Correlation of Superpave $G^*/\sin \delta$ with Rutting Susceptibility from Laboratory Mixture Tests

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The objective of this study was to compare the Superpave $G^*/\sin \delta$ of five binders with the rutting parameters given by laboratory mixture tests. Superpave uses the $G^*/\sin \delta$ from the dynamic shear rheometer to specify binders according to rutting susceptibility. The conventional designations for the five binders are AC-5, AC-10, AC-20, Novophalt, and Styrelf 1-D. All five binders were used in a surface mixture having a nominal maximum aggregate size of 19.0 mm. The AC-5 and AC-20 binders were also used in a base mixture having a nominal maximum aggregate size of 37.5 mm to determine whether the effects of binder type on rutting susceptibility varies with maximum aggregate size. The data showed that binders with higher $G^*/\sin \delta$ produce mixtures less susceptible to rutting. The Georgia loaded-wheel tester provided a very good relationship between $G^*/\sin \delta$ and rutting susceptibility. The French pavement rutting tester and Hamburg wheel-tracking device provided reasonably good relationships. The main discrepancy for these latter two devices was that even though the Styrelf mixture had a very low susceptibility to rutting, the data suggest that the rut depths are slightly high compared with the $G^*/\sin \delta$ of the binder. The data also showed that increased maximum aggregate size did not significantly reduce the effects of binder type on rutting susceptibility. The Marshall stabilities and flows and the gyratory testing machine data did not differentiate between the mixtures according to rutting susceptibility; therefore, there were no relationships between these tests and $G^*/\sin \delta$.

The FHWA is validating Superpave (*Sup*erior *Per*forming Asphalt *Pave*ments) binder tests and specifications, Superpave mixture tests and performance models, and other accelerated laboratory tests for mixtures. Pavements were constructed at the Turner-Fairbank Highway Research Center (TFHRC) in McLean, Virginia, to assist in validating the tests for rutting and fatigue cracking. The pavements are being tested by the Accelerated Loading Facility (ALF).

The pavement testing facility consists of 12 lanes with two nominal maximum aggregate sizes and five binders. Each lane consists of one full-depth mixture. The binders are AC-5, AC-10, AC-20, Novophalt, and Styrelf 1-D. The mixtures consist of a surface aggregate blend and a base aggregate blend. The surface mixtures include all five binders. The base mixtures include only AC-5 and AC-20. The purpose of including a base mixture is to determine whether the effects of binder type on rutting vary with the maximum aggregate size.

The five surface mixtures were designed to meet the 1991 Virginia Department of Transportation specification for SM-3B mixtures, whereas the two base mixtures were designed to meet a modification of the specification for BM-3 mixtures. Uniform gradations and binder contents were used in each type of mixture in order to investigate the effects of binder properties on rutting and fatigue cracking. The aggregates and binders used in the pavements are stockpiled at TFHRC. These materials are used to produce laboratory samples for testing.

Quality control and quality assurance (QC/QA) testing was conducted by the paving contractor and FHWA to ensure that the specifications of the project were met. Samples of the five binders were obtained during the mixture designs from the terminal immediately before shipping, from the hot-mix plant after they arrived from the terminal, and daily during construction. These samples were tested to ensure that the properties of the binders did not change while they were being used. Two samples of each plant-produced mixture per lift were taken during construction. The aggregate gradations, percent natural sand, percent binder, and maximum specific gravities were determined. Specimens were also compacted for voids analyses during construction. Nuclear density tests and 72 cores taken after construction were used to determine the air void content. This information was essential for duplicating the average properties of the ALF pavements using the stockpiled materials. A separate report documenting the QC/QA testing will be published.

The initial data from the research project are presented in this paper. The Superpave binder specification uses the $G^*/\sin \delta$ from the dynamic shear rheometer (DSR) determined after subjecting a binder to the rolling thin-film oven test (RTFOT) to specify a binder according to rutting susceptibility. The first phase of the research project is concerned with how well the $G^*/\sin \delta$ parameter agrees with rutting parameters given by laboratory mixture tests. Besides the mixture tests presented in this paper, the Superpave shear tester and the NCHRP asphalt-aggregate mixture analysis system (AAMAS) will also be evaluated (*1*). Eventually, the results will be compared with ALF pavement performance. A correlation between $G^*/\sin \delta$ and rutting susceptibility will enable asphalt paving technologists to classify binders according to performance. This will lead to longer-lasting pavements and lower maintenance costs.

OBJECTIVES

The primary objective of this study was to determine whether the Superpave $G^*/\sin \delta$ ranks binders the same as laboratory mixture tests for rutting. Comparisons among the mixture tests were also included. A second objective was to determine whether the effects of binder type on rutting susceptibility vary with maximum aggregate size.

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BINDERS

Five binders were used: AC-5, AC-10, AC-20, Novophalt, and Styrelf 1-D. The AC-5, AC-10, and AC-20 were from Venezuela's Lagoven base stock. Koch Materials Company, Pennsauken, New Jersey, supplied these asphalts. The Novophalt binder was formulated by blending the Lagoven AC-10 asphalt with 5 percent low-density polyethylene by mass. A high shear mill was used for blending by Advanced Asphalt Technologies, Sterling, Virginia, at the paving contractor's hot-mix plant in Leesburg, Virginia. The Styrelf 1-D binder was formulated by reacting the Lagoven AC-20 asphalt with 4 percent styrene-butadiene by volume. Styrelf is a product of the Koch Materials Company and is shipped in bulk form. The traditional physical properties of the binders and the Superpave performance grades are given in Table 1.

Samples of the five binders were exposed to the RTFOT and tested by the DSR to determine $G^*/\sin\delta$. The DSR is used to evaluate the viscous and elastic behavior of asphalt binders by measuring the complex shear modulus (G^*) and phase angle (δ). These values are highly dependent on the temperature and frequency of loading (*2*). $G^*/\sin\delta$ was measured at temperatures of 10, 20, 30, 40, 50, 60, and 70°C and frequencies ranging from 0.1 to 10.0 rad/sec. This allowed a direct correlation of the $G^*/\sin\delta$ with the results of the mixture tests, which are performed at different temperatures and frequencies. The DSR frequencies corresponding to the mixture tests were based on 80 km/hr being equivalent to 10 rad/sec as established by the Strategic Highway Research Program (SHRP). The speeds of the mixture tests were divided by 8 to obtain the DSR frequency in rads per second. Table 2 provides all values of $G^*/\sin\delta$. Higher amounts of rutting were expected from the mixtures that used binders with lower values of $G^*/\sin\delta$.

As expected, $G^*/\sin\delta$ decreased with an increase in temperature and a decrease in frequency. The binders were ranked from lowest to highest $G^*/\sin\delta$ using statistical analyses. These rankings varied with the temperature and frequency. The rankings applicable to this study are given in the *Results and Discussion* section.

TABLE 1 Physical Properties of Binders

	AC-5	AC-10	AC-20	Novo-phalt	Styrelf
Original Binder					
Penetration, 25°C, 0.1 mm	172	113	73	55	47
Absolute Viscosity, 60°C, dPa·s	665	1 195	2 644	12 714	58 774
Kinematic Viscosity, 135°C, mm^2/s	256	322	476	2 184	2 484
Specific Gravity, 25/25°C	1.007	1.024	1.022	1.022	1.020
Solubility in Trichloroethylene, %	100.00	100.00	100.00	95.92	100.00
Flash Point, COC,°C	304	304	304	326	312
Thin Film Oven Residue					
Weight Loss, %	0.01	0.33	0.13	0.34	0.12
Penetration, 25°C, 0.1 mm	102	66	47	40	35
Absolute Viscosity, 60°C, dPa·s	1 758	3 223	7 173	29 844	208 185
Kinematic Viscosity, 135°C, mm^2/s	372	509	684	3 686	4 197
SUPERPAVE™ Performance Grade	58-34	58-28	64-22	76-22	82-22
Original Binder					
Temperature at a $G^*/\sin\delta$ of 1.00 kPa and 10 rad/s, °C	59.4	61.9	67.9	83.4	87.2
Rolling Thin Film Oven Residue					
Temperature at a $G^*/\sin\delta$ of 2.20 kPa and 10 rad/s, °C	59.3	65.0	70.2	79.3	88.0
Rolling Thin Film Oven/Pressure Aging Vessel Residue					
Temperature at a $G^*\sin\delta$ of 5 000 kPa and 10 rad/s, °C	9.1	14.5	17.3	26.0	24.8
Temperature at a Creep Stiffness (S) of 300 MPa and 60 s, °C	-26.9	-22.1	-19.8	-20.2	-20.9
Temperature at an m-value of 0.30 and 60 s, °C	-25.3	-20.3	-17.1	-13.4	-17.4

TABLE 2 Determination of $G^*/\sin\delta$ in Pascals at Different Temperatures and Frequencies

Temp. (°C)	AC-5	AC-10	AC-20	Novophalt	Styrelf
$G^*/\sin\delta$ at ω=10.0 rad/s, Standard Frequency for the DSR:					
10	5 172 000	11 990 000	17 880 000	33 050 000	22 340 000
20	862 000	2 001 000	3 074 000	7 587 000	5 055 000
30	173 100	386 600	666 300	1 478 000	1 036 000
40	38 640	82 800	159 900	379 300	268 100
50	7 528	15 880	30 660	94 330	74 590
60	2 096	4 202	7 897	27 200	28 120
70	653	1 238	2 226	8 381	11 260
$G^*/\sin\delta$ at ω=2.25 rad/s, Frequency for the ALF Machine:					
10	2 240 000	5 364 000	8 335 000	16 860 000	10 970 000
20	351 800	833 500	1 383 000	3 387 000	2 270 000
30	62 220	143 900	267 700	626 300	460 200
40	11 910	26 350	54 470	151 000	116 300
50	2 057	4 446	9 002	32 550	31 140
60	526	1 084	2 100	8 393	11 390
70	155	299	549	2 376	4 378
$G^*/\sin\delta$ at ω=0.875 rad/s, Frequency for the French Pavement Rutting Tester:					
10	1 276 000	3 111 000	4 954 000	10 630 000	6 822 000
20	182 100	461 000	796 200	1 967 000	1 345 000
30	30 900	73 360	141 800	348 700	270 500
40	5 382	12 210	26 240	81 020	67 480
50	856	1 926	3 911	15 790	17 790
60	212	442	871	3 789	6 338
70	61	118	219	1 022	2 357
$G^*/\sin\delta$ at ω=0.125 rad/s, Frequency for the Georgia Loaded Wheel Tester, German Hamburg Wheel Tracking Device, and Gyratory Testing Machine:					
10	346 000	873 800	1 437 000	3 629 000	2 332 000
20	50 080	118 500	216 500	567 400	421 200
30	6 358	16 100	33 210	94 120	84 440
40	899	2 215	5 060	21 000	20 600
50	130	348	635	3 128	5 232
60	28	60	124	661	1 750
70	8	16	29	167	589

AGGREGATES

All five binders were used in a surface mixture; the AC-5 and AC-20 binders were also used in a base mixture. The surface mixtures consisted of No. 68 diabase, No. 10 diabase, and natural sand. The base mixtures consisted of No. 357 diabase, No. 8 diabase, No. 10 diabase, and natural sand. The diabase aggregates used in the surface mixtures were supplied by Virginia Trap Rock, Leesburg, Virginia. The diabase aggregates used in the base mixtures were supplied by Luck Stone Corporation, Leesburg, Virginia. To eliminate moisture damage, 1 percent hydrated lime was added to both mixtures. The natural sand was supplied by Solite Corporation, Fredricksburg, Virginia. The hydrated lime was supplied by Chemston, Strasburg, Virginia.

The aggregates used in the laboratory mixtures were blended to meet the average gradations of the plant-produced mixtures. The gradations are shown in Tables 3 and 4. The target gradations are the gradations of the plant-produced mixtures. The nominal maximum aggregate sizes for the surface and base mixtures are 19.0 and 37.5 mm.

MIXTURE TESTING PROGRAM

The following mixture properties were determined:

- Marshall mixture properties at 60°C.
- French pavement rutting tester at 60°C, including the percent rut depth at 300, 1,000, 3,000, 10,000, and 30,000 cycles;

TABLE 3 Aggregate Properties for the SM-3B Surface Mixtures

Aggregate Gradations, Percent Passing:

Sieve Size (mm)	61% No. 68 Diabase	30% No. 10 Diabase	8% Natural Sand	1% Hydrated Lime	Target	Blend
25.0	100.0				100.0	100.0
19.0	97.9				98.7	98.7
12.5	60.7				76.0	76.0
9.5	37.7	100.0	100.0		62.0	62.0
4.75	9.2	99.2	95.8		44.0	44.0
2.36	2.2	75.6	88.2		32.5	32.1
1.18	1.7	52.5	74.8		23.5	23.8
0.600	1.4	37.8	46.0		17.5	16.9
0.300	1.3	27.9	14.1		11.5	11.3
0.150	1.1	19.6	4.8		8.0	7.9
0.075	0.9	12.5	2.9	100.0	5.1	5.5

The diabase aggregates were from Virginia Trap Rock.

Specific Gravities and Percent Absorption:

	61% No. 68 Diabase	30% No. 10 Diabase	8% Natural Sand	1% Hydrated Lime	Target	Blend
Bulk Dry	2.943	2.914	2.565			2.892
Bulk SSD	2.962	2.945	2.601			2.916
Apparent	2.999	3.007	2.659	2.262		2.961
% Abs	0.6	1.1	1.4			0.8

Bulk Dry = Bulk-Dry Specific Gravity.
Bulk SSD = Bulk-Saturated-Surface-Dry Specific Gravity.
Apparent = Apparent Specific Gravity.
% Abs = Percent Water Absorption.

and the slope of the relationship between log rut depth and log cycles.

- Georgia loaded-wheel tester (GLWT) at 40.6°C, including the rut depth at 8,000 cycles.
- Hamburg wheel-tracking device to 20,000 passes at 50°C, including the creep slope.
- U.S. Corps of Engineers gyratory testing machine (GTM) at 60°C, including the maximum static shear strength (Sg), gyratory stability index (GSI), gyratory elastoplastic index (GEPI), and the refusal air void level.

The target air void level for the specimens was 8 ± 1 percent, except for the Marshall specimens. The surface mixtures had a binder content of 4.85 percent by mixture mass. The base mixtures had a binder content of 4.0 percent. These levels duplicated the average air void level and binder contents of the pavements.

The data were analyzed by comparing rankings of the average test values, comparing rankings given by Fisher's least significant difference (LSD) statistical procedure, and by performing regressions. Fisher's LSD determines which averages are not significantly different from other averages. Groups of averages that are not significantly different are formed. These groups are ranked from highest to lowest. Fisher's LSD is performed in conjunction with an analysis of variance at a 95 percent confidence level.

TABLE 4 Aggregate Properties for BM-3 Base Mixtures

Aggregate Gradations, Percent Passing:

Sieve Size (mm)	41% No. 357 Diabase	15% No. 8 Diabase	38% No. 10 Diabase	5% Natural Sand	1% Hydrated Lime	Target	Blend
37.5	100.0					100.0	100.0
25.0	64.9					85.6	85.6
19.0	36.3					73.9	73.9
12.5	14.9	100.0				65.1	65.1
9.5	5.5	85.0	100.0	100.0		59.0	59.0
4.75	3.0	25.3	96.8	95.8		47.6	47.6
2.36	1.8	2.7	68.0	88.2		32.5	32.4
1.18	1.6	2.0	47.5	74.8		24.0	23.7
0.600	1.4	1.5	34.3	46.0		17.4	17.1
0.300	1.2	1.2	24.9	14.1		12.3	11.8
0.150	1.1	0.9	17.3	4.8		8.0	8.4
0.075	0.8	0.8	11.5	2.9	100.0	5.7	6.0

The diabase aggregates were from Luck Stone Corporation.

Specific Gravities and Percent Absorption:

	41% No. 357 Diabase	15% No. 8 Diabase	38% No. 10 Diabase	5% Natural Sand	1% Hydrated Lime	Target	Blend
Bulk Dry	2.971	2.956	2.894	2.565			2.907
Bulk SSD	2.984	2.981	2.935	2.601			2.934
Apparent	3.013	3.030	3.017	2.659	2.262		2.987
% Abs	0.5	0.8	1.4	1.4			0.9

Bulk Dry = Bulk-Dry Specific Gravity.
Bulk SSD = Bulk-Saturated-Surface-Dry Specific Gravity.
Apparent = Apparent Specific Gravity.
% Abs = Percent Water Absorption.

AGING STUDY

Superpave recommends that loose mixtures be oven-aged for 4 hr at 135°C before compaction (*3*). This process is termed short-term oven aging (STOA). The SHRP final report states that STOA produces the average amount of aging at 6 months to 2 years of service life. In order to better simulate the degree of aging that occurred during plant production of the ALF mixtures, an aging study was performed.

The study consisted of aging laboratory mixtures for various periods of time, extracting and recovering the binders from these mixtures and from ALF pavement cores, and performing three Superpave binder tests on the recovered binders. The laboratory aging periods were 0, 1, 2, and 4 hr. Three replicate samples were prepared for each aging period. The mixtures consisted of the surface mixture with AC-5, the base mixture with AC-5, and the surface mixture with AC-20. Cores were taken from four ALF pavements constructed with these mixtures, including two pavements with the AC-20 as a check on pavement-to-pavement variability. The recovered binders were tested by the DSR at 10, 30, 50, and 70°C; by the bending beam rheometer (BBR) at −24°C; and by the Brookfield viscometer at 135°C. Three binder tests were performed to fully examine the capability of simulating hot-mix plant aging using a forced draft oven, even though the pavements were only to be tested in the range of 10 to 60°C. All three tests should provide the same aging period if oven aging duplicates plant aging and provides the same binder chemistry. The testing program was also developed to show which of the Superpave binder parameters are most sensitive to aging.

The recovered binder properties from the aged laboratory mixtures were plotted with respect to the aging period. A regression was performed to generate a second-order polynomial equation. The aging periods required to duplicate the properties of the binders in the ALF pavements were computed for each binder and test. The differences among the data for the two AC-20 pavements were not significant; thus, averaged data were evaluated.

The results are given in Table 5. The DSR provided aging periods up to 2.5 hr and an average of 1.3 hr. The BBR stiffnesses provided no definitive conclusions. The BBR slopes provided aging periods greater than or equal to 3 hr, but the data varied very little with the aging period. The Brookfield viscosities indicated that 2.3 hr was needed for the AC-20 mixture. However, the AC-5 binders recovered from the laboratory mixtures were stiffer than the AC-5 binders recovered from the cores, even at an aging period of 0 hr.

Overall, the required oven-aging period depended on the mixture type and the binder test performed. A previous study found that the absolute viscosity at 60°C and penetration at 25°C can also give different oven-aging periods for a given mixture (*1*). This indicates that oven aging may not effectively simulate hot-mix plant aging. An aging period of 2 hr was used as a compromise.

TABLE 5 STOA Data

Binder/ Mixture Type	Laboratory Aging Period (h)				Req'd Pavement Core Property	Req'd Lab Aging (h)
	0	1	2	4		
Average G (Pa) at ω=10 rad/s Determined by the Dynamic Shear Rheometer:*						
AC-5 Surface						
at 10°C	2 974 000	2 682 000	4 192 000	4 422 000	3 181 000	1.3
at 30°C	118 500	110 300	181 500	221 800	125 800	1.2
at 50°C	7 062	6 798	10 930	14 760	7 319	1.1
at 70°C	630	627	916	1 301	626	1.0
AC-5 Base						
at 10°C	2 990 000	4 295 000	5 546 000	5 516 000	3 453 000	0.3
at 30°C	97 360	152 900	211 900	246 100	144 600	0.7
at 50°C	5 234	8 462	12 120	15 150	8 534	0.9
at 70°C	464	726	1 038	1 284	709	0.8
AC-20 Surface						
at 10°C	8 359 000	8 922 000	10 730 000	11 580 000	9 827 000	1.4
at 30°C	302 800	372 900	423 600	585 300	455 800	2.4
at 50°C	15 690	20 810	22 750	35 240	26 210	2.5
at 70°C	1 160	1 549	1 650	2 526	1 868	2.4
Average Creep Stiffness, S, (MPa) at 60 s and -24°C Determined by the Bending Beam Rheometer:						
AC-5 Surface	92	98	124	110	139	ND
AC-5 Base	139	183	218	206	165	0.6
AC-20 Surface	284	288	312	353	333	2.5
Average Slope, m, of Log Creep Stiffness vs. Log Time at 60 s and -24°C Determined by the Bending Beam Rheometer:						
AC-5 Surface	0.40	0.40	0.38	0.36	0.36	4.0
AC-5 Base	0.38	0.37	0.36	0.34	0.35	3.0
AC-20 Surface	0.33	0.31	0.31	0.29	0.30	3.0
Average Absolute Viscosity (Pa-s) at 135°C Determined by the Brookfield Viscometer:						
AC-5 Surface	0.36	0.33	0.41	0.44	0.29	< 0
AC-5 Base	0.34	0.49	0.65	0.64	0.31	< 0
AC-20 Surface	0.45	0.51	0.52	0.63	0.55	2.3

ND = No data. A laboratory aging period could not be predicted from the data.

MIXTURE TEST DESCRIPTIONS

Marshall Mixture Properties

Marshall mixture properties were determined to verify whether the mixtures fabricated from the stockpiled materials were equivalent to the plant-produced mixtures and to evaluate the relationship between $G^*/\sin\delta$ and Marshall stability and flow.

Surface mixtures were compacted by the 75-blow Marshall method (*4*). Base mixtures were compacted using 112 blows (*5*). These blows are used to compact mixtures subjected to heavy traffic levels. The diameter and height of the surface mixture specimens were 101.6 and 63.5 mm. The base mixture specimens were 152.4 by 95.3 mm.

French Pavement Rutting Tester

The French (Laboratoire Central des Ponts et Chaussées) pavement rutting tester evaluates a slab for permanent deformation at 60°C (*6*). Each slab is 500 mm long, 180 mm wide, and 100 mm thick. The French plate compactor was used to compact the slabs; this machine employs a reciprocating, pneumatic rubber tire. The AC-5, AC-10, AC-20, Novophalt, and Styrelf surface mixtures had average air void levels of 8.4, 7.1, 7.3, 8.1, and 8.4 percent, respectively. The two base mixtures were not tested because the test method is not valid for mixtures with nominal maximum aggregate sizes greater than 20 mm.

The French pavement rutting tester tests two slabs simultaneously using two reciprocating pneumatic rubber tires that have a diameter of 415 mm and a width of 109 mm. They are inflated to 600 ± 30 kPa. The tires are always at a fixed elevation. Hydraulic jacks underneath the slabs push them upward to provide the load of 5,000 ± 50 N. Approximately 67 cycles are applied per minute. One cycle is defined as two passes of the tire. Slabs are tested in their molds.

Initially, 1,000 cycles are applied at 25°C to densify the mixture and to provide a smoother surface. The height of each slab is then calculated by averaging measurements taken at 15 positions using a depth gauge with an accuracy of 0.1 mm. This average height is considered the initial height, or point of zero rut depth. The slabs are then heated to 60°C for 12 hr. The test is started and the rut depth in each slab is measured at 300, 1,000, 3,000, 10,000, and 30,000 cycles. A mixture is acceptable if the average rut depth at 30,000 cycles is less than or equal to 10 mm. Slopes for different mixtures taken from log rut depth versus log cycle plots can also be compared. Rut-susceptible mixtures generally have higher slopes.

GLWT

The GLWT tests a beam for permanent deformation at 40.6°C (*6*). Each beam was 320 mm long, 120 mm wide, and 80 mm thick. Replicate beams were fabricated by compacting a slab and sawing it in half. The slabs had a length of 320 mm, a width of 260 mm, and a thickness of 80 mm. Each slab was compacted in two lifts using a vibratory hammer. A steel wheel roller was then used until the surface of the specimen was flat. The AC-5, AC-10, AC-20, Novophalt, and Styrelf surface mixtures had average air void levels of 7.0, 7.5, 7.1, 7.2, and 7.3 percent, respectively. The AC-5 and AC-20 base mixtures had average air void levels of 7.0 and 7.7 percent. Air void levels closer to the 8 percent target level were not obtainable. Attempts to increase the air void levels led to increased porosity around the edges and sides of the slabs.

The sides of the beam are confined by steel plates during testing except for the top 12.7 mm. A stiff rubber hose pressurized at 690 kPa with air is positioned across the top of the beam, and a loaded steel wheel runs back and forth on top of this hose for 8,000 cycles to create a rut. One cycle is defined as two passes of the wheel.

The load on the beam changes with the direction of travel. When the wheel is moving from right to left (viewed from the front of the machine), the load is approximately 740 N at the center of the beam, whereas the load is 630 N when the wheel is moving from left to right. Across the central region of the beam where the deformations are recorded, each of these loads has a variation of less than 5 percent. The load varies because the two arms that connect the wheel to the motor undergo a circular action at the motor. This "locomotion effect" shifts the distribution of the load during the test.

Deformations are measured at the center of the beam 51 mm left of center and 51 mm right of center. If the average rut depth exceeds 7.6 mm, the mixture is considered susceptible to rutting by the Georgia Department of Transportation.

Hamburg Wheel-Tracking Device

The Hamburg wheel-tracking device measures the combined effects of rutting and moisture damage by rolling a steel wheel across the surface of a slab that is submerged in water at 50°C (*6*). Slabs having a length of 320 mm, a width of 260 mm, and a thickness of 80 mm were tested. The slabs were compacted by the same method used to compact the slabs for the GLWT. The AC-5, AC-10, AC-

20, Novophalt, and Styrelf surface mixtures had average air void levels of 7.3, 6.9, 7.1, 7.4, and 7.4 percent, respectively. The AC-5 and AC-20 base mixtures had average air void levels of 6.3 and 7.0 percent. Air void levels closer to the 8 percent target level were not obtainable.

The device tests two slabs simultaneously using two reciprocating solid steel wheels that have a diameter of 203.5 mm and a width of 47.0 mm. The load is 710 N. Each wheel rolls 230 mm before reversing in direction, and the device operates at 53 ± 2 passes/min. The standard maximum number of passes is 20,000. The data from this device are customarily reported versus passes rather than versus cycles; a cycle is two passes.

A maximum allowable rut depth of 4 mm at 20,000 passes is used in Hamburg, Germany. The Colorado Department of Transportation (CDOT) recommends a maximum allowable rut depth of 10 mm at 20,000 passes (*7*). The rut depth in each slab is measured automatically and continuously by a linear variable differential transformer that has an accuracy of 0.01 mm.

The data analysis from the Hamburg wheel-tracking device includes the postcompaction consolidation, creep and stripping slopes, and stripping inflection point (*8*). The postcompaction consolidation, or the deformation at 1,000 passes, is so called because the steel wheel is compacting the mix early in the test. The creep slope relates to rutting primarily from plastic flow. It is the number of passes required to create a 1-mm rut depth. The stripping inflection point is the number of passes at the intersection of the creep slope and the stripping slope. It is the number of passes at which stripping starts to dominate performance. The stripping slope is a measure of the accumulation of rutting primarily due to moisture damage. It is the number of passes required to create a 1-mm rut depth after the stripping inflection point.

In this study, the creep slopes were used to compare the mixtures in terms of rutting. Higher creep slopes (passes per 1-mm rut depth) indicate less rutting. The postcompaction consolidations were also determined for informational purposes.

U.S. Corps of Engineers GTM

Shear susceptibility was measured using the static shear strength (Sg), gyratory stability index (GSI), gyratory elastoplastic index (GEPI), and refusal air void levels provided by the GTM, Model 8A-6B-4C. The GTM is a combination compaction and plane strain shear testing machine that applies stresses simulating pavement conditions.

The GTM was operated in accordance with NCHRP AAMAS with one modification. The NCHRP AAMAS procedure is based on ASTM D 3387 (*1*). The diameter and height of each specimen were 152.4 mm. A vertical pressure of 0.83 MPa, a 0.012-rad gyratory angle, and the GTM oil-filled roller were used. NCHRP AAMAS specifies a 0.035-rad gyratory angle; however, 0.012-rad angle was used because FHWA studies of previous pavements tested by the ALF indicated that this angle provided closer agreement between the GTM refusal densities and ultimate pavement densities. The 0.035-rad angle was found to be too high.

The GSI is the ratio of the maximum angle that occurs at the end of the test to the minimum intermediate angle. It is a measure of shear susceptibility at the refusal density. The minimum intermediate angle is the smallest angle that occurs after the compaction process has started. The GSI at 300 revolutions is close to 1.0 for a stable mixture and is significantly above 1.1 for an unstable mixture (*9*). When designing a mixture, the manufacturer states that the optimum binder content should be less than the binder content at the point at which the GSI begins to exceed 1.0. The GSI and the Sg are the principal GTM parameters used to evaluate rutting susceptibility.

The GEPI is the ratio of the minimum intermediate angle to the initial machine angle set by the operator. A GEPI of 1.0 indicates high internal friction. A GEPI significantly above 1.0 indicates lower internal friction, generally resulting from the use of rounded aggregates or from moisture damage. The manufacturer suggests using an acceptable range of 1.0 to 1.5.

The mixtures were first compacted to an 8 ± 1 percent air void level at 135°C. They were cooled to 60°C in an oven for 3 hr and then compacted and tested to their refusal densities. A trace of the gyratory angle versus number of revolutions was obtained to determine the maximum and minimum intermediate angles.

RESULTS AND DISCUSSION

Mixture Design

The Marshall data are given in Table 6 along with the gradations collected during construction, these data indicated that the plant-produced mixtures and the laboratory mixtures were essentially the same. For example, the air voids ranged from 2.5 to 4.1 percent for the plant-produced mixtures and from 2.9 to 4.3 percent for the laboratory mixtures.

The Marshall data were compared with the $G^*/\sin \delta$ at 60°C and a frequency of 0.125 rad/sec. The frequency of the Marshall test is approximately 0.00038 rad/sec, but 0.1 rad/sec was the lowest frequency used in the DSR test, and extrapolation could produce significant error. In order to combine the data from the surface mixtures with the data from the base mixtures, the stabilities of the base mixtures were reduced by a factor of 2.25 and the flows by a factor of 1.5. These factors theoretically account for the difference in the specimen size.

TABLE 6 Marshall Mixture Properties

Mixture Type	Binder Type	Optimum Binder Content (%)	MSG	Stability (N)	Flow, (0.25-mm)	Air Voids (%)	VMA (%)	VFA (%)
Properties of Plant-Produced Mixtures:								
Surface	AC-5	4.80	2.683	12 422	15.0	2.8	14.1	80.2
Surface	AC-10	4.80	2.691	13 046	15.8	2.7	13.8	80.4
Surface	AC-20	4.90	2.688	15 248	16.5	2.5	13.8	81.7
Surface	Novophalt	4.70	2.686	16 573	20.8	4.1	15.1	72.8
Surface	Styrelf	4.90	2.684	19 794	16.4	3.4	14.7	76.9
Base	AC-5	4.00	2.746	13 678	13.5	2.5	11.6	78.4
Base	AC-20	4.10	2.755	16 442	13.3	3.4	12.2	72.1
Properties of Laboratory-Prepared Mixtures:								
Surface	AC 5	4.85	2.699	11 565	14.5	3.0	13.9	78.4
Surface	AC-10	4.85	2.707	12 047	14.6	3.6	14.1	74.5
Surface	AC-20	4.85	2.706	11 232	17.6	2.9	13.5	78.5
Surface	Novophalt	4.85	2.699	16 125	16.8	4.2	14.9	71.8
Surface	Styrelf	4.85	2.701	18 536	22.8	4.0	14.7	72.8
Base	AC-5	4.00	2.750	13 295	12.8	4.3	13.1	67.2
Base	AC 20	4.00	2.750	14 168	12.4	4.2	13.0	67.7

Note: The stabilities of the base mixtures have been divided by 2.25, and the flows by 1.5, to account for the differences in specimen size.

Compaction Temperatures:

AC-5 = 121°C
AC-10 = 127°C
AC-20 = 135°C
Novophalt = 141°C
Styrelf = 141°C

Marshall Design Blows Per Side:

Surface = 75
Base = 112

MSG = Maximum Specific Gravity of the Mixture.
VMA = Voids in the Mineral Aggregate.
VFA = Voids Filled with Asphalt.

The ranking of the average $G^*/\sin\delta$ at 60°C and 0.125 rad/sec from lowest to highest was AC-5, AC-10, AC-20, Novophalt, and Styrelf. The ranking of average stabilities from lowest to highest for the plant-produced surface mixtures was AC-5, AC-10, AC-20, Novophalt, and Styrelf. These two rankings matched each other. The ranking using the laboratory surface mixtures was AC-20, AC-5, AC-10, Novophalt, and Styrelf. This ranking did not match the $G^*/\sin\delta$ as well as the ranking provided by the plant-produced surface mixtures.

Fisher's LSD did not provide rankings that clearly separated the stabilities of either the plant-produced or laboratory surface mixtures. Rankings that clearly separated the stabilities after combing the surface mixtures with the base mixtures were not provided either. The differences among the average stabilities of the mixtures were small compared with the variabilities of the replicate measurements. The effect of aggregate size was also not discernable.

In summary, the analyses based on a comparison of averages indicated a trend of increasing stability with increasing $G^*/\sin\delta$, but the statistical analyses indicated that stability cannot be used to predict rutting performance. There were no significant differences between most of the stabilities. Furthermore, the stabilities of all mixtures were above the minimum stability of 8006 N required for heavy traffic levels.

Rankings that clearly separated the flows did not exist. The differences among the average Marshall flows of the mixtures were very small compared with the variabilities of the replicate measurements.

TABLE 7 Rutting Performance Based on Accelerated Laboratory Testing

	Surface Mixture					Base Mixture	
	AC-5	AC-10	AC-20	Novophalt	Styrelf	AC-5	AC-20
French Pavement Rutting Tester at 60°C and 0.875 rad/s:							
Cycles:	*Percent Rut Depths:*						
300	2.97	2.98	2.59	1.44	1.84	NA	NA
1,000	3.79	3.99	3.21	1.67	2.22		
3,000	4.93	5.33	4.09	2.17	2.95		
10,000	8.23	9.23	4.90	2.38	3.25		
30,000	15.50	13.77	6.38	2.60	3.74		
Slope	0.35	0.34	0.19	0.14	0.16		
G*/sinδ, Pa	212	442	871	3 789	6 338		
Georgia Loaded-Wheel Tester at 40°C, 0.125 rad/s, and 8,000 cycles:							
Rut Depth, mm	7.38	5.38	3.72	1.42	1.87	6.29	3.46
G*/sinδ, Pa	899	2 215	5 060	21 000	20 600	899	5 060
Hamburg Wheel-Tracking Device at 50°C and 0.125 rad/s:							
Post CC, mm	ND	3.70	3.36	0.87	1.45	4.26	2.03
Rut Depth, mm	>30	>30	8.5	1.9	2.8	>30	8.6
Creep Slope	296	634	6 224	24 594	17 947	468	3 781
G*/sinδ, Pa	130	348	635	3 126	5 232	130	635
Post CC is the post compaction consolidation. Rut Depths are at 20,000 passes. Creep Slope is passes per 1-mm rut depth.							
Gyratory Testing Machine at 60°C and 0.125 rad/s:							
Sg, kPa	370	430	370	370	370	400	410
GSI	1.10	1.14	1.16	0.97	1.10	1.09	0.98
GEPI	1.14	1.18	1.02	0.84	1.10	1.07	0.83
Refusal Air-Void Level, %	2.13	2.03	3.30	5.91	5.97	4.20	5.46
G*/sinδ, Pa	28	60	124	661	1 750	28	124

NA = Test is not applicable for mixtures with aggregate greater than 20 mm.
ND = No data because the mixture failed too rapidly.

French Pavement Rutting Tester

The French pavement rutting tester data are given in Table 7. The AC-5 and AC-10 surface mixtures exceeded the 10-mm maximum allowable rut depth at 30,000 cycles; the other three mixtures met the criterion.

The ranking of the average $G^*/\sin\delta$ at 60°C and a frequency of 0.875 rad/sec from lowest to highest was AC-5, AC-10, AC-20, Novophalt, and Styrelf. The ranking of the average percent rut depths from highest to lowest was AC-5, AC-10, AC-20, Styrelf, and Novophalt. These two rankings provided reversals for the Styrelf and Novophalt binders. The slopes provided the same ranking as the percent rut depths.

Fisher's LSD divided the $G^*/\sin\delta$ into four groups: (*a*) AC-5 and AC-10, (*b*) AC-20, (*c*) Novophalt, and (*d*) Styrelf. The rut depths divided into three groups: (*a*) AC-5 and AC-10, (*b*) AC-20 and Styrelf, and (*c*) Styrelf and Novophalt. The slopes produced the same three groups. The analyses suggest that the $G^*/\sin\delta$ for Styrelf is high compared with its percent rut depth and slope.

Regressions between the $G^*/\sin\delta$ and the percent rut depths, slopes, and inverse slopes provided poor r^2 values of 0.62, 0.57, and 0.62, respectively. The inverse slopes were evaluated because the slopes from the Hamburg wheel-tracking device are inverse slopes.

Georgia Loaded-Wheel Tester

The GLWT data are given in Table 7. All of the mixtures met the 7.60-mm maximum allowable rut depth at 8,000 cycles.

The ranking of the average $G^*/\sin\delta$ at 40°C and a frequency of 0.125 rad/sec from lowest to highest was AC-5, AC-10, AC-20, Styrelf, and Novophalt. The ranking of the average rut depths for the surface mixtures from highest to lowest was AC-5, AC-10, AC-20, Styrelf, and Novophalt. These two rankings are identical. The rut depths for the two base mixtures agreed with their corresponding $G^*/\sin\delta$.

Fisher's LSD divided the $G^*/\sin\delta$ into four groups: (*a*) AC-5, (*b*) AC-10, (*c*) AC-20, and (*d*) Styrelf and Novophalt. The rut depths divided into four groups: (*a*) AC-5 surface and AC-5 base, (*b*) AC-10 surface and AC-5 base, (*c*) AC-20 surface and AC-20 base, and (*d*) Styrelf and Novophalt. These two rankings are identical using the surface mixture data. The only discrepancy between the two rankings was that the AC-5 base mixture ranked with both the AC-5 and AC-10 surface mixtures according to the rut depths. However, the true effect of maximum aggregate size based on pavement performance is not known; therefore, there may or may not be a real discrepancy.

Regressions between the $G^*/\sin\delta$ and the rut depths provided a good r^2 value of 0.84 for the surface mixtures, and a fair r^2 value of 0.79 for the surface and base mixtures combined. However, these r^2 values may be artificially high because of the large gap between the $G^*/\sin\delta$ of the unmodified and modified binders. The regressions and Fisher's LSD both indicated that aggregate size had little effect on rutting performance.

Hamburg Wheel-Tracking Device

The Hamburg wheel-tracking device data are given in Table 7. The AC-5, AC-10, and AC-20 surface mixtures and the AC-5 and AC-20 base mixtures exceeded the maximum allowable rut depth of 4 mm at 20,000 passes used in Hamburg, Germany. The AC-5 and AC-10 surface mixtures and the AC-5 base mixture exceeded the maximum allowable rut depth of 10 mm at 20,000 passes used by CDOT. No moisture damage was observed in any of the slabs; therefore, the $G^*/\sin\delta$ could be directly compared with the creep slopes. The $G^*/\sin\delta$ could not be compared with the rut depths at 20,000 passes because of the limitation that the device cannot measure rut depths deeper than 30 mm.

The ranking of the average $G^*/\sin\delta$ at 50°C and a frequency of 0.125 rad/sec from lowest to highest was AC-5, AC-10, AC-20, Novophalt, and Styrelf. The ranking of the average creep slopes for the surface mixtures from lowest to highest was AC-5, AC-10, AC-20, Styrelf, and Novophalt. These two rankings provided reversals for the Styrelf and Novophalt binders. The creep slopes for the two base mixtures agreed with their corresponding $G^*/\sin\delta$.

Fisher's LSD divided the $G^*/\sin\delta$ into three groups: (*a*) AC-5, AC-10, and AC-20, (*b*) Novophalt, and (*c*) Styrelf. The creep slopes divided into three groups: (*a*) AC-5 surface and base, AC-10 surface, and AC-20 surface and base; (*b*) AC-20 surface and Styrelf; and (*c*) Styrelf and Novophalt. The analysis suggests that the $G^*/\sin\delta$ for Styrelf is high compared with its creep slope.

Regressions between the $G^*/\sin\delta$ and the creep slopes provided a fair r^2 value of 0.70 for the surface mixtures and a fair r^2 value of 0.74 for the surface and base mixtures combined. However, these r^2 values may be artificially high because of the large gap between the data of the unmodified and modified binders. Regressions between the $G^*/\sin\delta$ and the slopes in terms of rut depth per pass were very poor. Aggregate size had little effect on rutting performance.

Fisher's LSD did not provide rankings that clearly separated the postcompaction consolidations of the mixtures. The AC-5 surface mixture failed rapidly; therefore, a postcompaction consolidation could not be determined.

Gyratory Testing Machine

The GTM data are given in Table 7. Relationships between $G^*/\sin\delta$ and Sg, GSI, and the GEPI were not found. There was very little variation in each parameter from mixture to mixture. The refusal air voids had the highest amount of variation. Regressions between $G^*/\sin\delta$ and the refusal air voids provided a fair r^2 value of 0.70 for the surface mixtures and a poor r^2 value of 0.42 for the surface and base mixtures combined.

Regressions Between the Wheel-Tracking Machines

A regression between the rut depths from the GLWT and the French pavement rutting tester for the five surface mixtures provided a very good r^2 value of 0.95. Regressions between the creep slopes from the Hamburg wheel-tracking device and the rut depths from the GLWT and French pavement rutting tester for the five surface mixtures provided good r^2 values of 0.85 and 0.83. Regressions between the Hamburg wheel-tracking device and the GLWT for the surface and base mixtures combined provided a fair r^2 value of 0.78.

CONCLUSIONS

1. An oven-aging period of 2 hr was needed to simulate the average degree of aging that occurred during plant production of the ALF mixtures. However, the data indicated that oven aging may not effectively simulate hot-mix plant aging.
2. As expected, the $G^*/\sin\delta$ of the binders increased as frequency increased or temperature decreased.
3. The study incorporated five binders, and it was assumed that this would provide five levels of $G^*/\sin\delta$, but the statistical analyses indicated that some binders had $G^*/\sin\delta$ that were not statistically different from others. This reduced the experiment to three or four groups of binders. How binders statistically group together can vary with temperature and frequency.
4. The Marshall stabilities and flows and the GTM parameters did not differentiate the mixtures according to rutting susceptibility.
5. The French pavement rutting tester, GLWT, and Hamburg wheel-tracking device differentiated the surface mixtures. The rut depths varied with the type of binder.
6. The GLWT and Hamburg wheel-tracking device did not differentiate the AC-5 surface mixture from the AC-5 base mixture or the AC-20 surface mixture from the AC-20 base mixture. Increased maximum aggregate size did not significantly reduce the rut depths or the influence of binder type on rutting susceptibility.
7. A general correlation between $G^*/\sin\delta$ and rutting susceptibility is that a binder with a higher $G^*/\sin\delta$ will provide a mixture that has a lower rutting susceptibility. However, the degree of correlation varied with the mixture test. The GLWT at 40°C provided a very good relationship. The French pavement rutting tester at 60°C and Hamburg wheel-tracking device at 50°C provide reasonably good relationships. The main discrepancy in these latter two devices was that even though the Styrelf mixture had a very low susceptibility to rutting, the data suggest that the rut depths are slightly high compared with the $G^*/\sin\delta$ of the binder. (The GLWT may also provide this discrepancy if the test were to be performed at 50°C or 60°C. The data in Table 2 at a frequency of 0.125 rad/sec show that the $G^*/\sin\delta$ of Styrelf becomes higher than that of Novophalt above 40°C.)

RECOMMENDATIONS

1. The results of this study should be compared with ALF pavement performances. The initial pavement tests indicate low amounts of rutting in the Novophalt and Styrelf surface mixtures; high amounts of rutting in the AC-5, AC-10, and AC-20 surface mixtures; and lower amounts of rutting in the AC-5 and AC-20 base mixtures compared with the AC-5 and AC-20 surface mixtures. The data from the GLWT and Hamburg wheel-tracking device do not agree with this last observation.
2. The reversals provided by the Styrelf and Novophalt binders should be evaluated.
3. Additional binders should be tested to develop firm relationships between $G^*/\sin\delta$ and the rutting parameters given by laboratory mixture tests.

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DISCUSSION

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The objective of the Corps of Engineers gyratory testing machine and method is to design an essentially rut-free pavement for whatever design stress is anticipated. The GTM procedure states, "In no case, however, should a bitumen content be selected that will be high enough to cause more than a faint spreading of the gyrograph trace." By this analysis, all of these mixtures except the Novophalt contain an excessive amount of asphalt and would be expected to rut if subjected to the 120-psi vertical stress employed in the GTM test. Please note that although the rutting test results show some rutting for all mixes, the least amount occurred for the Novophalt in each instance.

Referring to Table 7, the GEPI values are in error since the GEPI cannot be less than 1. The GEPI is defined as the ratio of the minimum intermediate gyrograph band width to the initial gyratory angle (i.e., the machine setting). Obviously the gyrograph, which is a recording of the gyratory angle, cannot be less than the machine angle controlled by the upper and lower rollers. It is not immediately evident how this error could occur.

Gyrographs for different aggregate types are also shown in order to illustrate how the gyrograph responds to the stress-strain properties of the material. The gyrograph is a recording of shear strain; the wider the gyrograph, the flatter the stress-strain curve. There is no question that S is a direct measure of plain strain simple shear and the fact that S is practically constant for these tests means that it is largely reflecting the internal friction of the aggregate, which is the same for all mixes. Any difference brought about by changes in the bitumen will more likely be reflected by changes in cohesion (not internal friction) and would be reflected in a Mohr's-type diagram, which can be readily prepared from the GTM results if $S\delta$ is plotted against increments of vertical stress.

Even more important would be changes observed in densification rate and recovery properties when using the GTM as a traffic simulator employing the air-filled upper roller in conjunction with cyclic loading (*1*).

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AUTHORS' CLOSURE

McRae states that the GTM is used to produce rut-free pavements and implies that the GTM parameters should not be correlated with rut depth. The data in our paper support the second part of this statement in that no correlation was found. However, it is the first author's experience that if an asphalt mixture test cannot be used as an analysis tool because it does not discriminate mixtures with widely different levels of performance, it may not always provide the required performance when used to design a mixture. Whether the GTM is an exception to this experience needs to be shown. We have tested mixtures with 100 percent rounded coarse aggregate using the GTM. The GTM has provided optimum binder contents for the mixtures, but the GTM parameters, including shear strength, have not always indicated that the mixtures will be susceptible to rutting. Perhaps changing the applied gyratory angle would provide better results.

Concerning the errors in the reported GEPI, we have only found the GEPI to be less than 1 for a few mixtures. These low GEPI have only been obtained when testing 152.4-mm diameter specimens and not with 101.6-mm diameter specimens. Perhaps this is coincidental. GEPIs less than 1 indicate there is a problem with the procedures used to apply or calibrate the desired angle. We have tried to independently verify the applied angle using a digital protractor. This has not been successful. Repeating the calibration procedures have indicated that the machine may not be capable of measuring or applying the small angles involved at the level of accuracy that is needed.

The use of Mohr's circles and the air-filled roller are also discussed. Perhaps these would provide different results, but these alternate methods were not evaluated. We also only used a single vertical stress and a single angle. These could also be varied.

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