Use of Gyratory Testing Machine to Evaluate Shear Resistance of Asphalt Paving Mixture

SIGURJON SIGURJONSSON AND BYRON E. RUTH

Procedures currently used in the design of mixtures have several major deficiencies that affect the reliability of the designed mix. The results obtained from investigations of mix behavior in the gyratory testing machine (GTM) indicate that deficiencies in mix design are primarily associated with the characteristics of the aggregates, particularly the gradation. Mixtures compacted in the GTM to simulate field compaction were tested at 60°C (140°F) in the GTM to simulate traffic densification. It was observed that high-quality aggregate blends (no significant rutting) exhibited low sensitivity to change in asphalt content and maintained high shear resistance except at the highest asphalt content. GTM tests conducted on mixtures duplicating those observed to have early and excessive pavement rutting exhibited high sensitivity to asphalt content, lower shear resistance, and sensitivity to changes in gradation. The results obtained from this investigation indicated that the GTM can be used to evaluate the effect of aggregate characteristics on hot-mix properties and to develop procedures for mix design.

Asphalt concrete paving mixtures are conventionally designed by using either the Marshall or the California (Hveem) design procedure. These procedures require the selection of blended aggregates conforming to quality and gradation requirements. A fixed level of compactive effort is used to prepare specimens at different asphalt content levels for testing and determination of the design asphalt content. The effects of variation in aggregate blend typical of hot-mix plant production and of traffic densification on the properties of the mix are not evaluated by these design methods. Currently, there is limited use of laboratory rolling-wheel testing equipment to evaluate a mixture's resistance to consolidation rutting and shoving (plastic deformation). However, this method is time consuming and not very adaptable for use as a mix design procedure.

Gyratory compaction and testing offers numerous advantages over other methods for evaluation or design of asphalt mixtures. Not only does gyratory compaction provide aggregate particle orientation comparable with that of roller compaction in the field, but it can be used to simulate field-compacted densities (*1–3*). Standard test method ASTM D3387 provides procedural information on the compaction and shear properties of bituminous mixtures by means of the U.S. Army Corps of Engineers gyratory testing machine (GTM). Two testing modes for the GTM equipped with either a fixed roller or an oil-filled roller are presented in this standard test method. Both rollers act as a fixed roller that maintains the angle of gyration (fixed strain) until the mix becomes plastic (flushed). Kallas (*4*) developed a mix design procedure by using the fixed roller on the GTM. The GTM can also be equipped with an air roller that allows the angle of gyration to decrease (reduced strain) when shear resistance of the mixture increases (*1,5*). GTM air roller test procedures have been developed to simulate field compaction and traffic densification. Monitoring gyratory shear resistance for 250 or more revolutions during densification testing of samples at 60°C (140°F) provides a profile of gyratory shear (G_s) values to assess the effects of aggregate characteristics and binder content. During densification, the interaction between material characteristics, air void content, and voids in the mineral aggregate (VMA) determines the level of shear resistance (G_s). It is generally assumed that air void contents computed from maximum density values based on either the Rice or the impregnated specific gravity tests are correct. However, the bulk density of GTM-densified mixtures occasionally exceeds the maximum density test values. Therefore, errors or testing variability associated with the computation of air void and VMA parameters for mix evaluation can be eliminated by using one test parameter, G_s, because it is sensitive to all variables relating to mixture design properties.

The ensuing description of GTM tests on different aggregate blends illustrates that mixtures with different types of aggregate but similar gradations can produce totally different gyratory shear response. Information will also be presented to illustrate how small changes in aggregate gradation can drastically alter the behavior of sensitive mixtures.

MATERIALS AND TESTING PROCEDURES

This investigation involved the preparation and testing of structural mixtures (S-I) prepared to duplicate those used on various paving projects. Three projects representing the best, satisfactory, and rutting-susceptible mixtures (A, B, and C, respectively) were evaluated by the GTM by using the air roller. The job mix formula of Mix A was obtained by using four sources of aggregates. These sources were 67 stone (20 percent), S-I-B stone (30 percent), screenings (25 percent), and local sand (25 percent). The job mix formula for Mix B consisted of aggregates from four sources: S-I-A stone (25 percent), S-I-B stone (25 percent), screenings (25 percent), and a local sand (25 percent). The S-I-A and S-I-B stone can be considered the same as a No. 78 and No. 89 stone, respectively.

Department of Civil Engineering, University of Florida, 345 Weil Hall, Gainesville, Fla. 32611.

The job mix formula for Mix C consisted of aggregates from three sources: S-I stone (55 percent) from Southern Stone, Maylene, Alabama; and coarse sand (25 percent) and fine sand (25 percent) from Columbia Paving, Inc. Tables 1 and 2 present the job mix formula and basic properties for Mixes A, B, and C. The gradation curves are shown in Figure 1.

In addition to these three projects, four other mixtures (E, F, G, and H) composed of aggregates from different states other than Florida and asphalt-rubber mixtures (D) were evaluated in the GTM.

The job mix formulas for Mixes D-1 through D-4 consisted of aggregates from two sources: screenings (50 percent) and an FC-4 sand (50 percent). In addition to the aggregate, ground tire rubber was added to Mixes D-1, D-2, and D-3. Mix D-1 had 3 percent (of total binder content) of −80 mesh ground rubber, Mix D-2 had 5 percent of −80 mesh rubber, and Mix D-3 had 10 percent of −40 mesh rubber with 5 percent extender oil. Mix D-4 was representative of the control section without any addition of ground tire rubber. The aggregate gradations, job mix formula, and the basic properties of the FC-4 mixtures are given in Tables 3 and 4. Figure 2 shows the typical gradation curve for the D mixtures.

Aggregates used to prepare Mixes E, F, G, and H varied greatly in gradation and aggregate characteristics. The composition of aggregate blends for these mixes was as follows:

- Mix E
  - −39 percent pit run gravel
  - −20 percent crushed fine
  - −25 percent concrete sand
  - −16 percent blend sand

TABLE 1 JOB MIX FORMULAS FOR THE S-I MIXTURES

Aggregate Passing Sieves	Mix A	Mix B	Mix C
3/4"	100	100	100
1/2"	93	99	98
3/8"	85	90	84
No. 4	61	63	57
No. 10	47	47	44
No. 40	32	35	35
No. 80	11	13	17
No. 200	3.9	4.0	3.0
Sp. Gr. of Aggregate Blend	2.466	2.404	2.698

TABLE 2 BASIC PROPERTIES OF THE S-I MIXTURES

	Mix A	Mix B	Mix C
Marshall Stability (lb.)	1,995	2,013	1,362
Marshall Flow	11.0	10.0	10.0
Air Voids (%)	4.0	3.0	3.0
V.M.A. (%)	16.4	14.5	15.4
Design A.C. Content (%)	6.3	6.5	5.5
Eff. A.C. Content (%)	5.8	5.4	5.1
Max. Theoret. Den. (pcf)	143.0	141.5	155.4
Marshall Density (pcf)	137.3	137.3	151.5
Type of A.C.	AC-30	AC-20	AC-20

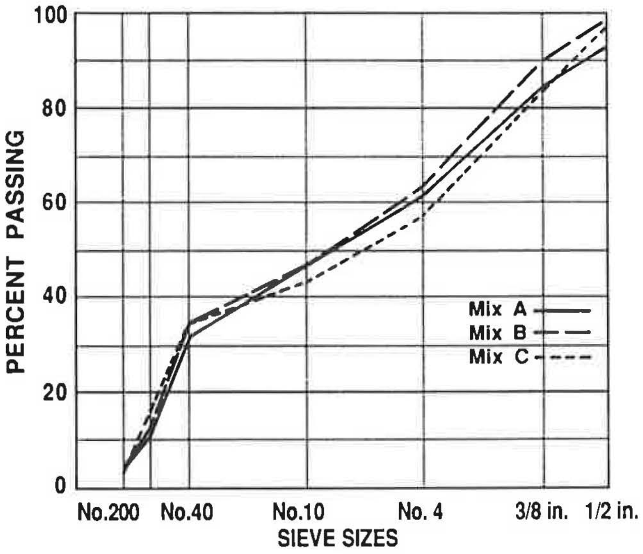

FIGURE 1 **Comparison of aggregate gradations for mixes A, B, and C.**

–96 percent passing ½ in. sieve (nominal size) for the blend

- Mix F

–83 percent crushed limestone; slightly rounded cubical shape

–17 percent field sand

–95 percent passing ¾ in. sieve (nominal size) for the blend

- Mix G

–85 percent crushed trap rock; very angular, elongated particle shape

–15 percent natural sand

–86 percent passing ¾ in. sieve (nominal size) for the blend

- Mix H

–40 percent coarse pit run gravel

–60 percent fine pit run gravel

–95 percent passing ½ in. sieve (nominal size) for the blend.

The aggregate gradations for these mixtures are shown in Figure 2.

Before any testing was performed in the GTM, samples were made to obtain the actual gradation of the materials at hand. That was accomplished by performing wash gradings and extractions on the samples. Also, the Rice maximum theoretical densities (MTD) were obtained for the mixtures at different asphalt contents. Two separate testing programs were designed, one for the S-I mixtures and the other for the FC-4 mixtures.

The testing of the samples consisted of two parts. First, the samples were compacted in the GTM by using test parameters that resulted in similar compaction densities as those obtained in the field. After the samples were cooled to room temperature, they were heated to 60°C (140°F) and densified in the GTM.

The testing program for the S-I mixtures (A, B, C) used 4-in.-diameter asphalt concrete samples to accommodate Marshall stability and flow tests for evaluation of test results. Asphalt and aggregate were heated and mixed at conventional mix temperatures (285° to 300°F). Asphalt contents conforming to design, 0.5 percent lower in 0.5 percent increments above design, were used to prepare test specimens in each project. Three replicate samples were prepared at each asphalt content.

The GTM was calibrated to yield a 3-degree angle of gyration, an initial air roller pressure of 10 psi, and a ram pressure of 100 psi. Compaction of hot-mix samples was achieved by using these settings and 18 revolutions in the GTM. Traffic densification simulation testing was performed by using a 2-degree angle of gyration, an initial air roller pressure of 13 psi (no load condition, air cell at maximum extension), and a ram pressure of 100 psi. Densification continued in the GTM up to 300 revolutions unless the shear resistance dropped excessively.

TABLE 3 AGGREGATE GRADATIONS FOR THE FC-4 MIXTURES

Aggregate Passing Sieves	JMF	Mix D-1	Mix D-2	Mix D-3	Mix D-4
3/8"	100	100	100	100	100
No. 4	94	93	90	91	93
No. 10	79	81	76	77	79
No. 40	32	35	32	31	34
No. 80	8	10	9	7	9
No. 200	3.9	3.5	2.4	1.4	2.6
Sp. Gr. of Agg.	2.422	--	--	--	--
Rice MTD	--	2.341	2.304	2.292	2.326

TABLE 4 BASIC PROPERTIES OF THE FC-4 MIXTURES

	Mix D-1	Mix D-2	Mix D-3	Mix D-4
Type Rubber	80 mesh	80 mesh	40 mesh	
Percent Rubber	3	5	10	
Marshall Stability (lb)	910	1,050	847	850
Marshall Flow	9.5	9.1	13.0	11.0
Air Voids (%)	15.1	14.1	15.5	12.5
V.M.A. (%)	25.3	24.8	28.0	23.1
Binder Content (%)	7.22	7.37	8.25	7.0
Eff. Binder Content (%)	7.09	7.29	8.12	
Extr. Binder Content (%)	6.52	6.84	7.65	6.8
Max. Theoret. Den. (pcf)	145.6	144.8	147.3	142.9
Marshall Density (pcf)	123.6	124.3	124.4	125.0
Type of A.C.	AC-30	AC-30	AC-30	AC-30
140 F Vis. (poises), A.C.	2,439	2,470		2,445
140 F Vis. (poises), binder	2,683	3,260	4,280	2,450

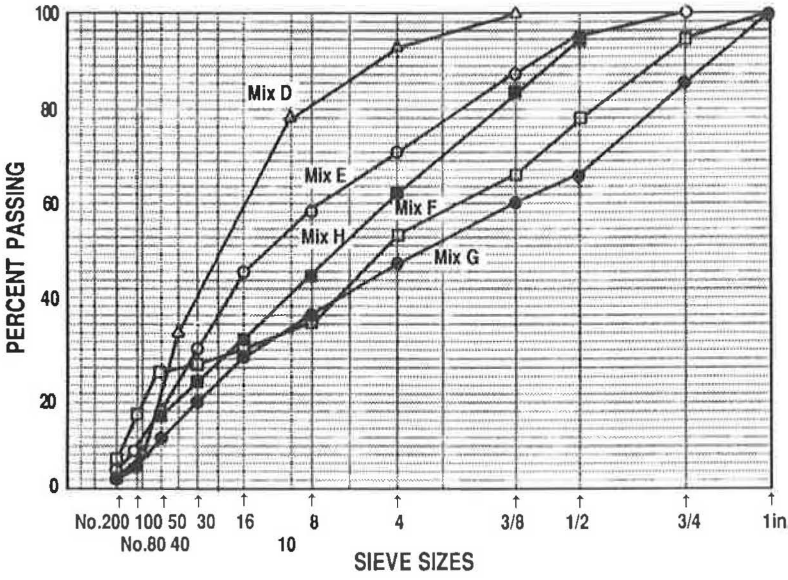

FIGURE 2 Typical aggregate gradation for mixes D-1–D-5.

If the sample's shear resistance became excessively low (e.g., $G_s = 45$), the testing of that sample was terminated. The criterion for stopping the test was when the air roller pressure dropped to about 15 to 16 psi.

The same procedures were used for compaction and testing of D mixes (D-1 through D-4) with the exception that plant-produced hot-mix conveyed to the laboratory in an insulated container was used rather than hot-mix prepared in the laboratory. However, Mix D-5 was blended and mixed in the laboratory for the purpose of evaluating G_s-values and mix characteristics at different binder contents without the addition of rubber.

ANALYSIS OF COMPACTED DENSITIES

A comparison of densities for the different mixtures is presented in Table 5. Core density information was not available for Mixes A, B, and C. GTM compaction achieved on the average about 98.5 percent of the standard 50-blow Marshall

TABLE 5 COMPARISON OF GTM, MARSHALL, AND FIELD DENSITIES AT DESIGN ASPHALT CONTENT

Mix	Marshall[a] Density pcf	GTM[b] Density pcf	Mean Core Density pcf	Percent Compaction GTM/Marshall	Field/GTM	Field/Marshall
A	137.3	135.0	--[c]	98.3	--	--
B	137.3	134.3	--	97.8	--	--
C	151.5	148.5	--	98.0	--	--
D-1	124.5	122.8	121.5	98.6	98.9	97.6
D-2	125.7	124.9	123.4	99.4	98.8	98.2
D-3	123.8	120.1	119.8	97.0	99.8	96.8
D-4	126.8	126.5	125.2	99.8	99.0	98.7
				98.4	99.1	97.8

[a] 50-Blow
[b] 18 Revolutions, 3-degree angle, 100 psi Ram pressure, and 10 psi Air Roller pressure
[c] No available data

density. This is similar to field compaction as a percent of Marshall, which generally is in the range of 97 to 98 percent. The percent field compaction based on the GTM averaged about 99.1 percent for the D mixes. It would appear that the GTM more consistently approximated the level of field compaction of the mixtures when the results for Mix D and those presented by Ruth and Schaub (*1*) are considered.

BEHAVIOR AND SENSITIVITY OF MIXTURES TO TRAFFIC DENSIFICATION SIMULATION

The GTM densification test results for the different mixtures are presented in Figures 3–11, which show the change in G_s, density, air void content, and VMA with densification for each of the different mixes. Comparison of G_s-value trends for Mix A and Mix B (Figures 3 and 4) indicate that the mixtures are similar except that Mix A tends to give higher shear resistance. However, when this test response is compared with that attained from Mixes C-1, C-2, and C-3 (Figures 5–7), it becomes apparent that Mixes A and B are not very sensitive to changes in asphalt content, whereas the C mixes seem extremely sensitive to both asphalt content and minor changes in aggregate gradation. Obviously, these C mixtures have mineral filler contents that exceed the job mix formula value of 3.0 percent by 1.5 to 2.6 percent as a result of poor production control or poor judgment in allowing the mix to be produced with the higher mineral filler content.

This sensitivity can be observed in the figures or denoted as the percentage of asphalt content above the design that is required to reduce the G_s-value to 52.0 at a fixed number of revolutions (e.g., 200). The increase in asphalt content for Mixes A, B, C-1, C-2, and C-3 was approximately 1.0, 0.8, 0.5, −0.2, and 0.25 percent, respectively. Tables 6–9 give the mean G_s-values based on the average of G_s-values at 25, 50, 100, and 200 revolutions. Test conditions 1 and 2 correspond to GTM compaction of 12 and 18 revolutions, respectively. The change in the mean values of G_s is indicative of sensitivity. Mix C was poorly designed, as indicated by its high sensitivity to small changes in asphalt content and aggregate gradation. Mix C-3 was within tolerances of the job mix formula and provided about the same G_s-response as Mix C-1, which conformed in general to the plant-produced hot-mix gradation. Mix C-2 was almost identical to Mix C-1 except that the percent passing the No. 80 sieve was 2.4 percent greater. The G_s-values for Mix C-2 were 5.0 and 5.5 percent, and asphalt contents were lower than in Mixes C-1 and C-3.

Sieve analyses for Mixes A and B are given in Tables 10 and 11, respectively. The aggregate gradations from extraction tests on laboratory mixtures conformed closely to the job mix formula. Because Mix C had rutted excessively, as indicative of the excess fines and low air void contents, an effort was made to evaluate slight changes in aggregate gradation that would correspond to changes in rut depth as indicated by the field data given in Table 12. Mix C-1, Table 13, simulated the gradation for the last sample in Table 12, which represented the portion of the pavement with the greatest rut depth. Obviously, the largest discrepancy was in the mineral filler content, which was 3.0 percent according to the job mix formula, 4.7 to 5.5 percent in the field, and 5.5 percent for Mix C-1. Mix C-2 was prepared by washing the aggregate and adding mineral filler. This produced about the same gradation except that the percent passing the No. 80 sieve increased from 18.2 to 20.6 percent as indicated in Table 14. Similarly, Mix C-3 (Table 15) was washed and less mineral filler added, which changed the No. 80 to 15.5 percent passing and reduced

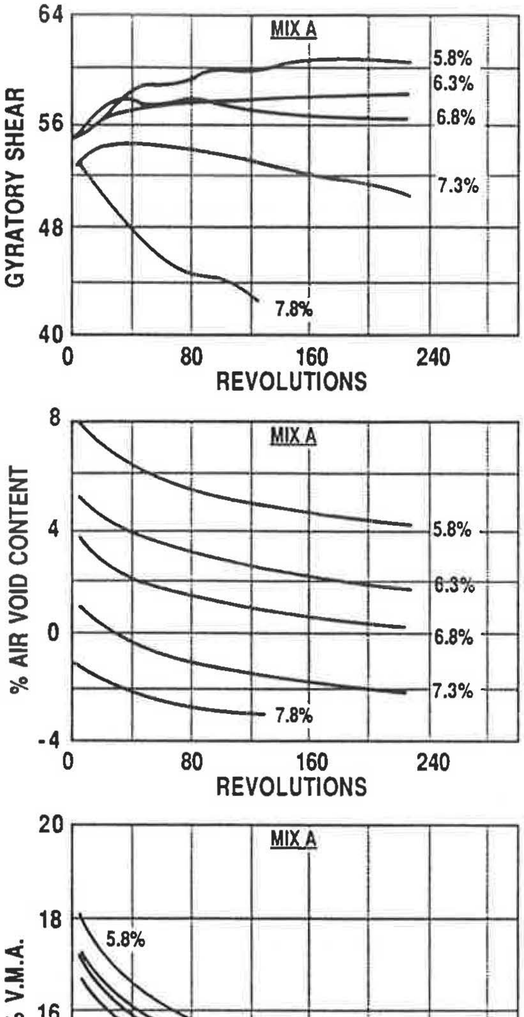

FIGURE 3 Mix A: GTM results.

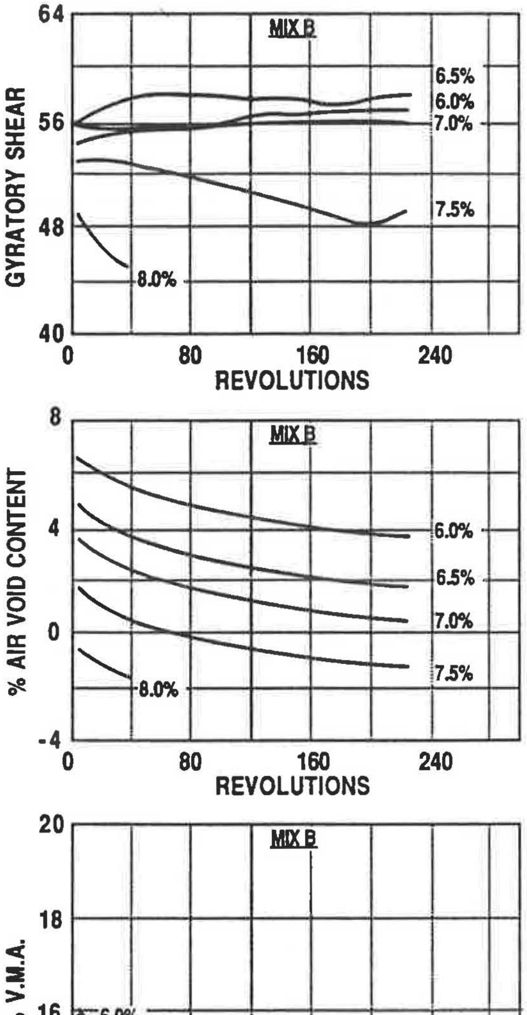

FIGURE 4 Mix B: GTM results.

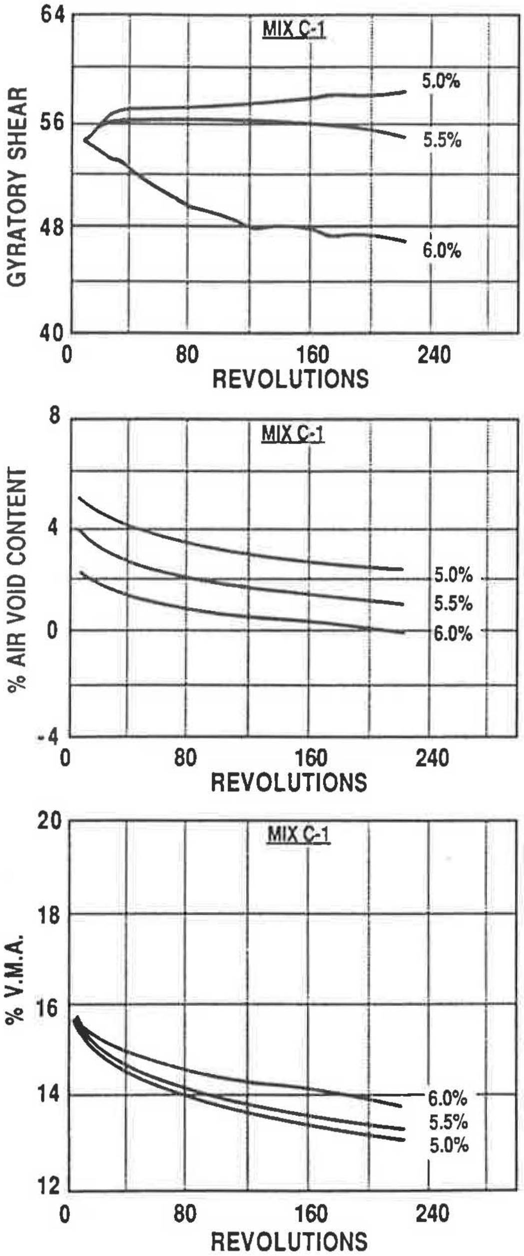

FIGURE 5 Mix C-1: GTM results.

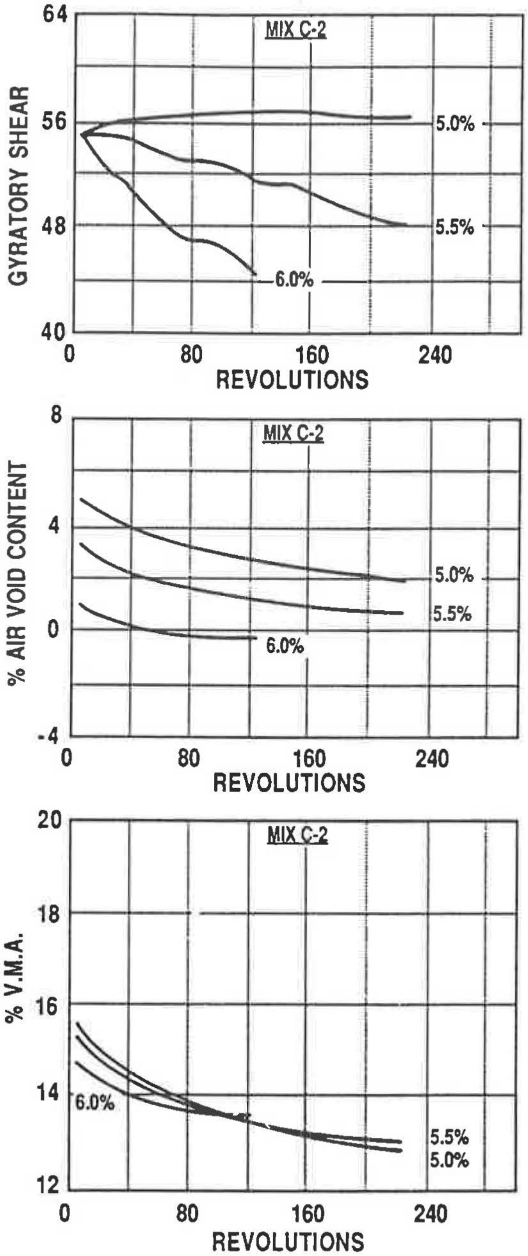

FIGURE 6 Mix C-2: GTM results.

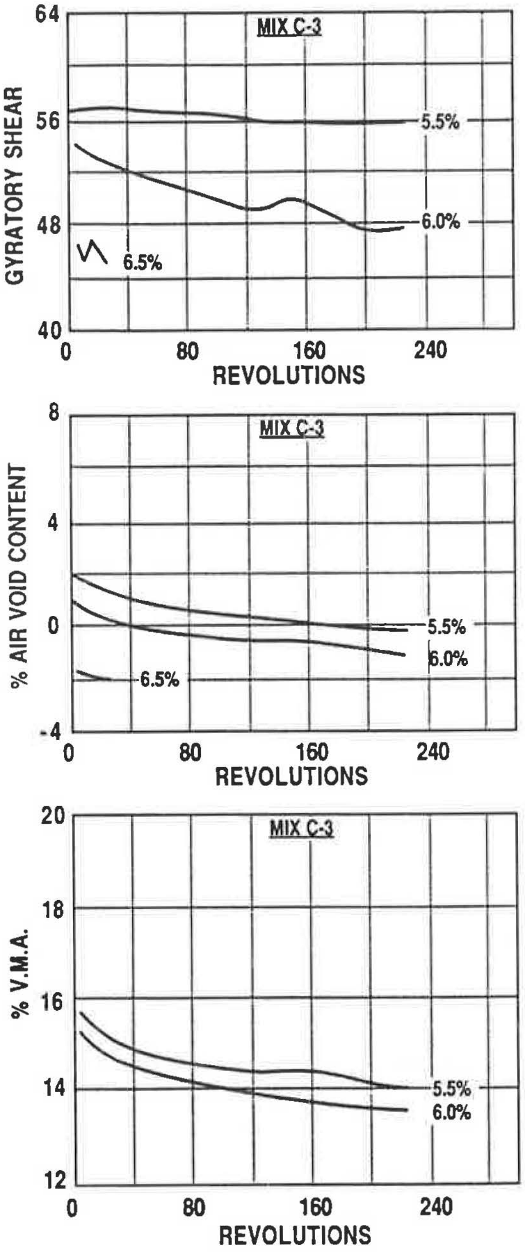

FIGURE 7 Mix C-3: GTM results.

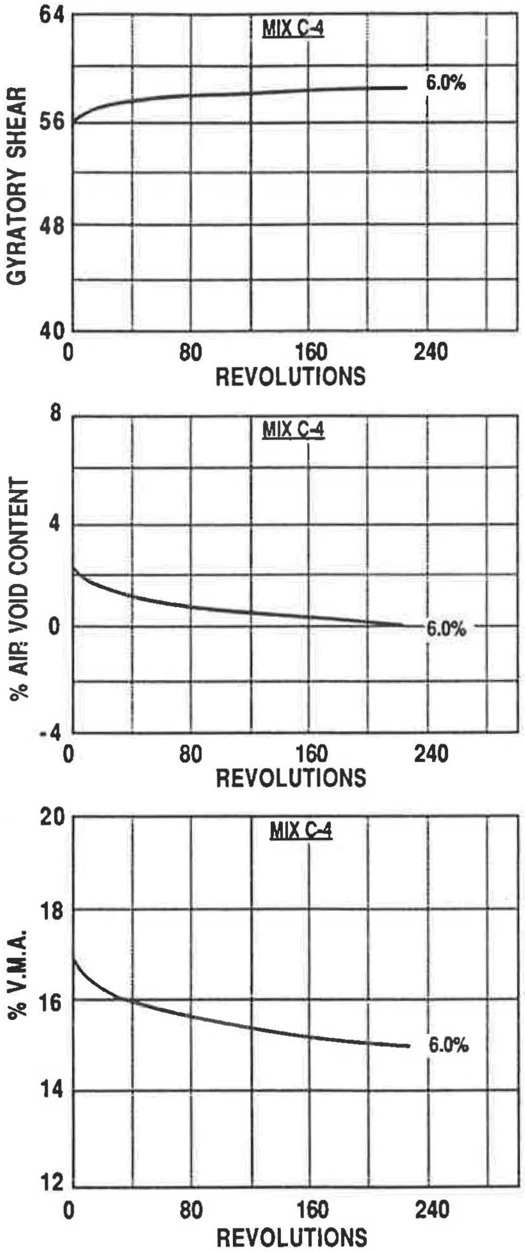

FIGURE 8 Mix C-4: GTM results.

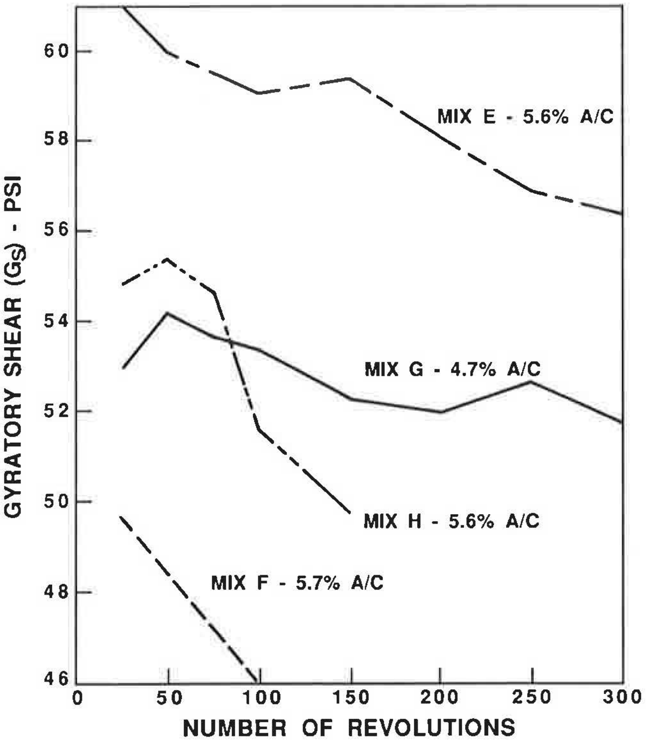

FIGURE 9 Comparison of gyratory shear response for mixes E, F, G, and H.

the mineral filler content to 4.5 percent. Finally, Mix C-4 was prepared by working without the addition of any mineral fillers, which reduced the No. 80 and No. 200 to 13.7 and 0.6 percent passing, respectively (see Table 16).

The design asphalt content for Mix C-1 was 5.5 percent. The G_s-data in Table 8 and Figure 5 indicated good shear resistance ($G_s = 56$) at 5.5 percent but a drastic reduction in shear resistance ($G_s = 48$) at the 6.0 percent asphalt content level. This was considered indicative of a sensitive mix unlike the G_s-response for Mix A in Figure 3. A mix with a G_s-value less than 54 at 200 revolutions was considered to have insufficient shear strength. Mix C-2 (Figure 6) gave substandard shear resistance (52.6) at 5.5 percent asphalt concrete content and an adequate G_s-value at the 5.0 percent content. The subsequent changes in gradation for Mix C-3 did not have a much different effect on gyratory shear response (Figure 7) than for Mix C-1. It is obvious that the high percentage of coarse and fine sand resulted in the sensitivity of the C mixtures to minor changes in asphalt content and aggregate gradation. Reduction of mineral filler content (e.g., Mix C-4, Figure 8) provided more tolerance to an increase in asphalt content above the design value. However, mixture deficiencies can only be corrected by changing gradation or improving the quality of the fine aggregates by substituting screenings or crusher fines, or both, for the natural sand.

The influence of aggregate characteristics on the shear response of asphalt concrete mixtures at the design asphalt content is shown in Figure 9. Mix G, prepared with trap rock aggregate and compacted to an air void content of about 8 percent at the design asphalt content of 4.7 percent, exhibited little change in G_s during densification as compared with pit run gravel mix H, which lost shear strength rapidly. Similarly, crushed limestone mix F exhibited low initial G_s-values and rapid reduction in G_s during densification. Both Mixes E and F were high on the percent passing the No. 30 sieve. Mix H had a very poor gradation, almost exactly approximating the $n = 0.45$ gradation. In comparison, Mix G provided better shear resistance than Mixes F and H because Mix G had better particle angularity and gradation. However, the gradation of Mix G could have been altered slightly to increase shear resistance and initial density and to reduce the harshness of the mix. Although the G_s-values for Mix E were much greater than those for the other mixtures, other test results indicated that it was sensitive to asphalt content and compacted density variations. This is attributable to the poor gradation (excessive fines).

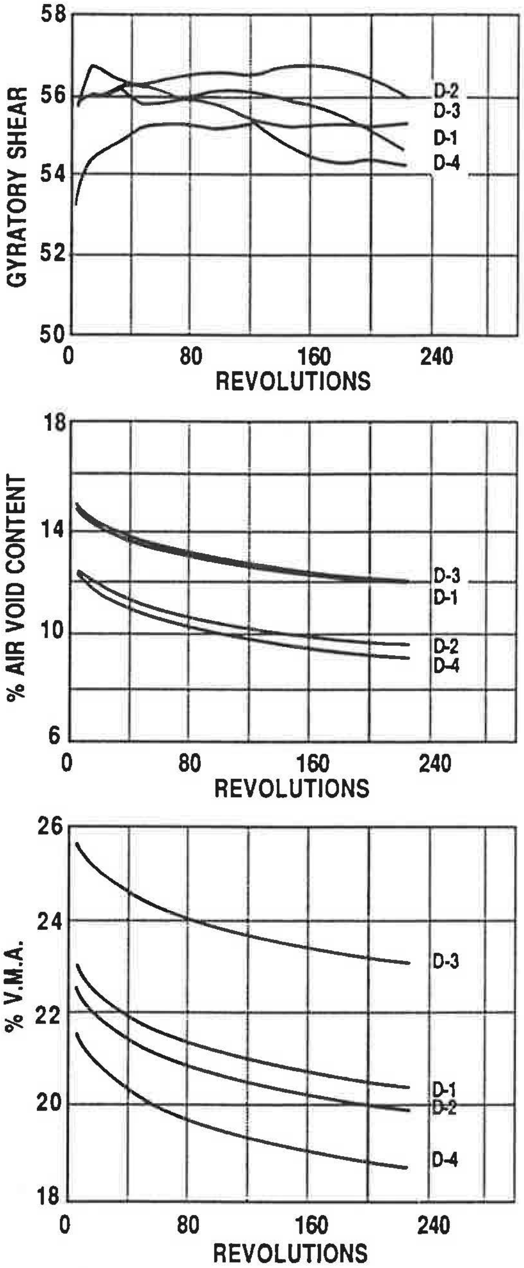

FIGURE 10 Mixes D-1–D-4: gyratory test results.

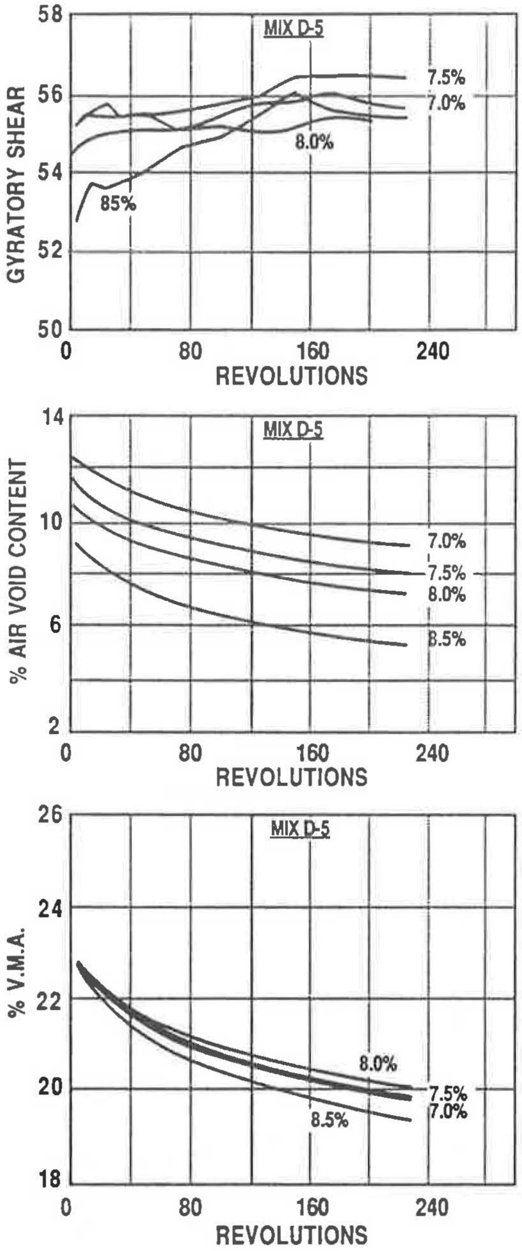

FIGURE 11 Mix D-5: asphalt content effect.

In all cases, gravel mixtures E and H had much greater rates of densification than the crushed stone mixtures. An air void content of about 2 to 3 percent after some amount of densification corresponded to a G_s-value of about 53.0 to 55.0 for all mixtures except Mix F, which supposedly had air void contents in the range of 6.5 to 4.0 percent during densification. Although Mix F was identified as being totally unacceptable, Marshall stability and flow values of 3,200 lb and 12, respectively, suggested a satisfactory mix. Interpretation of the G_s-test data indicated that Mixes F and H were totally unsatisfactory. Mix G could be improved but was probably adequate, and Mix E could be satisfactory but its sensitivity to asphalt content or aggregate gradation changes could result in poor field performance.

DISCREPANCIES IN AIR VOID CONTENTS

The GTM densification test procedure is capable of identifying errors in Rice or other maximum theoretical density (MTD) calculations. Densified mixtures, particularly those at high asphalt contents, will exhibit very low G_s- and air void content values. It is not unusual to find that the bulk density of the densified specimen exceeds the MTD or Rice test value. Air void contents in the range of a negative 2.0 to 3.0 percent were obtained with Mixes A and B. The air void contents for Mixes C-1 and C-2 appear to be reasonable because they are about zero at the highest asphalt content. Obviously, MTD values should be corrected when negative air void contents are encountered. This problem may be related to the effect of highly absorptive aggregates (e.g., Mixes A and B). Even the test results obtained from this investigation when compared with those for the original mix design (Tables 17, 18, and 19) show insufficient differences to account for the magnitude of negative air void contents. The key factor is that the G_s-response identifies the interactive effect of air void, binder content, and aggregate characteristics during densification.

EVALUATION OF DENSE GRADED FRICTION COURSE MIX

An FC-4 (Mix D) mixture with different binders and binder contents was evaluated in the GTM. Although the FC-4 mix-

TABLE 6 MEAN G_s-VALUES FOR MIX A

	Testing	A.C. Content				
	Condition	5.8%	6.3%[a]	6.8%	7.3%	7.8%
1	G_s[b]	60.0	58.1	55.8		
	std. dev.	1.73	1.82	1.76		
2	G_s[b]	59.1	57.3	57.2	53.5	48.0
	std. dev.	1.95	1.24	2.11	1.89	2.28

[a] Design asphalt content
[b] Mean of G_s values at 25, 50, 75, and 100 revolutions

TABLE 7 MEAN G_s-VALUES FOR MIX B

Testing Condition		A.C. Content				
		6.0%	6.5%(a)	7.0%	7.5%	8.0%
1	G_s(b)	55.9	55.7	55.4		
	std. dev.	0.49	0.51	0.98		
2	G_s(b)	56.0	57.8	55.4	51.2	48.8
	std. dev.	0.93	1.15	1.41	2.70	3.38

(a) Design asphalt content
(b) Mean of G_s values at 25, 50, 75, and 100 revolutions

TABLE 8 MEAN G_s-VALUES FOR MIX C-1

Testing Condition		A.C. Content		
		5.0%	5.5%(a)	6.0%
1	G_s(b)	58.1	57.0	52.2
	std. dev.	1.05	0.95	2.90
2	G_s(b)	57.1	56.0	50.9
	std. dev.	1.06	0.85	2.54

(a) Design asphalt content
(b) Mean of G_s values at 25, 50, 75, and 100 revolutions

TABLE 9 MEAN G_s-VALUES FOR MIXES C-2, C-3, AND C-4

Mix		A.C. Content			
		5.0%	5.5%	6.0%	6.5%
C-2	G_s(a)	56.2	52.6	49.6	
	std. dev.	1.31	2.51	2.68	
C-3	G_s(a)		56.4	50.8	45.2
	std. dev.		1.86	2.38	--(b)
C-4	G_s(a)			57.8	
	std. dev.			2.02	

(a) Mean of G_s values at 25, 50, 75, and 100 revolutions
(b) No available data

TABLE 10 SIEVE ANALYSIS AND EXTRACTION RESULTS FOR MIX A

Aggregate Passing Sieves	Wet Sieve Analyses		Extractions		JMF
	Avg.	Range	Avg.	Range	
1/2"	93.7	93.5-93.8	93.6	92.8-94.4	93
3/8"	85.8	85.7-86.0	85.5	85.1-86.0	85
No. 4	62.8	62.2-63.4	62.7	62.1-64.9	61
No. 10	48.1	47.9-48.4	48.3	47.9-48.5	47
No. 40	33.9	33.5-34.3	33.3	31.6-34.4	32
No. 80	11.2	11.1-11.2	11.1	10.1-11.9	11
No. 200	4.6	4.6	4.5	4.0-5.0	3.9

TABLE 11 EXTRACTION RESULTS FOR MIX B

Aggregate Passing Sieves	Extractions		JMF
	Avg.	Range	
1/2"	99.1	98.7-99.4	99
3/8"	90.4	90.3-90.4	90
No. 4	63.7	63.5-63.8	63
No. 10	47.4	47.2-47.6	47
No. 40	36.9	36.9-37.0	35
No. 80	13.1	13.0-13.3	13
No. 200	4.2	4.1-4.3	4.0

TABLE 12 FIELD DATA FOR MIX C

Rut Depth (in.)	0.25	0.25	0.60	0.65	0.78
A.C. Content (%)	5.2	5.8	5.5	5.6	5.5
Air Voids (%)	2.1	0.7	0.8	1.4	1.5
Bulk Density (pcf)	155.0	152.0	152.2	152.4	153.6
Agg. Passing Sieve:					
1/2"	99	99	99	98	99
3/8"	90	90	89	90	83
No. 4	59	62	61	61	61
No. 10	43	47	47	47	46
No. 40	35	38	38	38	38
No. 80	18	19	20	19	19
No. 200	4.7	5.0	5.5	5.1	5.2

(a) Data collected about 1.0 years after construction (Average values listed)

TABLE 13 SIEVE ANALYSES AND EXTRACTION RESULTS FOR MIX C-1

Aggregate Passing Sieves	Wet Sieve Analyses		Extractions		JMF
	Avg.	Range	Avg.	Range	
1/2"	97.9	97.8-97.9	98.2	97.8-98.6	98
3/8"	85.3	85.3	85.5	85.4-85.5	84
No. 4	59.9	59.3-60.4	59.5	59.3-59.6	57
No. 10	47.2	47.0-47.4	47.3	47.3	44
No. 40	40.5	40.3-40.6	39.8	39.7-39.9	35
No. 80	20.0	19.6-20.4	18.2	18.0-18.3	17
No. 200	7.7	7.5-7.8	5.5	5.4-5.5	3.0

TABLE 14 SIEVE ANALYSES AND EXTRACTION RESULTS FOR MIX C-2

Aggregate Passing Sieves	Wet Sieve Analyses		Extractions		JMF
	Avg.	Range	Avg.	Range	
1/2"	98.5	98-99	98.5	98.4-98.7	98
3/8"	85.5	85-86	86.6	86.5-86.7	84
No. 4	59.5	59-60	59.1	58.9-59.3	57
No. 10	45	45	44.9	44.9	44
No. 40	39	39	38.7	38.6-38.9	35
No. 80	22	22	20.6	20.3-20.8	17
No. 200	7.5	7.3-7.6	5.6	5.6	3.0

TABLE 15 SIEVE ANALYSES AND EXTRACTION RESULTS FOR MIX C-3

Aggregate Passing Sieves	Wet Sieve Analyses		Extractions		JMF
	Avg.	Range	Avg.	Range	
1/2"	97.8	97.7-97.8	98.3	98.1-98.4	98
3/8"	84.9	84.6-85.2	85.6	84.9-86.2	84
No. 4	58.3	58.2-58.4	58.4	58.1-58.6	57
No. 10	44.9	44.9-45.0	44.9	44.7-45.0	44
No. 40	37.9	37.8-38.0	37.4	37.1-37.6	35
No. 80	16.0	15.8-16.2	15.5	15.2-15.7	17
No. 200	4.9	4.8-4.9	4.5	4.3-4.7	3.0

TABLE 16 SIEVE ANALYSES AND EXTRACTION RESULTS FOR MIX C-4

Aggregate Passing Sieves	Wet Sieve Analyses	Extractions	JMF
1/2"	97.8	98.1	98
3/8"	84.7	86.1	84
No. 4	57.8	59.4	57
No. 10	44.8	44.9	44
No. 40	37.1	36.8	35
No. 80	13.2	13.7	17
No. 200	0.7	0.6	3.0

TABLE 17 MAXIMUM THEORETICAL DENSITY FOR MIX A

Asphalt Content	MTD Tested	MTD Predicted	MTD From Mix Design
5.8%	2.327	2.332	2.314
6.3%	2.301	2.301	2.292
6.8%	2.286	2.270	2.286
7.3%	2.222	2.239	
7.8%	2.212	2.208	

TABLE 18 MAXIMUM THEORETICAL DENSITY FOR MIX B

Asphalt Content	MTD Tested	MTD Predicted	MTD From Mix Design
6.0%	2.301	2.301	2.282
6.5%	2.276	2.277	2.268
7.0%	2.255	2.252	2.254
7.5%	2.232	2.228	2.240
8.0%	2.201	2.203	

tures are termed "dense graded," they are in reality partially open graded, usually compacted to air void contents of 12 to 14 percent.

Figures 10 and 11 present the GTM test results for the D mixtures. Mixes D-1, D-2, and D-3 contained asphalt rubber binders, and Mix D-4 was the control mix with an AC-30. Mix D-5 conformed to Mix D-4 except that Mix D-5 was prepared in the laboratory and the asphalt content was varied to identify the effect of binder content on shear resistance. A complete description of these tests is given by Ruth et al. (*6*). Inspection of these figures and the mean G_s-values in Table 20 indicates that all mixtures should behave reasonably well ($G_s > 54.0$). However, Mix D-5 at the 8.5 percent asphalt content exhibits low initial shear resistance, probably because of excessive film thickness, which may reduce during densification. It is apparent that the asphalt-rubber mixtures (D-1, D-2, and D-3) are similar in shear resistance to D-5 mixtures. However, in consideration of the initial densities and binder contents, it is apparent that the asphalt-rubber mixtures provide greater shear resistance during initial densification even though their as-compacted densities were less than the D-5 mixtures without rubber. Mix D-2 containing 5 percent rubber appeared to yield good field- and laboratory-compacted densities, lower air voids than Mixes D-1 and D-3, and consistently the highest level of gyratory shear response.

These mixtures did not attain sufficiently low air void contents to produce a major reduction in gyratory shear. However, the combined effect of mixture composition was apparent when both as-compacted density and G_s-response are considered in the comparison of these mixtures. In general, there does not appear to be any significant difference in the mixtures except for Mix D-2 with uniformly high G_s-values and Mix D-5 at the 8.5 percent asphalt content, which gave low initial G_s-values.

TABLE 19 MAXIMUM THEORETICAL DENSITY FOR MIXES C-1 AND C-2

Asphalt Content	MTD Tested	MTD Predicted	MTD From Mix Design
5.0%	2.526	2.526	2.510
5.5%	2.500	2.499	2.491
6.0%	2.472	2.472	2.472

TABLE 20 MEAN G_s-VALUES FOR THE FC-4 MIXTURES

Mixture		Binder Content				
		(a)	7.0%	7.5%	8.0%	8.5%
D-1	G_s	55.8				
	std. dev.	0.78				
D-2	G_s	56.5				
	std. dev.	1.15				
D-3	G_s	55.9				
	std. dev.	0.74				
D-4	G_s	54.9				
	std. dev.	0.98				
D-5	G_s		55.3	55.8	55.5	54.5
	std. dev.		0.71	0.64	1.06	1.61

(a) Binder contents are 7.09, 7.29, 8.12 and 6.8% for mixtures D-1 through D-4, respectively.

SUMMARY AND CONCLUSIONS

The results of GTM tests on mixtures of known performance indicated that the gyratory shear response can be used to evaluate the adequacy of asphalt mixtures and their relative resistance to rutting. The key factor in achieving good mixture performance is to design a mix not sensitive to reasonable changes in binder content, gradation, and mineral filler content. For example, a 0.5 percent increase in binder content combined with a 1.0 or 1.5 percent increase in mineral filler above the design values should have very little effect on the gyratory shear value. Any mixture that gives a substantial reduction in shear resistance with an asphalt content only 0.5 percent over design should be considered as highly sensitive. A mix of this type combined with small variations in aggregate gradation could result in low shear resistance and early rutting of the pavement.

Although general in nature, the key conclusions that can be derived from these GTM studies are as follows:

1. The combined effects of aggregate particle shape, surface texture, and gradation of the aggregate blend can be evaluated at different asphalt concrete contents by using the described procedures and the gyratory shear value (G_s).
2. The GTM densification procedure identifies how a mix will behave at different levels of density regardless of air void content, VMA, or binder properties.
3. Field compaction can be simulated by using the GTM air roller procedures and between 12 and 18 revolutions.
4. Although a tentative G_s-value of 54.0 minimum has been established in prior investigations, the actual G_s-requirement is dependent on lift thickness. Obviously, a 1.0-in.-thick wearing or friction course will not require as great a G_s-value as 3 or 4 in. (one or two lifts) of new asphalt concrete paving.

In summary, it should be obvious that the GTM can provide a more comprehensive appraisal of a mixture's resistance to rutting than existing mix design methods. Furthermore, it eliminates the need for multiple parameter criteria, which can eventually simplify both the design and quality control process.

REFERENCES

1. B. E. Ruth and J. H. Schaub. Gyratory Testing Machine Simulation of Field Compaction of Asphaltic Concrete. *Proc., Association of Asphalt Paving Technologists*, Vol. 35, 1966, pp. 451–480.
2. L. Ortolani and H. A. Sanberg, Jr. The Gyratory Method of Molding Asphaltic Concrete Test Specimens: Its Development and Correlation with Field Compaction Methods—A Texas Highway Department Procedure. *Proc., Association of Asphalt Paving Technologists*, Vol. 21, 1952.
3. H. W. Busching and W. H. Goetz. Use of a Gyratory Testing Machine In Evaluating Bituminous Mixtures. In *Highway Research Record 51*, HRB, National Research Council, Washington, D.C., 1964, pp. 19–43.
4. B. F. Kallas. Gyratory Testing Machine Procedure for Selecting the Design Asphalt Content of Paving Mixtures. *Proc., Association of Asphalt Paving Technologists*, Vol. 33, 1964, pp. 341–359.
5. B. E. Ruth and J. H. Schaub. Experiences with Gyratory Testing Machine. In *Highway Research Record 104*, HRB, National Research Council, Washington, D.C., 1965, pp. 164–189.
6. B. E. Ruth, S. Sigurjonsson, and C.-L. Wu. *Evaluation of Experimental Asphalt-Rubber, Dense Graded, Friction Course Mixtures: Materials and Construction of Test Pavements on N.E. 23rd Avenue.* Technical Report. UF Project No. 4910450426912. Department of Civil Engineering, University of Florida, Gainesville, 1989, pp. 1–161.

Publication of this paper sponsored by Committee on Characteristics of Bituminous Paving Mixtures To Meet Structural Requirements.