Effects of Laboratory Asphalt Concrete Specimen Preparation Variables on Fatigue and Permanent Deformation Test Results Using Strategic Highway Research Program A-003A Proposed Testing Equipment

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A study was carried out to determine the effects of laboratory specimen preparation variables on permanent deformation, fatigue, and flexural stiffness performance, as measured with test equipment and methods by a Strategic Highway Research Program contractor. The specimen preparation variables included in the project were binder type, aggregate type, fines content, air-void content, compaction method, mixing viscosity, and compaction viscosity. Asphalt rubber was included as one of the binders in the experiment. The test methods used were the constant-height repetitive shear test for permanent deformation and the controlled-stress beam apparatus for flexural fatigue and stiffness. The investigation indicates that the variables included in the study affect the test results. Of particular interest were the results showing that (a) compaction method (gyratory, rolling wheel, and kneading compaction were included in the study) is a significant factor in permanent deformation performance; (b) a reduction in fines content of 3 percent significantly affects both permanent deformation and fatigue performance; and (c) the temperatures at which a mix is mixed and compacted also significantly affect fatigue performance. In addition, the constant-height repetitive shear test results showed asphalt-rubber mixes to be superior to the conventional asphalt mixes at 60°C (140°F).

The purpose of laboratory testing of an asphalt-aggregate mix is to estimate the performance of the mix as it will be compacted in the field, both compared with other asphalt-aggregate mixes and in terms of field conditions such as traffic and environment. Toward this goal, Strategic Highway Research Program Project A-003A (SHRP A-003A) at the University of California at Berkeley (UCB) has developed test methods and equipment for evaluating the permanent deformation and fatigue properties of asphalt concrete, including constant-height repetitive shear testing of cores 15.2 cm (6 in.) in diameter and repetitive flexural bending of beams, respectively. The results presented in this paper are from a project investigating the effects of specimen preparation variables on test results using the SHRP A-003A mix analysis equipment and laboratory-prepared specimens (*1*).

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It is important to avoid arbitrary decisions in laboratory specimen preparation if correct decisions about field performance of a mix are to be made from laboratory mix testing results. If a laboratory-compacted mix does not perform as it would if it were compacted in the field, the sensitivity of a test method and equipment is of little use in evaluating its expected performance. For several years it has been understood that the commonly used Marshall method of laboratory compaction does not produce specimens that perform the same as field-compacted specimens, primarily because of the impactive nature of the compaction mechanism. Several alternatives have been proposed, and some preliminary comparisons of specimens compacted using these methods have been performed (*2–4*). However, these comparisons have not provided definitive results.

In addition, other important variables in laboratory specimen preparation affect specimen performance. The laboratory specimen preparation variables included in this study were binder type, aggregate type, fines (passing a No. 200 sieve) content, air-void content, compaction method, mixing viscosity, and compaction viscosity.

There is also considerable need to develop a mix design procedure for asphalt-rubber concrete (RAC), which uses scrap vehicle tires as part of the binder. Conventional laboratory specimen preparation and test methods often have been found to be unsuitable for modified asphalt mixes. The applicability of the specimen preparation and testing methods used in this study was evaluated with regard to rubber-modified asphalt, which was included as one of the binders.

VARIABLES AND FACTOR LEVELS

Specimen Preparation Variables

Binder Type

The following binders were included in the experiment:

- V, California Valley AR-4000 asphalt cement (SHRP code AAG-1);

- B, Boscan petroleum AC-30 asphalt cement (SHRP code AAK-1); and
- R, asphalt-rubber cement, California Coastal AR-4000 asphalt cement (SHRP code AAD-1) and finely ground vehicle tire rubber (Atlos 1710).

Asphalt contents were determined for the conventional binders using the standard Hveem procedure (California Test 366, with minimum stability of 35) and were 5.2 percent for both asphalts for Pleasanton gravel, and 4.9 and 5.1 percent for Watsonville granite for Valley and Boscan asphalts, respectively, by weight of aggregate. The asphalt contents for the rubber-modified binder were set following the recommendations of the binder designer (*5*) that the maximum binder content be used that resulted in a minimum 3.0 percent air-void content using Marshall 50-blow compaction (ASTM 1559), which was 7.0 percent for both aggregates, by weight of aggregate. The rubber-modified binder contained 18 percent rubber by weight of the total binder. The same aggregate gradations used for the conventional mixes were also used for the RAC, with no gap included for the rubber. The asphalt used for the RAC was heated to 204°C (400°F) and the crumb rubber to 79°C (175°F) before being stirred together. The binder was then reacted for 1 hr at 177°C (350°F) before mixing with the aggregate.

Both the conventional and the RAC mixes were placed in an oven at 135°C (275°F) for 4 hr to simulate short-term aging.

Aggregate Type

The following aggregates were included in the experiment:

- P, Pleasanton gravel (SHRP code RH), which is partly crushed, generally semispherical, with a somewhat smooth surface texture; and
- W, Watsonville granite (SHRP code RB), which is completely crushed and angular, with a rough surface texture.

Fines Content

Two aggregate gradations were used in the experiment: low fines content gradation (2.5 percent fines) and normal fines content gradation (5.5 percent fines). The normal fines content gradation is dense graded with a top size of 1 in. The low fines content gradation is essentially the same, except for a 3 percent reduction in the fines content. Both gradations are within ASTM D3515 specification limits.

Air-Void Content

Air-void contents of 4 and 8 percent ± 1 percent were used with air-void contents measured using parafilm (*6*).

Compaction Method

Three compaction methods were included in the experiment:

- G, Texas gyratory,
- R, UCB rolling wheel, and
- K, California kneading.

All permanent deformation specimens were cored and cut to a disk shape 15.2 cm (6 in.) in diameter and 5.1 cm (2 in.) tall. All fatigue beams were cut to their final 3.8- × 3.8- × 38.1-cm (1.5- × 1.5- × 15-in.) shape.

The gyratory compaction method was adapted from Texas Method Tex-126-E and requires the use of the large Texas gyratory compaction machine, with an inclination angle of approximately 6 degrees and a standard mold 17.8 cm (7 in.) in diameter. Mass-volume calculations were used to calculate the final height (and volume) necessary to achieve the desired air-void contents. Gyratory compaction was not included in the fatigue portion of the experiment because fatigue beams cannot be produced by this method.

A standard ASTM kneading compactor, with modified mold dimensions and different compaction feet, was used for making all permanent deformation and fatigue kneading specimens. Fatigue beams were compacted using equipment similar to that described in ASTM D3202.

Permanent deformation specimens were compacted in a cylinder 19.3 cm (7.6 in.) in diameter, using a foot proportional to the standard ASTM kneading compaction (ASTM D1561) foot, as shown in Figure 1. The pressures and numbers of blows necessary to obtain the desired air-void content were determined by trial and error for each specimen.

The UCB rolling wheel (*7*) compaction method was used to prepare all rolling wheel permanent deformation and fatigue specimens for this project. The UCB rolling wheel compactor, shown in Figure 2, is a commercially available sidewalk compactor weighing between 365 and 545 kg (800 and 1,200 lb). The roller was used only in the static mode.

The compaction mold has a lift height of 7.6 cm (3 in.). For this project a steel plate insert was used to divide the mold into three cells. Each compacted specimen weighs approximately 20 kg (45 lb) and provides three or four fatigue beams and one permanent deformation specimen or three permanent deformation specimens.

Calculations are used to determine the mass of material to be compacted within a mold of known volume. The passes of the compactor are varied so that the edge of the compactor wheel passes over each of the cells in the mold.

Mixing Viscosity

Two mixing temperatures were used in the experiment for each binder. For the conventional binders the temperatures were those that provided viscosities of 6.0 (high viscosity) and 1.7 poise (optimal viscosity), shown below. The mixing and compaction temperatures used for the asphalt-rubber mixes, also shown below, were based on recommendations from the binder designer (*5*).

	Mixing Temperature (°F)		*Compaction Temperature (°F)*	
	Low	*Optimal*	*Low*	*Optimal*
Valley	243	280	208	243
Boscan	273	320	230	273
Asphalt rubber	325	350	275	300

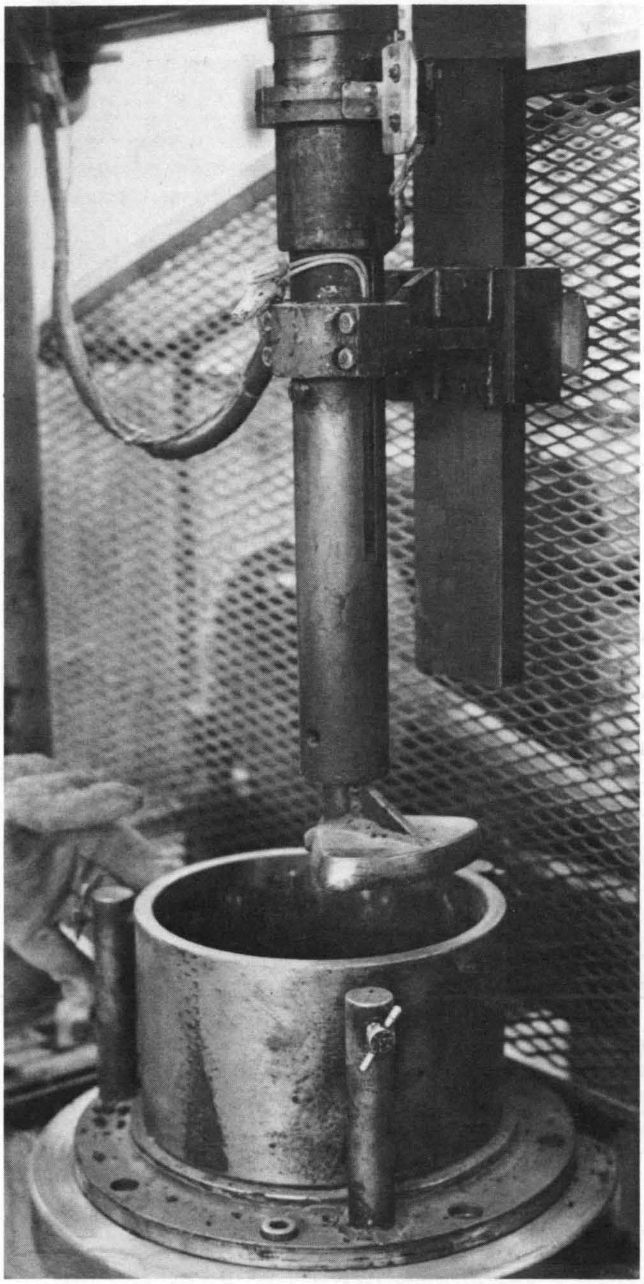

FIGURE 1 ASTM kneading compactor modified for a mold 7.5 in. in diameter.

Compaction Viscosity

For the conventional binders, compaction temperatures were selected that resulted in viscosities of 6.0 (optimal viscosity) and 25 poise (high viscosity), shown above. The compaction temperatures for the asphalt-rubber binder are the upper and lower limits of the range recommended by the binder designer (*5*).

Test Variables

Constant-Height Permanent Deformation Test

The constant-height permanent deformation test was performed using the Universal Testing Machine (UTM) (*8*). The UTM uses closed-loop computer-driven control of vertically and horizontally operating hydraulic pistons.

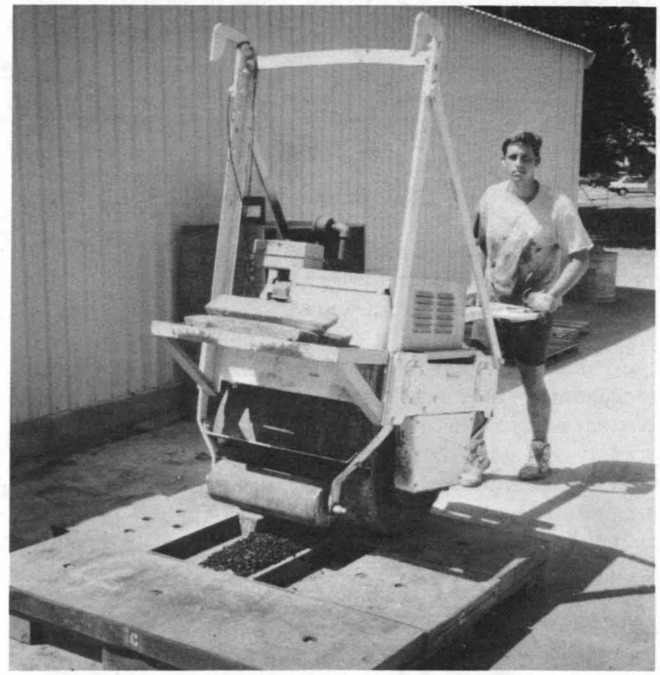

FIGURE 2 UCB rolling wheel compactor with "ingot" mold.

The specimen is maintained at a constant height and a constant temperature of 60°C (140°F) throughout the test. The shear load is applied to the specimen in the form of a half sine wave with an amplitude of 820 N (184 lb), 0.1-sec duration, and frequency of 1.429 Hz. The shear stress is 44.8 kPa (6.5 psi). Shear displacement is measured between two brackets mounted on the specimen 3.8 cm (1.5 in.) apart. Failure was set as occurring at a 2.0 percent permanent shear strain. The measured variable is repetitions to failure. Testing was continued until failure, or until 45,000 repetitions had occurred, in which case the shear deformation was extrapolated to failure.

Preliminary use of the constant-height repetitive simple shear test at UCB has shown that it is very effective in distinguishing the permanent deformation performance of various asphalt-aggregate mixes (*8*). The actual values and sequence of stresses felt by an element in the pavement subjected to a passing wheel depend on the load, pavement location, temperature, and the changing position of the element relative to the wheel. The methods available to analyze these stresses are based on assumptions that the material is linear elastic or linear viscoelastic, which it is not (*9,10*). For these reasons selection of a "field" state of stress at which to characterize the material is difficult, and the constant-height simple shear mode was selected.

During the repetitive shear loading that takes place in the test, both the binder and the aggregate structure resist shear deformation. The shear deformation mechanism has been previously proposed as being the most important for permanent deformation of reasonably well-compacted mixes and almost the only mechanism once the material has been compacted by initial trafficking (*11*). During the test the binder provides the initial resistance. As permanent shear deformation increases, the aggregates are forced to try to move past or over each other, resulting in increased aggregate-to-aggregate contact, and confining and dilation stresses. The specimen is not allowed to dilate because of the maintenance of constant height, so it develops confining stresses in the aggregate structure that also help resist shear deformation.

In specimens with good aggregate structures the dilation and confinement occur at smaller shear strains. For specimens that do not have or do not develop much aggregate-to-aggregate contact (such as those that are not well compacted, have smooth rounded aggregates, or were compacted using the gyratory compactor), the binder has a more important role in resisting shear deformation. In specimens that already have good aggregate-to-aggregate contact (such as those that are more compacted, have rough angular aggregate, or were compacted using the kneading compactor), the aggregate may be responsible for shear resistance from the beginning. The presence of a higher fines content would result in less aggregate-to-aggregate contact, which would reduce permanent deformation resistance. It would also provide more "glue" when mixed with the binder, which would increase fatigue resistance. Mixing and compaction viscosity would be expected to affect the binder film and bonding of the binder to the aggregate, as well as the ability of the aggregates to orient themselves during compaction.

Flexural Beam Fatigue Test

The equipment used for the flexural beam testing, performed under constant stress conditions for this project, was originally developed by Deacon (*12*) and later modified by Epps (*13*). The system uses a third-point loading system, which applies a uniaxial bending stress to the simply supported specimen and creates a region of constant bending moment throughout the central third of the specimen. A load of 655 kPa (95 psi) is applied for a duration of 0.1 sec in a square wave form and repeated 100 times per minute, resulting in a rest period between loads of 0.57 sec, with loading continuing until fracture. All fatigue tests were performed at 20°C (68°F).

The fatigue response variables measured were initial stiffness, measured at 50 repetitions; total repetitions to failure; and total dissipated energy to failure.

Controlled-strain testing using a sine wave, larger beam dimensions, and hydraulic controls has been proposed for fatigue testing by SHRP A-003A. However, the test and machine used in this project are similar in all other respects.

EXPERIMENT DESIGN

All specimens were prepared and tested using a balanced one-quarter fractional factorial statistical design with mixing and compaction viscosity as the fractionalized variables.

The selected design had 72 permanent deformation cells ($3^2 * 2^{5-2}$) and 48 fatigue cells ($3 * 2^{6-2}$). Repeats of each cell were not included in the design. Instead, the use of a balanced factorial design results in replication of each variable; for example, the permanent deformation design had 24 replications each of gyratory, kneading, and rolling wheel compaction. For the statistical analysis of all data, a 95 percent confidence level was used to determine whether a variable had a significant effect on the properties of the mixture. This means that there is a 5 percent or smaller probability of getting an *F*-statistic larger than that observed, under the hypothesis of the general linear model. The experiment was carried out as designed, resulting in near orthogonality between the independent variables. For this reason, the entry of a variable into the model had almost no effect on the *P*-values (the measure of statistical significance) of the other variables.

PERMANENT DEFORMATION RESULTS

The significant variables affecting permanent shear deformation are summarized in Table 1. Submodels of the experiment design were analyzed separately to evaluate differences between the responses of the conventional and rubber-modified binders. The significant main effects and interactions for these two mix types are also shown in Table 1.

As can be seen in average values for the full experiment and conventional and RAC submodels, shown in Tables 2 through 4, respectively, specimens with the stiffer Boscan and rubber-modified binders, rougher and more angular aggregate, low fines content, and low air voids performed best, as expected.

The rubber-modified binder performed exceedingly well compared with the conventional asphalts, which is similar to field results but contrary to the usual results of Hveem stabilometer or Marshall stability tests. The resistance of the rubber-modified binder to permanent shear strain is an order of magnitude greater than that of the conventional asphalts at both high and low air-void contents.

Previous test results (*4*) using a repetitive direct simple shear device had shown that the kneading compactor produces specimens more resistant to shear deformation and with greater dilation under shear load than do rolling wheel or gyratory specimens, with rolling wheel specimens exhibiting properties between those of kneading and gyratory specimens. These results were decisively confirmed here using the SHRP A-003A equipment for both conventional and rubber-modified binders. As shown in Table 3, for conventional asphalts, rolling wheel specimens have on average six times more shear resistance than do gyratory specimens. Kneading specimens have 100 times more shear resistance than do gyratory specimens and 18 times more shear resistance than do rolling wheel specimens. Both gyratory and rolling wheel compaction have been proposed as alternative laboratory compaction methods for the SHRP mix design method, and several states also use the ASTM kneading compactor.

The effects of compaction are much more pronounced in well-compacted specimens in which each compaction method produces its own distinct aggregate structure. In poorly compacted specimens, the lack of compaction results in a poor aggregate structure regardless of the method used.

The analysis of variance for the submodel including only the gyratory and rolling wheel specimens also showed the compaction method to be statistically significant, indicating that significantly different results can be expected when comparing specimens prepared with any two of the three compaction methods used in this study.

TABLE 1 Summary of Permanent Deformation Statistical Results

	Log Repetitions to 2.0 % Strain		
	Full Experiment	Conventional Asphalts Data	Rubberized Asphalt Data
	R^2 = 0.851 75 tests	R^2 = 0.826 49 tests	R^2 = 0.549 26 tests
Main Effects	Significant Variables	Significant Variables	Significant Variables
AC - Binder Type	X	X	NA
Ag - Aggregate	X	X	
FC - Fines Content	X		X
AV - Air-Void Content	X	X	X
Co - Compaction Method	X	X	X
Vm - Mixing Viscosity			
Vc - Compaction Viscosity			
Interactions	Significant Interactions	Significant Interactions	Significant Interactions
Ag * AV		X	
Ag * Co	X	X	
FC * AV		X	
FC * Co		X	
AV * Co	X	X	
Significant at 95 percent confidence level			

TABLE 2 Average Permanent Deformation Results: Full Experiment

	Air Voids (%)	Nf (reps)	Air-Void Content (low 4 %) Nf (reps)	Air-Void Content (high 8 %) Nf (reps)
Asphalt Type				
Valley AR-4000	5.9	803	1455	97
Boscan AC-30	6.1	6585	12895	276
Rubberized	5.8	108045	195300	6247
Aggregate Type				
Pleasanton Gravel	5.9	8623	16397	849
Watsonville Granite	6.0	68637	118786	3739
% difference		155.4	151.5	126.0
Fines Content				
Low (2.5 %)	6.0	66476	120713	2667
Normal (5.5 %)	5.9	13886	24814	1744
% difference		130.9	131.8	41.8
Air-Void Content				
Low	4.0	74560		
High	8.0	2207		
% difference		188.5		
Compaction Method				
Gyratory	6.1	2321	3636	786
Rolling Wheel	5.7	3797	6508	861
Kneading	6.0	118000	231028	4973
Mix Viscosity				
Low	6.0	20724	38494	1968
Normal	5.9	58434	108823	2445
% difference		95.3	95.5	21.6
Compaction Viscosity				
Low	5.9	21635	40848	2422
Normal	5.9	56626	98958	1843
% difference		89.4	83.1	27.2

Percent difference = (difference/average) * 100 percent

TABLE 3 Average Permanent Deformation Results: Conventional Asphalts

	Air Voids (%)	Nf (reps)	Air-Void Content (low 4 %) Nf (reps)	(high 8 %) Nf (reps)
Asphalt Type				
Valley AR-4000	5.8	951	1652	191
Boscan AC-30	6.2	6432	12663	200
% difference		148.5	153.8	4.6
Aggregate Type				
Pleasanton Gravel	5.9	975	1778	173
Watsonville Granite	6.1	6189	11716	200
% difference		145.6	147.3	14.5
Fines Content				
Low (2.5 %)	6.2	2502	4762	241
Normal (5.5 %)	5.8	4723	8961	132
% difference		61.5	61.2	58.4
Air-Void Content				
Low	4.1	6946		
High	8.0	187		
% difference		189.5		
Compaction Method				
Gyratory	6.0	91	111	69
Rolling Wheel	5.9	572	951	193
Kneading	6.0	10464	20630	298
Mix Viscosity				
Low	5.8	5594	10517	260
Normal	6.2	1595	2935	255
% difference		111.3	112.7	1.9
Compaction Viscosity				
Low	6.0	5750	11382	118
Normal	6.0	1605	2851	255
% difference		112.7	119.9	73.5

Percent difference = (difference/average) * 100 percent

Each of the main effects were more pronounced in well-compacted specimens, as can be confirmed in the table of average values. This indicates that a specimen must be well compacted to receive the full benefit of the aggregate, binder, and gradation, in addition to the compaction method. (Note: in Table 3, the average low fines content values at low air-void contents are better than the average high fines content values when corrected for air-void content and transformation to log values.)

The coefficients of the interactions of the compaction method with aggregate and fines content showed that the compaction methods that create a stronger aggregate structure (rolling wheel and especially kneading compaction) increase the benefits of aggregate type and low fines content.

Although not significant at the 95 percent confidence level, the average results show that conventional asphalt specimens performed better when mixed and compacted at higher viscosities (lower temperatures), whereas the opposite was true for rubber-modified specimens. This indicates that the rubber-modified binder quickly becomes too viscous to mix and compact well when the temperature is reduced, even within a relatively narrow range.

FATIGUE RESULTS

Stiffness

The variables that significantly affected the log stiffness variable are summarized in Table 5. On average, Valley asphalt specimens were much stiffer than either Boscan or asphalt-rubber specimens, as can be seen in Tables 6 through 8. This reflects the lower penetration values for the Valley asphalt at the test temperature. Low air-void contents and optimum mixing viscosities, as well as the interaction of Valley asphalt and Watsonville granite, also produced stiffer mixes.

In the conventional asphalts submodel, the aggregate type and compaction viscosity interaction variable indicated that stiffer mixes are found with gravel aggregate (more round and smooth) and a high compaction viscosity and granite aggregate (more angular and rougher surface texture) and the optimum compaction viscosity. This effect of the lower viscosity (higher compaction temperature) achieving a stiffer structure during compaction of the "harsher" granite mix makes sense because it would allow the aggregates to become oriented into a low air-void structure without crushing them together, which removes or reduces the asphalt film between them.

TABLE 4 Average Permanent Deformation Results: Asphalt Rubber

	Air Voids (%)	Nf (reps)	Air-Void Content (low 4 %) Nf (reps)	Air-Void Content (high 8 %) Nf (reps)
Aggregate Type				
Pleasanton Gravel	5.9	23918	45635	2201
Watsonville Granite	5.8	180153	307548	10293
% difference		153.1	148.3	129.5
Fines Content				
Low (2.5 %)	5.7	171591	294639	7525
Normal (5.5 %)	6.0	33908	62847	4968
% difference		134.0	129.7	40.9
Air-Void Content				
Low	3.9	195300		
High	8.1	6247		
% difference		187.6		
Compaction Method				
Gyratory	6.1	6533	9981	2222
Rolling Wheel	5.4	9532	154000	2197
Kneading	6.0	333072	651822	14322
Mix Viscosity				
Low	5.8	52621		
Normal	5.9	155550		
% difference		98.9		
Compaction Viscosity				
Low	5.9	53406		
Normal	5.8	154878		
% difference		97.4		

Percent difference = (difference/average) * 100 percent

TABLE 5 Summary of Fatigue and Stiffness Statistical Results

	Log Initial Stiffness			Log Repetitions to Failure			Log Total Dissipated Energy		
	Full Experiment	Conventional Asphalts Data	Rubberized Asphalt Data	Full Experiment	Conventional Asphalts Data	Rubberized Asphalt Data	Full Experiment	Conventional Asphalts Data	Rubberized Asphalt Data
	$R^2 = 0.718$ 55 tests	$R^2 = 0.882$ 35 tests	$R^2 = 0.760$ 20 tests	$R^2 = 0.788$ 55 tests	$R^2 = 0.808$ 35 tests	$R^2 = 0.854$ 20 tests	$R^2 = 0.767$ 55 tests	$R^2 = 0.863$ 35 tests	$R^2 = 0.654$ 20 tests
Main Effects	Significant Variables	Significant Variables	Significant Variables	Significant Variables	Significant Variables	Significant Variables	Significant Variables	Significant Variables	Significant Variables
AC - Binder	X	X	NA	X	X	NA	X	X	
Ag - Aggregate									
FC - Fines Cont				X	X		X	X	
AV - Air-Void Cont	X	X	X	X	X	X	X	X	X
Co - Compaction									
Vm - Mixing Visc	X		X	X		X	X		X
Vc - Compact Visc				X	X		X	X	
Interactions	Significant Interactions	Significant Interactions	Significant Interactions	Significant Interactions	Significant Interactions	Significant Interactions	Significant Interactions	Significant Interactions	Significant Interactions
AC * Ag	X								
AC * AV								X	
AC * Vm				X			X		
Ag * AV		X		X	X		X	X	
AG * Vc		X				X			
FC * AV				X	X		X	X	
FC * Co		X							
AV * Co			X	X		X	X		X
Co * Vm								X	
Co * Vc		X				X			

Significant at 95 percent confidence level

TABLE 6 Average Fatigue and Stiffness Results: Full Experiment

	Air Voids (%)	Stiffness (psi)	Nf (reps)	Ef (psi)	Low Air Voids (4 %) Stiffness (psi)	Low Air Voids (4 %) Nf (reps)	Low Air Voids (4 %) Ef (psi)	High Air Voids (8%) Stiffness (psi)	High Air Voids (8%) Nf (reps)	High Air Voids (8%) Ef (psi)
Asphalt Type										
Valley AR-4000	6.1	690761	407794	9145	804897	704010	15797	576626	111578	2494
Boscan AC-30	6.4	397642	700692	34219	421016	1334806	63921	376866	137036	7818
Rubberized	6.0	402110	449130	13677	492751	835471	23199	311469	62788	4156
Aggregate Type										
Pleasanton Gravel	6.0	509684	629222	23413	568584	1113213	39334	450785	145232	7491
Watsonville Granite	6.2	480173	393201	13494	563424	700559	24014	390518	62200	2165
% difference		6.0	46.2	53.7	0.9	45.5	48.4	14.3	80.1	110.3
Fines Content										
Low (2.5 %)	6.3	469967	198560	7807	548241	306900	11711	391693	90220	3903
Normal (5.5 %)	5.9	521361	839814	29678	583766	1506872	51637	454155	121443	6029
% difference		10.4	123.5	116.7	6.3	132.3	126.1	14.8	29.5	42.8
Air-Void Content										
Low	4.3	566004	906886	31674						
High	8.1	421768	105253	4927						
% difference		29.2	158.4	146.2						
Compaction Method										
Rolling Wheel	6.0	485861	668818	22502	571060	1187753	39066	387555	70046	3389
Kneading	6.3	504878	352139	14439	560169	582808	23144	453536	137946	6355
% difference		3.8	62.0	43.7	1.9	68.3	51.2	15.7	65.3	60.9
Mix Viscosity										
High	6.3	463867	322324	10626	530814	541317	16530	391770	86486	4267
Optimal	6.0	525408	697568	26178	601194	1272455	46817	449623	122681	5539
% difference		12.4	73.6	84.5	12.4	80.6	95.6	13.8	34.6	25.9
Compaction Viscosity										
High	6.3	480740	227174	9109	544704	364663	12986	416775	89685	5232
Optimal	6.0	508158	769935	27002	584463	1376812	47870	426403	119710	4644
% difference		5.5	108.9	99.1	7.0	116.2	114.6	2.3	28.7	11.9

TABLE 7 Average Fatigue and Stiffness Results: Conventional Asphalts

	Air Voids (%)	Stiffness (psi)	Nf (reps)	Ef (psi)	Low Air Voids (4 %) Stiffness (psi)	Low Air Voids (4 %) Nf (reps)	Low Air Voids (4 %) Ef (psi)	High Air Voids (8%) Stiffness (psi)	High Air Voids (8%) Nf (reps)	High Air Voids (8%) Ef (psi)
Asphalt Type										
Valley AR-4000	6.1	690761	407794	9145	804897	704010	15797	576626	111578	2494
Boscan AC-30	6.4	397642	700692	34219	421016	1334806	63921	376866	137036	7818
% difference		53.9	52.8	115.6	62.6	61.9	120.7	41.9	20.5	103.3
Aggregate Type										
Pleasanton Gravel	6.1	533647	554221	23510	574480	985687	41407	496898	165903	7403
Watsonville Granite	6.3	565895	545116	18728	680234	1017919	35110	451556	72313	2347
% difference		5.9	1.7	22.6	16.9	3.2	16.5	9.6	78.6	103.7
Fines Content										
Low (2.5 %)	6.4	523104	227383	9206	610634	340982	13376	435575	113783	5035
Normal (5.5 %)	6.0	575161	891716	34155	639561	1743212	66643	517917	134831	5277
% difference		9.5	118.7	115.1	4.6	134.6	133.1	17.3	16.9	4.7
Air-Void Content										
Low	4.4	624247	1000855	38443						
High	7.9	476746	124307	5156						
% difference		26.8	155.8	152.7						
Compaction Method										
Rolling Wheel	5.9	541831	685755	25440	611531	1203545	43789	463419	103242	4797
Kneading	6.5	554583	421901	17437	638552	772828	32429	487408	141160	5443
% difference		2.3	47.6	37.3	4.3	43.6	29.8	5.0	31.0	12.6
Mix Viscosity										
High	6.4	518342	445410	14568	591442	777949	23786	445242	112870	5351
Optimal	6.0	580204	660864	28477	661153	1251624	54933	508250	135744	4961
% difference		11.3	39.0	64.6	11.1	46.7	79.1	13.2	18.4	7.6
Compaction Viscosity										
High	6.2	541897	302112	11661	621592	520466	18933	462201	83758	4388
Optimal	6.2	553857	758856	29462	626607	1427867	55785	488382	156747	5770
% difference		2.2	86.1	86.6	0.8	93.1	98.6	5.5	60.7	27.2

TABLE 8 Average Fatigue and Stiffness Results: Asphalt Rubber

					Low Air Voids (4 %)			High Air Voids (8%)		
	Air Voids (%)	Stiffness (psi)	Nf (reps)	Ef (psi)	Stiffness (psi)	Nf (reps)	Ef (psi)	Stiffness (psi)	Nf (reps)	Ef (psi)
Aggregate Type										
Pleasanton Gravel	5.8	459096	787558	23207	557969	1342761	35604	335503	93554	7711
Watsonville Granite	6.1	355486	172234	5881	407677	277412	9219	292857	46020	1875
% difference		25.4	128.2	119.1	31.1	131.5	117.7	13.6	68.1	121.8
Fines Content										
Low (2.5 %)	6.2	374320	146679	5289	435935	245553	8713	312706	47806	1866
Normal (5.5 %)	5.7	429900	751580	22066	509373	1191752	31628	310692	91322	7722
% difference		13.8	134.7	122.7	15.5	131.7	113.6	0.6	62.6	122.2
Air-Void Content										
Low	4.0	475992	761661	21212						
High	8.3	311811	67146	4469						
% difference		41.7	167.6	130.4						
Compaction Method										
Rolling Wheel	6.2	399362	642641	17961	510354	1164065	31982	266173	16933	1136
Kneading	5.7	405469	212616	8442	434757	278777	8288	368859	129913	8634
% difference		1.5	100.6	72.1	16.0	122.7	117.7	32.3	153.9	153.5
Mix Viscosity										
High	6.0	354917	76153	2741						
Optimal	6.0	440723	754292	22625						
% difference		21.6	163.3	156.8						
Compaction Viscosity										
High	6.4	382889	107273	5026						
Optimal	5.5	421332	790986	22329						
% difference		9.6	152.2	126.5						

The compaction method interaction variables indicated that rolling wheel compaction produced higher stiffness mixes in combination with lower fines contents and the optimum compaction viscosity. Kneading compaction produced higher stiffness mixes with normal fines contents and with the higher compaction viscosity. The role of the two different fines contents in producing stiffer mixes with the two compaction methods is not readily apparent but may be caused by the less concentrated shear force of the rolling wheel, compared with the kneading compactor, being better able to orient aggregates in the low fines content mixes without breaking them or stripping off the asphalt film. For the same reason, rolling wheel compaction is probably better able to orient the aggregates when the mix has a lower viscosity, whereas the kneading compactor is able to move or crush together the aggregates despite the higher viscosity and probably achieves more orientation after a few tamps than does a rolling wheel specimen compacted to the same high air-void content.

In the asphalt-rubber submodel, mixing viscosity played a significant role in determining stiffness, with specimens mixed at the optimum viscosity being stiffer. The conventional binder pattern of rolling wheel specimens performing better at low air-void contents and kneading specimens at high air-void contents was also true for asphalt-rubber specimens.

Repetitions to Failure

The variables found to significantly affect the log repetitions to failure are shown in Table 6. Well-compacted specimens with Boscan asphalt and the normal fines content and mixed and compacted at the optimum viscosities had longer fatigue lives, as can be seen in Tables 6 through 8. The interactions of Boscan asphalt and asphalt-rubber and mixing at the optimum viscosity improved fatigue life. Low air-void contents improved the performance of Watsonville granite, high fines content, and rolling wheel specimens. Asphalt-rubber specimens had particularly poor performance when not compacted to low air-void contents.

The poor performance of kneading specimens, especially at lower air-void contents, is probably the result of some cracking of the aggregates and the forcing of aggregate-to-aggregate contact caused by the highly concentrated shear force imparted by the compaction foot. All specimens with large cracked aggregates in the failure face were thrown out of the study; however, the presence of smaller cracked aggregates caused by kneading compaction probably contributed to poorer performance compared with rolling wheel specimens.

Lower compaction viscosities probably aid in the development of a more laminar aggregate structure by allowing the large aggregates to become oriented during compaction. Lower mixing and compaction viscosities would also be more likely to result in a more uniform binder film thickness and less chance of larger aggregates being pushed into contact with each other without a uniform asphalt film between them.

For the conventional asphalts, lower mixing and compaction viscosities improve fatigue life but result in less resistance to permanent deformation under repetitive shear. On the contrary, rubber-modified binder specimens have both better fatigue performance and greater resistance to shear permanent deformation when mixed and compacted at lower viscosities (higher temperatures).

The fines content and air-void content interaction variable indicated that the extra compactive effort required to obtain the required air-void content for low fines specimens is not as beneficial as it is for high fines specimens, again probably related to the crushing together of aggregates, possibly resulting in little or no binder film between them. Similarly, the aggregate type and air-void content variable indicates that compacting the more rounded, smooth, and harder Pleasanton gravel specimens to a low air-void content is not as beneficial as it is for the rougher and more angular Watsonville granite specimens. The Pleasanton gravel may achieve a somewhat laminated structure under even light compaction because of its aggregate shape and texture.

In the rubber-modified binder submodel, contrary to expectations, the interaction of optimum compaction viscosity and Pleasanton gravel produced better specimens than it did with the rougher, more angular Watsonville granite.

Total Dissipated Energy

Previous research has shown that fatigue life and total dissipated energy are related variables (*14*), and both are similarly sensitive to conventional asphalt type, aggregate type, asphalt content, and air-void content (*15,16*). This was confirmed in this project, as can be seen in Table 5. As can be seen by the average values for each factor level shown in Tables 6 through 8, the results are approximately parallel for the two dependent variables.

In the conventional asphalts submodel the higher-penetration (at the test temperature) Boscan asphalt improved performance at low air-void contents, and rolling wheel compaction specimens performed better when mixed at the optimum viscosity.

CONCLUSIONS

The following conclusions can be drawn from the results presented in this paper.

- The SHRP A-003A type tests for permanent deformation and fatigue are sensitive to the specimen preparation variables, and the results follow trends in agreement with engineering expectations. The performance of asphalt-rubber, as measured by these tests, follows the behavior generally observed in the field.
- In particular, the resistance of asphalt-rubber concrete to permanent deformation under repetitive shear loads shows it to be greatly superior to the conventional asphalt binder mixes at 60°C (140°F). In contrast, the Hveem stability test often ranks rubber-modified material well below conventional mixes.
- Other than the risk of exposure to fumes caused by heating of the binder, none of the compaction methods or procedures used in this study presented any special problems for use in the laboratory evaluation of asphalt-rubber mixes.
- The permanent deformation results were most sensitive to binder type, aggregate type, fines content, air-void content, and compaction method. Fatigue and dissipated energy test results were sensitive to binder type, fines content, air-void content, and mixing and compaction viscosities. Flexural stiffness results were sensitive to binder type, air-void content, and mixing viscosity. Fatigue and stiffness were also sensitive to interactions with compaction method. Asphalt-rubber test results are sensitive to a narrow range of mixing and compaction temperatures. These results indicate that arbitrary decisions cannot be made regarding these variables in any laboratory mix design evaluation procedure.
- The significant effect on both permanent shear deformation resistance and fatigue life of a reduction in fines content of only 3.0 percent from the prescribed gradation is surprising. On the other hand, it is logical when one considers that this essentially cuts in half the volume of fines in the mixture, reducing the amount of cementing material in the mix and changing the asphalt film thickness at the points of aggregate contact. This indicates that variations of fines content, even within typical gradation specifications, can have serious effects on mix performance.
- Gyratory, rolling wheel, and kneading compaction produce specimens that are significantly different with respect to resistance to repetitive shear permanent deformation test results, with average results differing by more than an order of magnitude between each method for conventional asphalts. The results presented show that gyratory specimens have the least permanent shear deformation resistance, kneading specimens have the most resistance, and rolling wheel specimens have intermediate resistance. These results indicate that selection of laboratory compaction method will have at least as much effect on mix performance as aggregate type, binder type, fines content, or air-void content. The results also indicate that the use of various compaction methods can significantly determine the ability of a mix to pass specifications and can significantly alter the output from mix performance prediction models that use test results as input. For this reason the compaction methods cannot be used interchangeably.

ACKNOWLEDGMENTS

This work was conducted as part of a doctoral research program at the University of California at Berkeley (UCB) and was supported by SHRP Project A-003A; International Surfacing, Inc.; the California Department of Transportation; and the Contra Costa County Materials Laboratory. Financial assistance was provided for 2 years by the United States Department of Transportation through the UCB Transportation Center. The authors also thank Jorge Sousa and Akhtar Tayebali and the UCB Asphalt Research Program laboratory staff for their support and help with testing and specimen preparation.

SHRP is a unit of the National Research Council that was authorized by Section 128 of the Surface Transportation and Uniform Relocation Assistance Act of 1987.

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The opinions expressed in this paper are those of the authors and are not necessarily those of the National Research Council, SHRP, or any of the other institutions, agencies, and companies that provided assistance to this project.

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