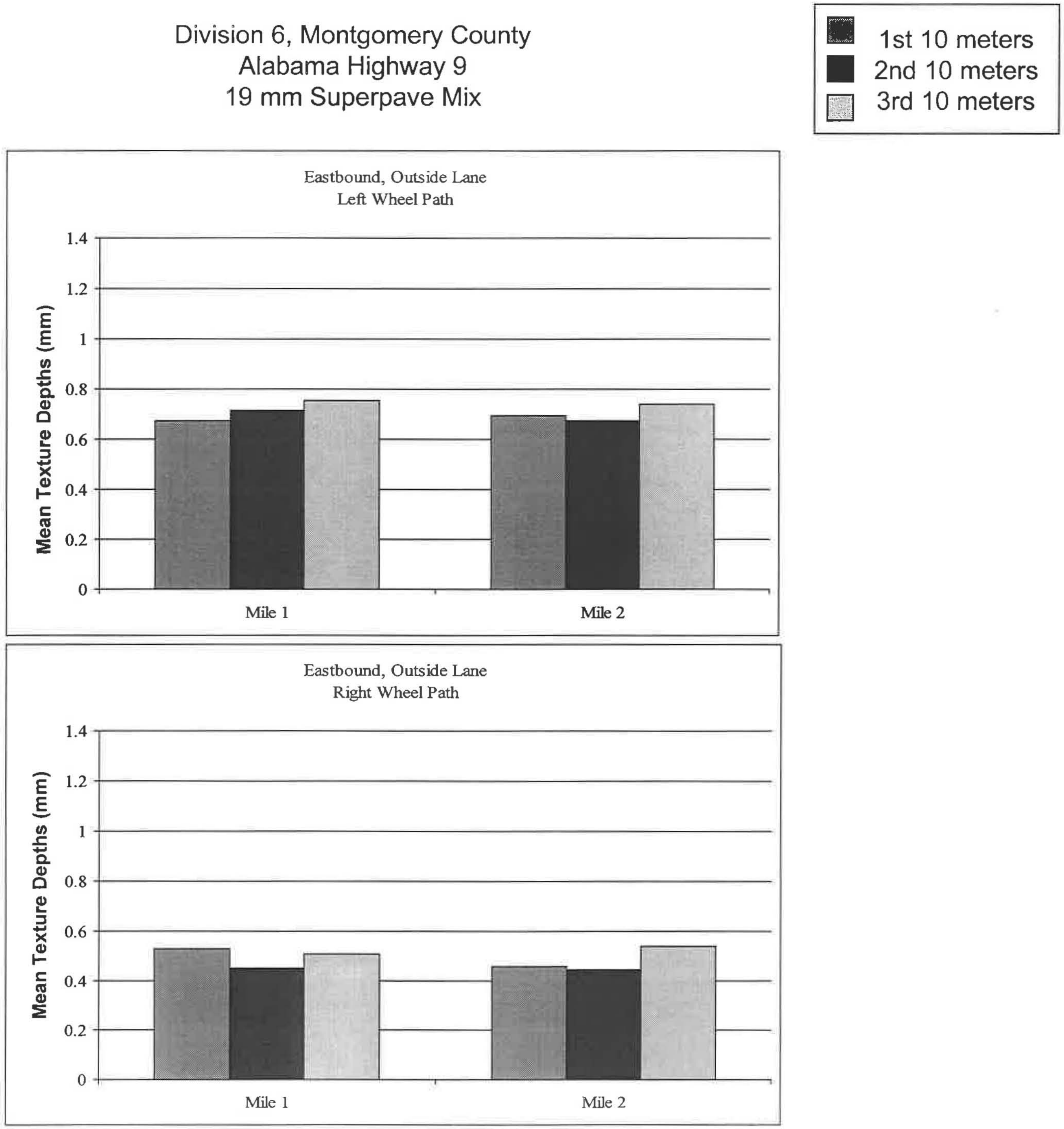
Division 5, Tuscaloosa County
US Highway 43
9.5 mm Marshall Mix

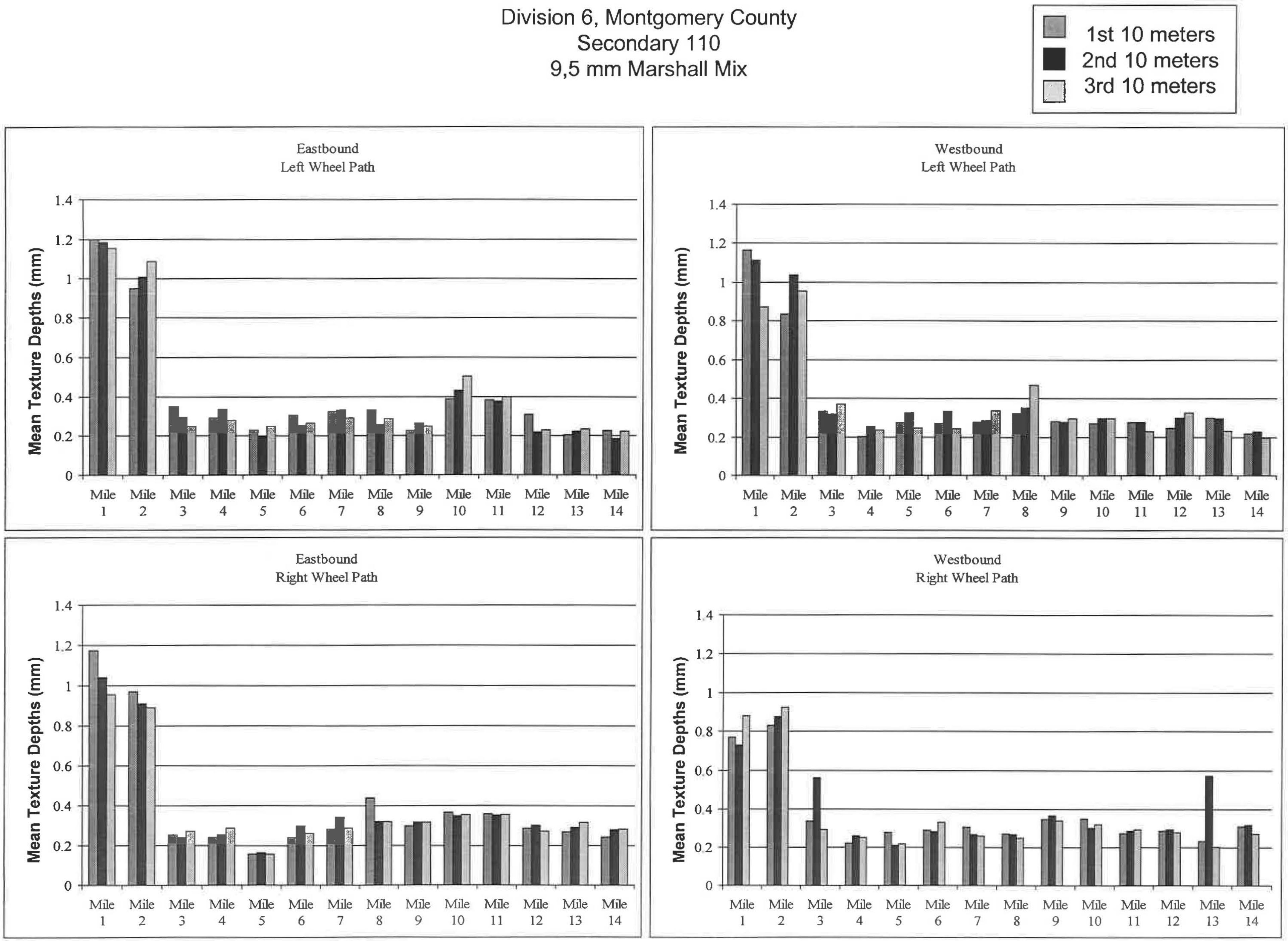




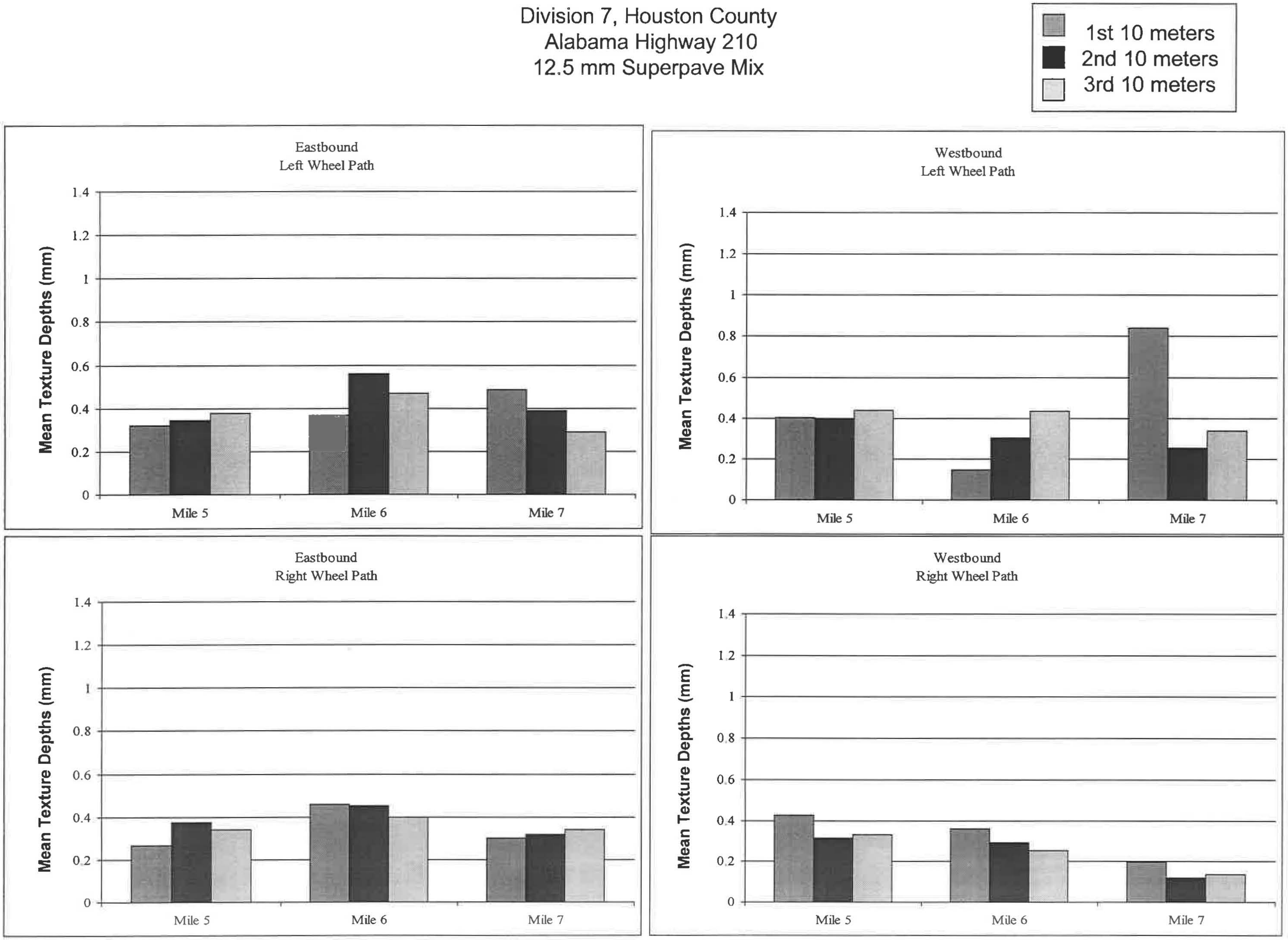

Division 5, Tuscaloosa County
US Highway 43
9.5 mm Marshall Mix
1st 10 meters
2nd 10 meters
3rd 10 meters
Southbound
Left Wheel Path
Mean Texture Depths (mm)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Mile 216
Mile 217
Mile 218
Mile 219
Mile 220
Mile 221
Mile 222
Mile 223
Mile 224
Mile 225
Mile 226
Mile 227
Mile 228
Mile 229
Southbound
Right Wheel Path
Mean Texture Depths (mm)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Mile 216
Mile 217
Mile 218
Mile 219
Mile 220
Mile 221
Mile 222
Mile 223
Mile 224
Mile 225
Mile 226
Mile 227
Mile 228
Mile 229

Division 6, Montgomery County
Alabama Highway 9
19 mm Superpave Mix

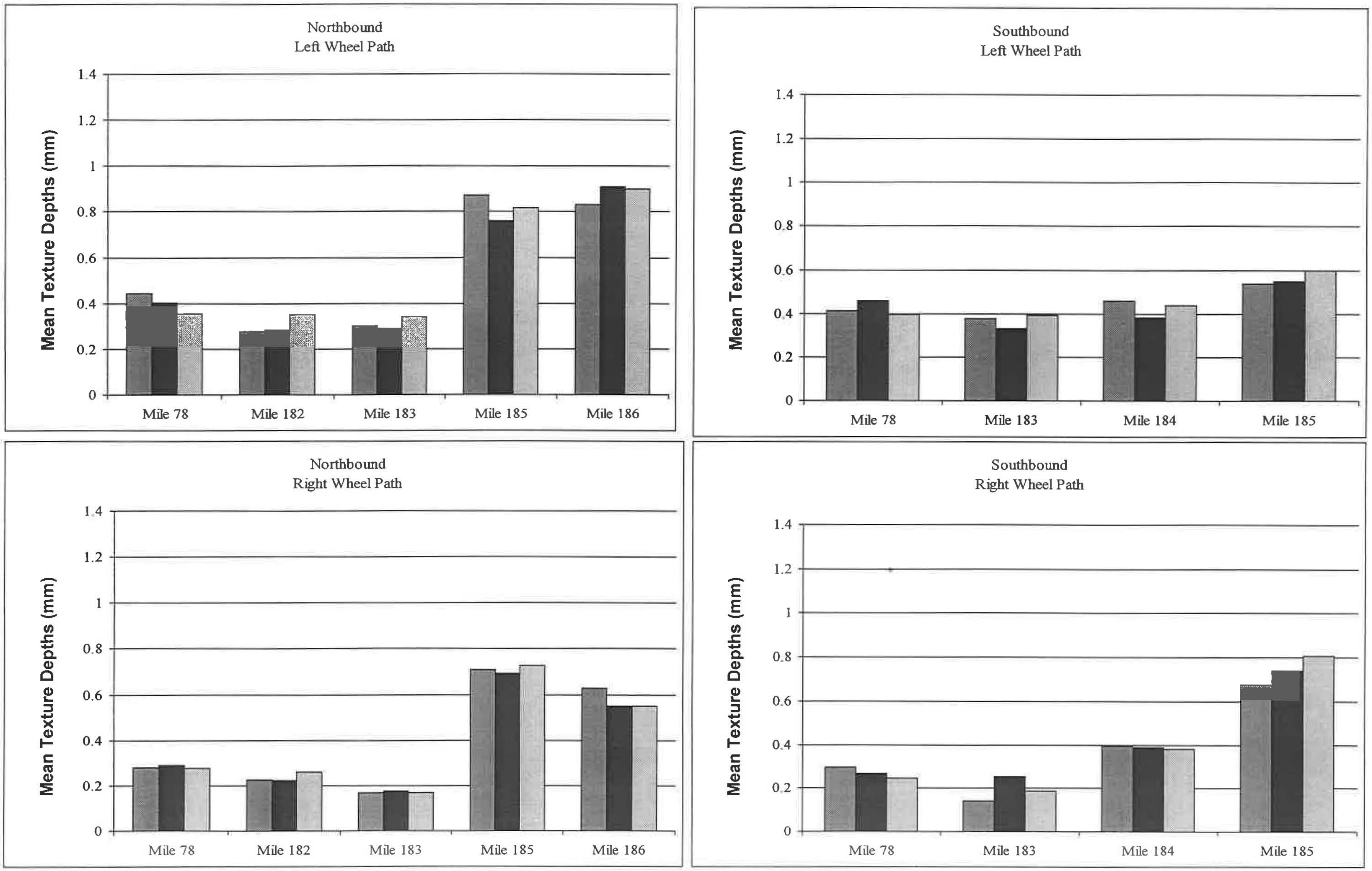


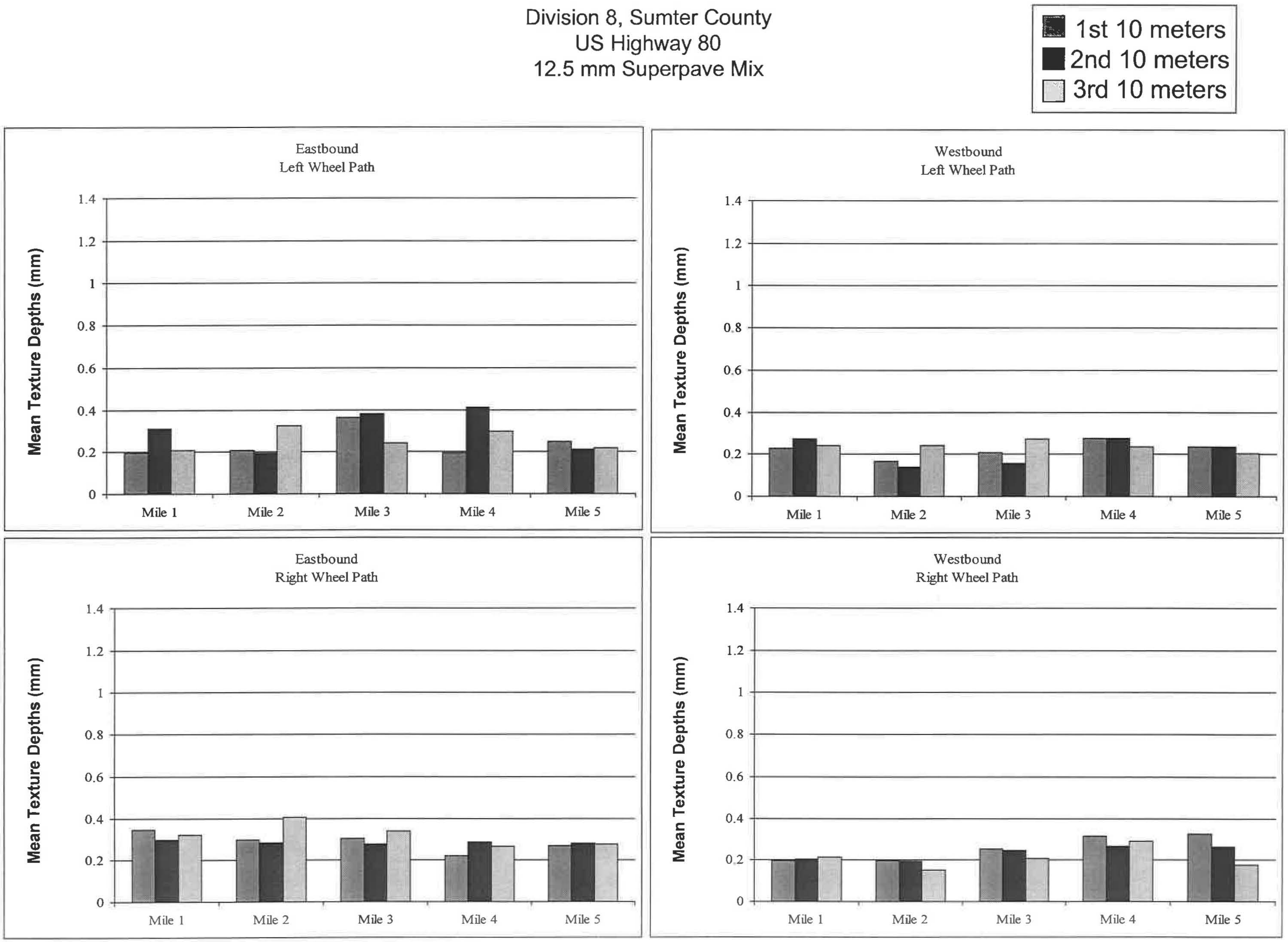

Division 6, Montgomery County
Secondary 110
9,5 mm Marshall Mix
1st 10 meters
2nd 10 meters
3rd 10 meters
Eastbound
Left Wheel Path
Westbound
Left Wheel Path
Eastbound
Right Wheel Path
Westbound
Right Wheel Path
Mean Texture Depths (mm)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Mile 1
Mile 2
Mile 3
Mile 4
Mile 5
Mile 6
Mile 7
Mile 8
Mile 9
Mile 10
Mile 11
Mile 12
Mile 13
Mile 14

Division 7, Houston County
Alabama Highway 210
12.5 mm Superpave Mix

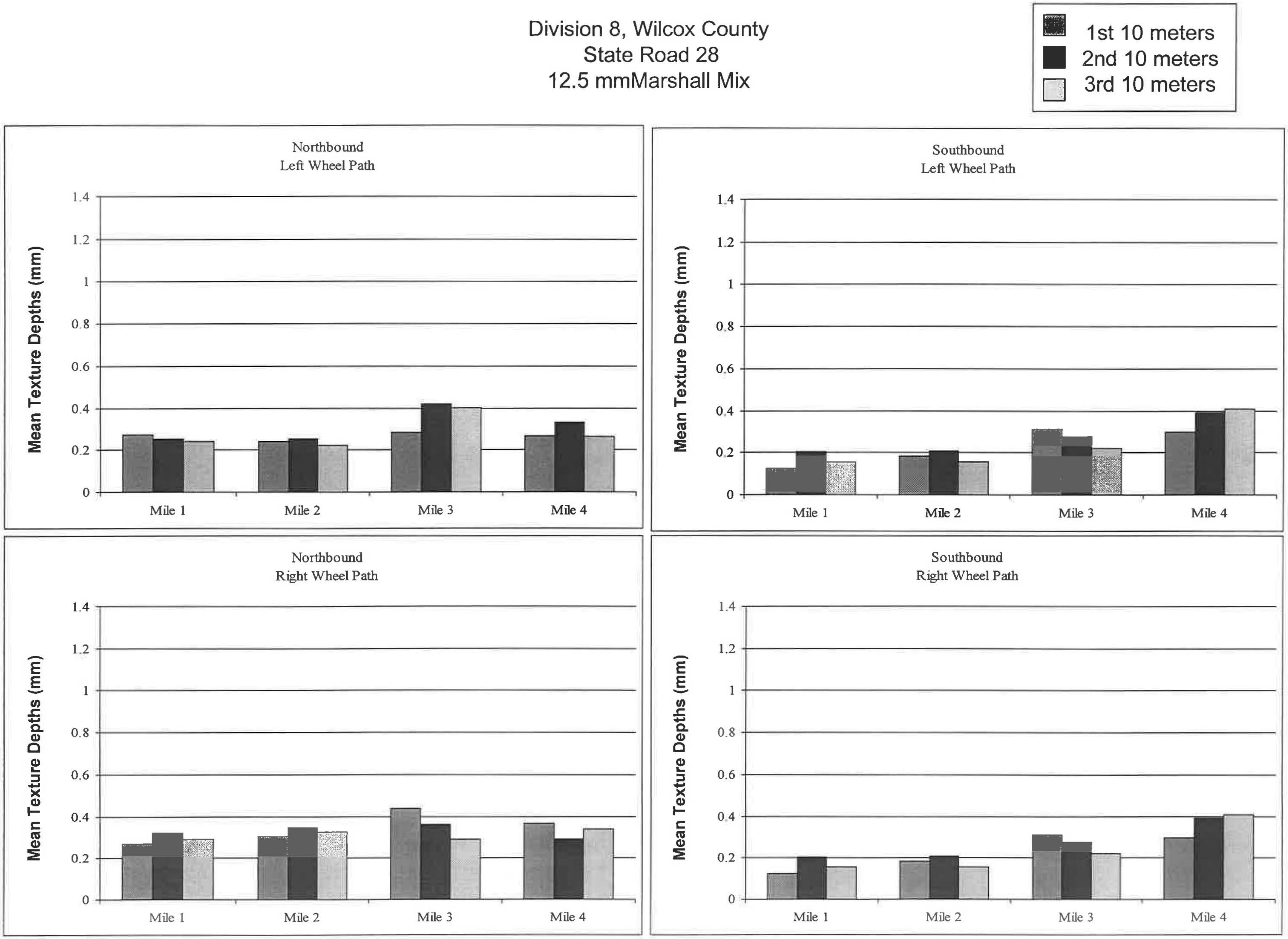


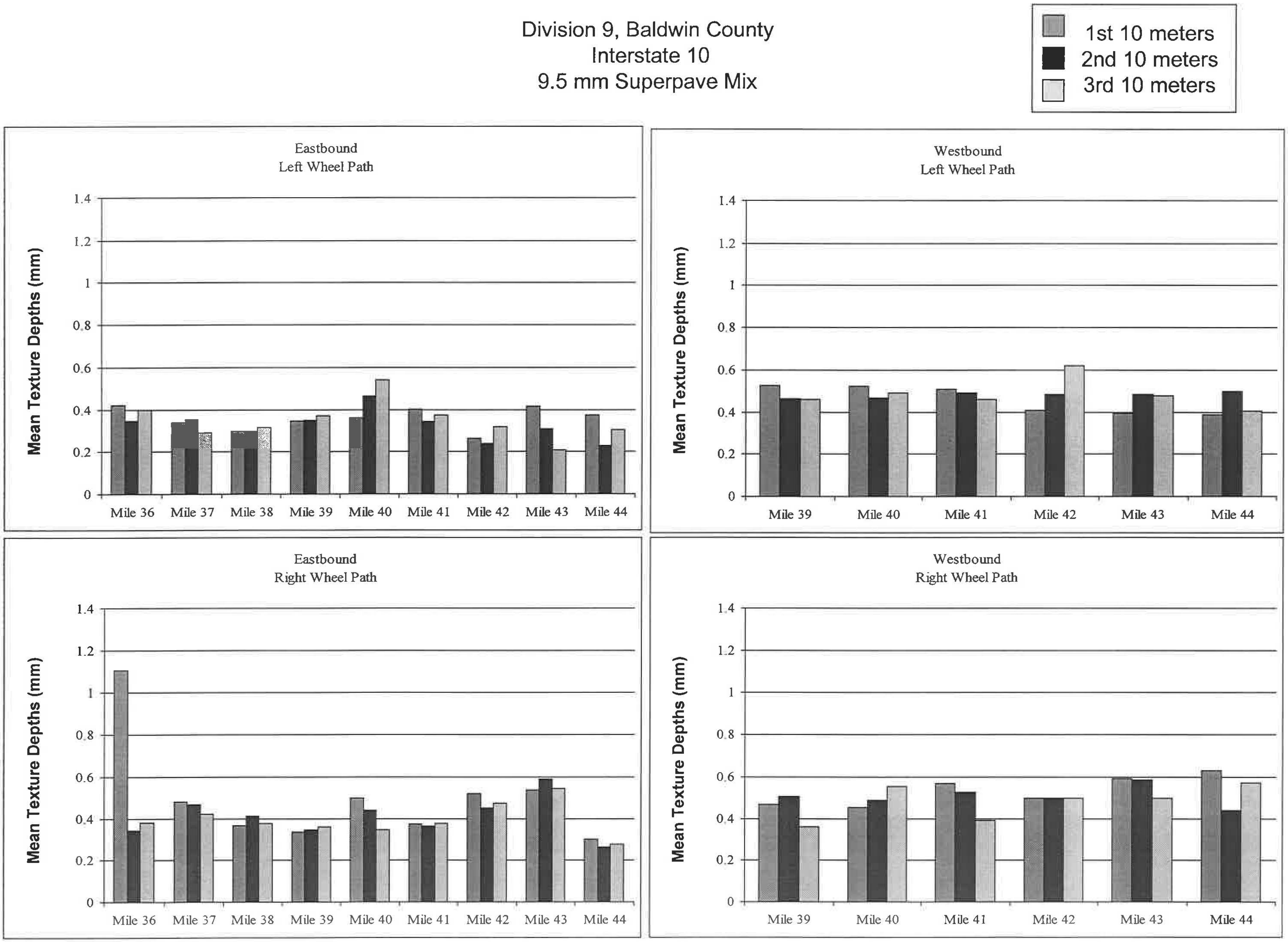
Division 7, Pike County
US Highway 231
19 mm Marshall Mix



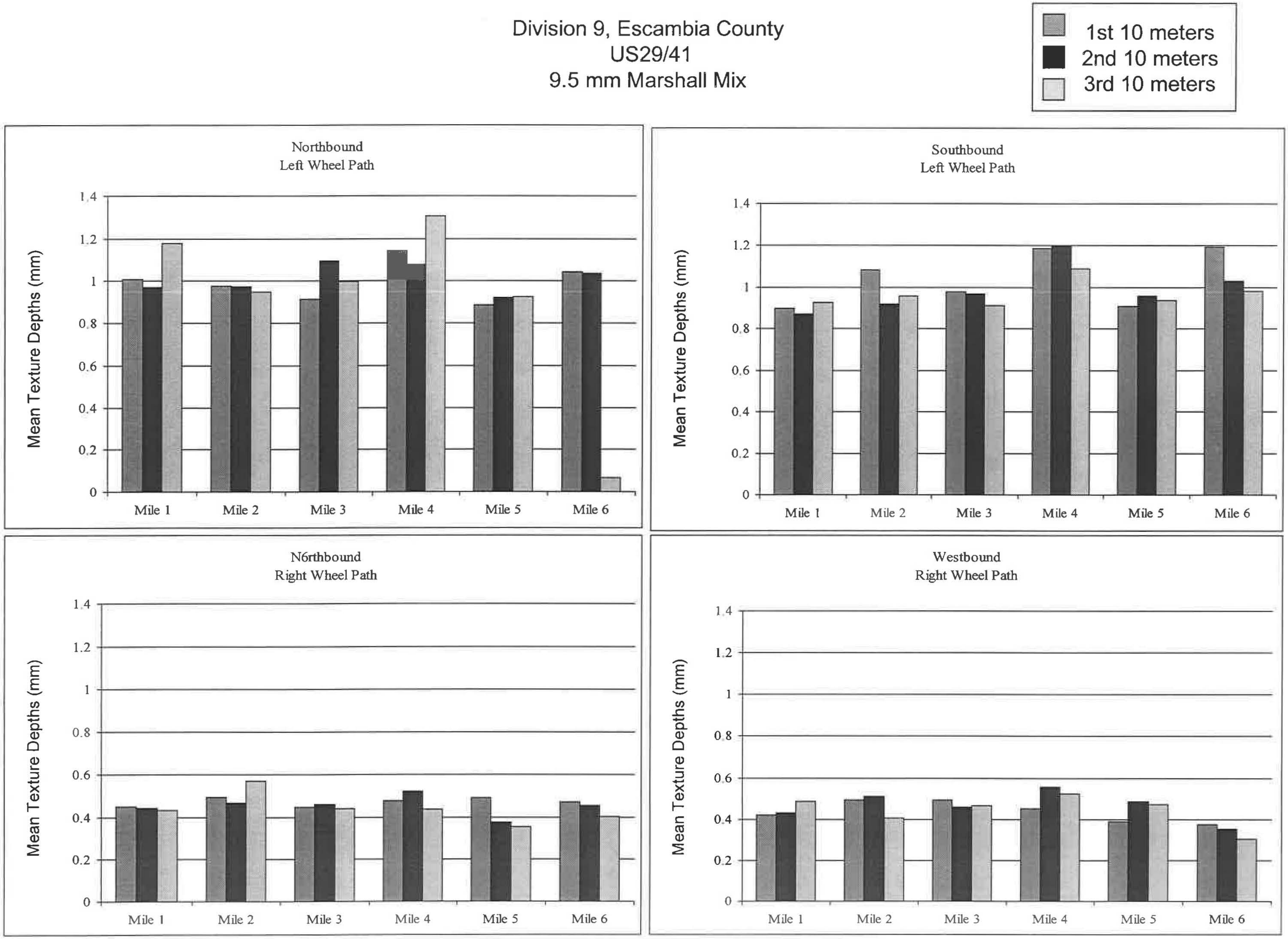

Division 8, Sumter County
US Highway 80
12.5 mm Superpave Mix
1st 10 meters
2nd 10 meters
3rd 10 meters
Eastbound
Left Wheel Path
Westbound
Left Wheel Path
Eastbound
Right Wheel Path
Westbound
Right Wheel Path
Mean Texture Depths (mm)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Mile 1
Mile 2
Mile 3
Mile 4
Mile 5

Division 8, Wilcox County
State Road 28
12.5 mmMarshall Mix





Division 9, Baldwin County
Interstate 10
9.5 mm Superpave Mix
1st 10 meters
2nd 10 meters
3rd 10 meters
Eastbound
Left Wheel Path
Westbound
Left Wheel Path
Eastbound
Right Wheel Path
Westbound
Right Wheel Path
Mean Texture Depths (mm)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Mile 36
Mile 37
Mile 38
Mile 39
Mile 40
Mile 41
Mile 42
Mile 43
Mile 44


Division 9, Escambia County
US29/41
9.5 mm Marshall Mix
1st 10 meters
2nd 10 meters
3rd 10 meters
Northbound
Left Wheel Path
Southbound
Left Wheel Path
N6rthbound
Right Wheel Path
Westbound
Right Wheel Path
Mean Texture Depths (mm)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Mile 1
Mile 2
Mile 3
Mile 4
Mile 5
Mile 6