Moisture Sensitivity Evaluation of Binder-Aggregate Mixtures

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This study assessed the moisture sensitivity of several binder-aggregate mixtures. This assessment included an evaluation of the effect of hydrated lime on the moisture sensitivity of asphalt-concrete mixtures, the effect of variations from the optimum binder content on the moisture sensitivity of asphalt-concrete mixtures, the moisture sensitivity of asphalt-rubber mixtures, and the potential use of controlled-strain fatigue beam testing to evaluate the moisture sensitivity of asphalt-concrete mixtures. Four aggregates, three asphalt contents, and two hydrated lime contents were used for the asphalt-concrete mixtures. The asphalt-rubber mixtures included asphalt-rubber gap-graded and dense-graded hot mix. Tests performed included AASHTO T283 and the controlled-strain fatigue beam test (Strategic Highway Research Program A-003A). It was found that hydrated lime in a slurry form could be effective in reducing moisture sensitivity of asphalt-concrete mixtures. The degree of its effectiveness was found to depend on asphalt content, lime content, and aggregate source. Also, it was found that a reduction in the binder content by 0.5 percent from the optimum could adversely affect the resistance to moisture damage. AASHTO T283 results showed that the asphalt-rubber mixtures may be more sensitive to moisture than conventional dense-graded asphalt-concrete mixtures. The fatigue beam test results indicated that the test had a potential use in moisture-sensitivity evaluation. The potential parameters were the flexural stiffness ratio and the fatigue life ratio.

Moisture sensitivity is one of the major problems in asphalt-concrete pavements, potentially leading to premature pavement distress. Recently, moisture sensitivity (stripping) was identified to be the major cause of distress in a number of pavements in northern California. The distress manifested in the form of cracking (alligator, longitudinal, and transverse) with varying degrees of severity (*1*). Rutting, raveling, bleeding, and potholes also occurred at various locations. As a result of an investigation conducted by the California Department of Transportation (Caltrans), it was recommended that moisture sensitivity of asphalt concrete mixtures be evaluated using AASHTO T283 and that moisture-sensitive aggregates be treated with hydrated lime in a slurry form before mixing with asphalt to increase the moisture resistance of asphalt-concrete mixtures (*2*).

This study evaluated (*a*) the effectiveness of hydrated lime in a slurry form in minimizing the moisture sensitivity of asphalt-concrete mixtures, (*b*) the use of AASHTO T283 in assessing the moisture sensitivity of asphalt-concrete mixtures, (*c*) the effect of variations from the optimum binder content (OBC) on the moisture sensitivity of asphalt-concrete mixtures, (*d*) the moisture sensitivity of asphalt-rubber mixtures, and (*e*) the potential use of the controlled-strain fatigue beam test, Strategic Highway Research Program (SHRP) A-003A, in evaluating the moisture sensitivity of asphalt-concrete mixtures.

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EXPERIMENTAL PROGRAM

The experimental program consisted of the following tests and variables.

AASHTO T283

1. Four aggregate sources: two non–moisture-sensitive and two moisture-sensitive aggregates based on field performance;
2. Three asphalt contents: the OBC as determined by Caltrans Test (CT) 367, and ± 0.5 percent variations from it (OBC −0.5 and OBC +0.5);
3. Two hydrated lime contents: 1.5 and 2.0 percent measured by dry weight of aggregate added in a slurry form (one part lime, three parts water);
4. Variable air-void levels, one at 95 percent relative compaction; and
5. Two asphalt-rubber mixtures identified as asphalt-rubber dense-graded hot mix (ARHM-DG) and asphalt-rubber gap-graded hot mix (ARHM-GG).

Controlled-Strain Fatigue Beam Test

1. Two aggregate sources (one non–moisture-sensitive and one moisture-sensitive aggregate), and
2. Two asphalt contents (OBC and OBC −0.5)

The moisture-sensitive aggregate was lime treated with 1.5 percent lime content at OBC. The specimens were compacted to 95 percent relative compaction.

MATERIALS

The four aggregate sources used in this study are identified as Kidder Creek, Clear Creek, Edsell, and Banhart. On the basis of their field performance, the Kidder Creek and Clear Creek aggregates are considered non–moisture-sensitive and the Edsell and Banhart aggregates are considered moisture-sensitive. A petrographic examination of the aggregates revealed the following:

1. Kidder Creek is composed of 75 percent metamorphic and 25 percent plutonic rocks;

2. Clear Creek is composed of 20 percent volcanic, 65 percent metavolcanic, and 10 percent plutonic rocks; and
3. Edsell and Banhart are mainly composed of andesite volcanic rock.

The gradations used for the dense-graded and the gap-graded mixes are shown in Table 1. The asphalt used in this study was AR-4000. The asphalt-rubber binder contained 17.0 percent tire rubber and 2.0 percent natural rubber (by total weight of binder).

SPECIMEN FABRICATION

The 102-mm-diameter AASHTO T283 specimens were compacted to a height of 64 mm using the California kneading compactor. The air-void levels selected for the moisture-damage specimens corresponded to 95 percent relative compaction (in-place density relative to the laboratory density) which is the minimum in-place compaction level considered satisfactory by Caltrans. Other tests were performed at different air-void levels. The air-void levels for the

TABLE 1 Mix Properties

			Aggregate Source			
Description		Test Method	Kidder	Banhart	Clear	Edsell
Bulk Coarse Specific Gravity		CT 206	2.878	2.600	2.638	2.569
Apparent Fine Specific Gravity		CT 208	2.888	2.720	2.700	2.682
Combined Specific Gravity		AASHTO T 209	2.883	2.661	2.672	2.630
Rice Specific Gravity (DGAC)(Untreated)		AASHTO T 209	2.697	2.501	2.489	2.450
Rice Specific Gravity (DGAC)(1.5% Lime)		AASHTO T 209	-[b]	2.493	-	2.461
Rice Specific Gravity (DGAC)(2.0% Lime)		AASHTO T 209	-	2.487	-	2.448
Rice Specific Gravity (ARHM - DG)(Untreated)		AASHTO T 209	2.595	2.419	-	*[c]
Rice Specific Gravity (ARHM - GG)(Untreated)		AASHTO T 209	2.610	2.403	-	*
Percent Water Absorption (Untreated)		CT 206	0.920	1.700	1.320	1.920
Percent Asphalt Absorption (Untreated)		AASHTO T 209	0.230	0.300	0.130	0.370
Percent Asphalt Absorption (1.5% Lime)		AASHTO T 209	-	0.280	-	0.350
Percent Asphalt Absorption (2.0% Lime)		AASHTO T 209	-	0.180	-	0.210
Crushed Particles		CT 205	95%	100%	97%	100%
Sand Equivalency		CT 217	76	76	78	81
Percent Air Voids(Untreated)		CT 367	4.30%	4.21%	5.06%	4.73%
Percent Air Voids(1.5% Lime)		CT 367	-	4.36%	-	5.76%
Percent Air Voids (2.0% Lime)		CT 367	-	4.00%	-	4.80%
Percent Air Voids (SSD)(Untreated)		AASHTO T 269	6.30%	6.24%	6.76%	7.47%
Percent Air Voids (SSD)(1.5% Lime)		AASHTO T 269	-	6.46%	-	7.96%
Percent Air Voids (SSD)(2.0% Lime)		AASHTO T 269	-	5.51%	-	5.76%
Percent Air Voids (SSD)(ARHM - DG)		--[a]	2.50%	2.50%	-	*
Percent Air Voids (SSD)(ARHM - GG)		--	2.00%	2.00%	-	*
Optimum Bitumin Content (OBC)(Untreated)		CT 367	4.30%	4.70%	5.00%	5.50%
Optimum Bitumin Content (OBC)(1.5% Lime)		CT 367	-	4.70%	-	5.00%
Optimum Bitumin Content (OBC)(2.0% Lime)		CT 367	-	4.70%	-	5.00%
Optimum Binder Content (ARHM - DG)		--	6.90%	7.60%	-	*
Optimum Binder Content (ARHM - GG)		--	7.40%	8.00%	-	*
Gradation			Percent Passing			
	Gap Graded		Dense Graded			
Sieve Size (mm)	Kidder	Banhart	Kidder	Banhart	Clear	Edsell
19.0	97	100	100	100	100	100
12.5	90	91	84	86	79	84
9.50	58	67	75	70	71	75
4.75	35	32	54	52	55	55
2.36	25	22	38	37	40	36
1.18	16	18	27	29	27	24
0.60	10	14	19	23	18	15
0.30	7	8	14	13	12	11
0.15	5	6	10	9	8	8
0.075	4	4	6	6	5	6
Lime Bulk Specific Gravity = 503 kg/m^3, Asphalt Grade AR-4000						
Absolute Viscosity=396.4 Pascals, Kinematic Viscosity=439 mm^2/s, Penetration=32 dmm						

[a]Caltrans practice for asphalt rubber mix design.
[b]Kidder Creek and Clear Creek aggregates were not tested with lime.
[c]Edsell was not tested with rubber.

moisture-damage specimens were computed based on AASHTO T269, which uses the Rice method for maximum theoretical specific gravity (AASHTO T209) and the saturated-surface dry-bulk specific gravity (AASHTO T166).

Compaction of the beam specimens was performed using the rolling wheel compactor, which was developed at the University of California at Berkeley (UCB) during the SHRP efforts (*3*). After compaction, the beams were cut to 50 mm × 63 mm × 38 mm. This portion of the study was accomplished through a cooperative effort between Caltrans and UCB in which staff members from Caltrans performed the testing at the research laboratory of UCB with the participation and assistance of the staff from UCB.

MIX DESIGN CONSIDERATIONS

Conventional Dense-Graded Asphalt-Concrete Mixes

Without lime treatment, the OBCs for the conventional mixes containing the 19.0-mm gradations were 4.3, 5.0, 5.5, and 4.7 percent by dry weight of aggregate for Kidder Creek, Clear Creek, Edsell, and Banhart, respectively. Edsell and Banhart were then lime treated with 1.5 percent and 2.0 percent lime. After lime treatment, the OBC for Edsell decreased to 5.0 percent for both the 1.5 percent and 2.0 percent lime. The OBC for Banhart after lime treatment was the same as before lime treatment. The selection of the OBCs was based on CT 367, which requires a minimum Hveem stability of 35, slight flushing, and a minimum of 4.0 percent air voids. This test method uses the calculated air voids based on the assumption of zero asphalt absorption. The bulk specific gravity is determined according to CT 308-C, which uses the weight of the specimen in air and in water.

The air voids for Kidder Creek, Clear Creek, Edsell and Banhart at OBC were 4.30, 5.06, 4.73, and 4.21 percent using CT 367, and 6.30, 6.76, 7.47, and 6.24 percent using AASHTO T269, respectively. The air voids according to CT 367 were 2.0, 1.7, 2.74, and 2.03 percent lower than those according to AASHTO T269 for the Kidder Creek, Clear Creek, Edsell, and Banhart aggregates, respectively. From this comparison it is obvious that the current Caltrans design practice results in high air voids (according to AASHTO T269), an issue that is addressed in this paper.

Asphalt-Rubber Mixes

The mix designs for the asphalt-rubber mixes were determined according to current Caltrans practices (i.e., 2.5 percent and 2.0 percent air-void criteria for ARHM-DG and ARHM-GG, respectively, and no stability requirement). The bulk specific gravity was determined using CT 308-A. The OBCs for the ARHM-DG and ARHM-GG mixes were 6.9 percent and 7.4 percent, respectively, for Kidder Creek and 7.6 percent and 8.0 percent respectively, for Banhart.

MOISTURE CONDITIONING

AASHTO T283

The conditioning of the specimens was conducted according to AASHTO T283. In the conditioning process, the compacted specimens were stored at room temperature for a period of 72 to 96 hr. Half of the specimens were partially vacuum-saturated with water to 60 to 80 percent saturation. The conditioned specimens were put in a freezer at −18°C (0°F) for 16 hr, and then soaked in a 60°C (140°F) water bath for 24 hr. Finally, the specimens were cooled in a 25°C (77°F) water bath for 2 hr before testing.

Controlled-Strain Fatigue Beam Test

The conditioning of beam specimens was conducted in a procedure similar to that developed as part of Project SHRP A-003A (*4*), which was developed for the Moisture Conditioning System. In the conditioning process, half of the beams were vacuum-saturated with water to 60 to 80 percent. These conditioned beams were then submerged and subjected to three cycles of 5 hr at 60°C followed by 4 hr at 25°C and then one 5-hr cycle at −18°C. The saturation of the beams was maintained by wrapping them with parafilm.

PROPERTIES ANALYZED

The properties analyzed were indirect tensile strength, tensile strength ratio (TSR), flexural stiffness, flexural stiffness ratio, fatigue life, and fatigue ratio.

Indirect Tensile Strength

The indirect tensile strength, referred to hereinafter as the tensile strength, is defined as the maximum stress from a diametral vertical force that a specimen can withstand. It can be computed using the following formula:

$$\sigma t = 2000P/(\Pi tD)$$

where

σt = tensile strength (kPa),
P = maximum load carried by the specimen (N),
t = thickness of specimen (mm), and
D = diameter of specimen (mm).

TSR

The TSR, which was first suggested by Lottman (*5*), is used as a parameter to identify moisture-sensitive mixtures. The TSR is defined as the ratio of the strength of conditioned (wet) specimens to the strength of unconditioned (dry) specimens and can be expressed mathematically as

$$TSR = \sigma\tau_{wet}/\sigma\tau_{dry}$$

where

TSR = tensile strength ratio,
$\sigma\tau_{wet}$ = tensile strength of conditioned specimens, and
$\sigma\tau_{dry}$ = tensile strength of unconditioned specimens.

Flexural Stiffness

The flexural stiffness is a function of the repeated flexural stress and the strain. Recent research has suggested that for controlled-strain testing, the effect of stiffness on fatigue life would vary (*6*). Tayebali et al. found that an increase in stiffness due to a change in asphalt type resulted in a decrease in fatigue life, whereas an increase in stiffness due to low air voids resulted in an increase in fatigue life. For controlled-stress testing, an increase in stiffness resulted in an increase in fatigue life regardless of whether it was caused by lower air voids or a change in asphalt type. The flexural stiffness ratio (FSR) was introduced as a parameter in this study. It is defined as the ratio of conditioned to unconditioned stiffness values.

$$FSR = S_{wet}/S_{dry}$$

where

FSR = flexural stiffness ratio,
S_{wet} = stiffness of conditioned specimens, and
S_{dry} = stiffness of unconditioned specimens.

Fatigue Life

Fatigue life is defined as the number of cycles to reach 50 percent of the initial flexural stiffness of the beam specimen. The fatigue life ratio was introduced as a parameter in this study:

$$FLR = FL_{wet}/FL_{dry}$$

where

FLR = fatigue life ratio,
FL_{wet} = fatigue life of conditioned specimens, and
FL_{dry} = fatigue life of unconditioned specimens.

EVALUATION OF RESULTS

The AASHTO T283 moisture-damage test results for the 95 percent relative compaction data are summarized in Table 2. To evaluate these results, two types of analysis were used: analysis of variance and *t*-test groupings. The data were first evaluated using analysis of variance to see if there were effects on tensile strength caused by variations from the OBC and changes in aggregate source, lime content, or condition (conditioned versus unconditioned strength). Table 3 shows the results of this analysis. Probabilities less than 0.05 were considered to have significant effects. Tensile strength was found to be significantly affected by variations from the OBC and changes in lime content, aggregate source and condition. After the analysis of variance, *t*-test groupings were used to show the levels at which the differences in strength occurred.

The controlled-strain fatigue beam test data were evaluated by examining the flexural stiffness and the strain-fatigue relations before and after conditioning. The FSR and FLR are two parameters that can be used in moisture-sensitivity evaluation. The evaluation of the results is described in the following section.

Effect of Variations from the OBC on Tensile Strength

Variations from the OBC affected the strength values significantly (Table 4 and Figure 1). As an example, for Kidder Creek, the tensile strength increased with the change in asphalt content from OBC −0.5 to OBC, and decreased as the asphalt content changed from OBC to OBC +0.5. For Edsell, Clear Creek and Banhart, the tensile strength generally increased with the change in asphalt content from OBC −0.5 to OBC and from OBC to OBC +0.5.

Table 4 shows the *t*-test results for all aggregates. The table shows that variations from the OBC generally produced significant differences in tensile strength values. For example, for Edsell at 1.5 percent and 2.0 percent lime contents, there were significant differences between the conditioned strength values at OBC −0.5 and OBC, and between the strength values at OBC −0.5 and OBC +0.05. However, there were fewer significant differences between the values at OBC and OBC +0.5.

Effect of Variations from the OBC on TSR

TSRs generally increased with increase in asphalt content (Table 2 and Figure 2). For example, Kidder Creek, a non–moisture-sensitive mixture, exhibited a low TSR (0.67) at the OBC −0.5 level and higher TSRs at OBC and OBC +0.5 (0.81 and 0.83, respectively). Edsell, a moisture-sensitive mixture, exhibited low TSRs at OBC −0.5 and OBC (0.52 and 0.55, respectively), and a higher TSR (0.81) at OBC +0.5. Since the TSR is a ratio between conditioned and unconditioned strength, a statistical analysis using *t*-test groupings was conducted to analyze the effect of conditioning on strength (Table 4).

Although the results showed some significant differences between the conditioned and the unconditioned specimens, fewer significant differences occurred among the lime-treated specimens. This is explained by the fact that the TSR values are high for the lime-treated specimens which means that the conditioned and unconditioned strengths are closer in values.

Effect of Aggregate Source on Tensile Strength and TSR

Tensile strength values were affected by aggregate source (Figure 1). For example, for conditioned specimens without lime treatment, Clear Creek showed the highest strength values at OBC−0.5 and OBC +0.5, and Kidder Creek had the highest strength values at OBC. There were no significant differences between Clear Creek and Kidder Creek at OBC −0.5 (Table 5). Therefore, Kidder Creek ranks highest, followed by Clear Creek, in terms of tensile strength values. Edsell had the lowest strength values at OBC −0.5 and OBC and ranks below Banhart. Banhart had the lowest strength values at OBC +0.5. There were no significant differences between Banhart and Edsell at all asphalt contents for the conditioned specimens (Table 5). Therefore, both Banhart and Edsell are expected to perform poorly. These findings agree with the reported field performance for all aggregates.

The TSRs at OBC for the different aggregates were 0.81, 0.72, 0.55 and 0.54, for Kidder Creek, Clear Creek, Edsell, and Banhart, respectively. This shows that Kidder Creek will perform best in terms of its resistance to moisture damage, followed by Clear Creek. Edsell and Banhart will perform poorly. At OBC −0.5, the TSRs are 0.67, 0.67, 0.52 and 0.43, for Kidder Creek, Clear Creek, Edsell, and Banhart, respectively. These ratios are lower than those at OBC. This shows that reducing the asphalt content results in increasing the potential for moisture damage of otherwise non–moisture-sensitive aggregates. At OBC +0.5, the TSRs were 0.83, 0.81, 0.81

TABLE 2 AASHTO T283 Moisture Damage Test Results

		95% Relative Compaction					Different Air Void Levels				
		Unconditioned		Conditioned			Unconditioned		Conditioned		
Asphalt Content	Aggregate Source	Air Voids (%)	TS[a] (kPa)[b]	Air Voids (%)	TS (kPa)	TSR[c]	Air Voids (%)	TS (kPa)	Air Voids (%)	TS (kPa)	TSR
OBC -0.5	Kidder Creek	12.88	783	12.91	526	0.67	7.77	1798	7.61	1132	0.63
OBC		10.99	1341	11.03	1084	0.81	7.19	1791	8.12	1539	0.86
OBC +0.5		9.78	926	9.48	769	0.83	7.46	1282	7.35	1086	0.85
OBC -0.5	Clear Creek	13.27	969	13.22	647	0.67	8.88	1812	8.73	1038	0.57
OBC		11.72	944	11.63	678	0.72	7.00	1955	7.01	1468	0.75
OBC +0.5		9.51	1181	9.43	955	0.81	8.03	1658	8.28	1373	0.83
OBC -0.5	Edsell	13.25	540	13.11	282	0.52	7.21	1394	7.28	1038	0.74
OBC		12.96	834	13.42	455	0.55	7.23	1773	7.32	1355	0.76
OBC +0.5		11.68	891	11.65	721	0.81	7.35	1656	7.38	1461	0.88
OBC -0.5	Edsell(1.5%)	14.63	1020	14.40	765	0.75	10.13	1424	10.13	1185	0.83
OBC		13.34	1036	13.09	981	0.95	7.28	1633	6.71	1277	0.78
OBC +0.5		11.24	1387	12.20	1056	0.76	6.89	1332	7.34	1238	0.93
OBC -0.5	Edsell(2.0%)	13.78	1171	13.69	967	0.83	7.85	1353	8.10	1164	0.86
OBC		10.61	1252	10.70	1100	0.88	7.30	1373	8.13	1254	0.91
OBC +0.5		11.80	1091	11.74	1034	0.95	6.73	1378	6.77	1286	0.93
OBC -0.5	Banhart	12.81	756	9.38	620	0.43	8.18	1632	8.00	974	0.47
OBC		10.83	967	11.44	521	0.54	9.61	1077	9.77	576	0.54
OBC +0.5		9.28	1132	12.79	714	0.55	8.08	1325	8.08	749	0.56
OBC -0.5	Banhart(1.5%)	13.02	863	12.79	714	0.83	8.80	1612	8.70	1387	0.86
OBC		11.27	856	11.33	847	0.99	7.03	1534	6.98	1546	1.01
OBC +0.5		10.90	1070	10.88	969	0.91	7.73	1387	7.80	1298	0.94
OBC -0.5	Banhart(2.0%)	12.50	756	12.71	597	0.79	6.99	1697	6.92	1656	0.98
OBC		10.31	864	10.03	898	1.04	9.40	1084	9.43	1130	1.04
OBC +0.5		9.71	902	9.44	838	0.93	8.01	1096	7.92	1020	0.93

[a]TS = Tensile Strength.

[b]1 psi = 6.89 kPa (kilo Pascals).

[c]TSR = Tensile Strength Ratio.

TABLE 3 Results of Analysis of Variance for Different Aggregates With and Without Lime

Source of Variation	Degree of Freedom	Sum Squares	Mean Squares	F Ratio	Probability
All Aggregates (without Lime)					
A	3	1043066	347689	57.44	< 0.0001
AC	2	1215864	607932	100.44	< 0.0001
C	1	1691880	1691880	279.52	< 0.0001
A*AC	6	831473	138579	22.89	< 0.0001
A*C	3	153684	51228	8.46	0.0010
AC*C	2	16155	8078	1.33	0.2729
A*AC*C	6	39832	6639	1.09	0.3780
Error	48	290530	6053		
Edsell Aggregate (with and without Lime)					
LC	2	2213824	1106912	117.03	< 0.0001
AC	2	756967	378483	40.02	< 0.0001
C	1	549643	549643	58.11	< 0.0001
LC*AC	4	221772	55443	5.86	0.0010
LC*C	2	48460	24230	2.56	0.0912
AC*C	2	3597	1798	0.19	0.8277
LC*AC*C	4	100067	25017	2.64	0.0493
Error	36	340495	9458		
Banhart Aggregate (with and without Lime)					
LC	2	250571	125286	20.49	< 0.0001
AC	2	591025	295513	48.34	< 0.0001
C	1	562428	562428	91.99	< 0.0001
LC*AC	4	84148	21037	3.44	0.0176
LC*C	2	454457	227229	37.17	< 0.0001
AC*C	2	28716	14358	2.35	0.1100
LC*AC*C	4	20142	5036	0.82	0.5188
Error	36	220093	6114		

A = Aggregate Source (Kidder Creek, Clear Creek, Edsell and Banhart)
LC = Lime content (0%, 1.5%, 2.0%)
AC = Asphalt content (OBC -0.5, OBC, OBC +0.5)
C = Condition (unconditioned and conditioned)
The level of significance is indicated by the probability of greater F.
Probabilities less than 0.05 are considered significant.

and 0.55 for Kidder Creek, Clear Creek, Edsell, and Banhart, respectively. These results show that the TSRs for Kidder Creek and Banhart did not change significantly, and TSRs increased for both Clear Creek and Edsell. This indicates that increasing asphalt content may result in increasing resistance to potential damage only in some aggregates.

Effect of Hydrated Lime on Tensile Strength and TSR

Lime treatment affected the strength values and tensile strength ratio (Table 2, Figures 1 and 2). Generally, the addition of lime increased the strength and TSR. The strength improvement in conditioned specimens caused by the addition of lime is shown in Table 6. The strength improvement was computed according to the following formula:

$$SI = [(\sigma\tau_{CL} - \sigma\tau_{CNL})/\sigma\tau_{CNL}] \times 100\%$$

where

SI = strength improvement (%),
$\sigma\tau_{CL}$ = tensile strength of conditioned lime treated specimens, and
$\sigma\tau_{CNL}$ = tensile strength of conditioned specimens without lime treatment.

The SI parameter gives a measure of the effect of lime treatment on the strength of conditioned specimens. Table 6 shows that there were strength improvements due to the addition of lime at both the 1.5 percent and 2.0 percent lime contents. For Edsell, the improvements were especially high at OBC −0.5, at which they were 171 percent and 243 percent for the 1.5 percent and 2.0 percent lime contents, respectively. At OBC the improvements were 116 percent and 142 percent for the 1.5 percent and 2.0 percent lime contents, respectively. For Banhart, the improvements were also high at OBC −0.5 where they were 120 percent and 84 percent for the 1.5 per-

TABLE 4 AASHTO T283 Results for *t*-Test Groupings at 95 percent Relative Compaction

Asphalt	Specimen	Kidder Creek		Clear Creek		Edsell		Edsell(1.5%)[c]		Edsell(2.0%)		Banhart		Banhart(1.5%)		Banhart(2.0%)	
Content	Condition	Mean[a]	T-grp[b]	Mean	T-grp	Mean	T-grp	Mean	T-grp	Mean	T-grp	Mean	T-grp	Mean	T-grp	Mean	T-grp
Comparision between Specimen conditions																	
OBC -0.5	Uncond.	783	A	969	A	540	A	1020	A	1018	A	756	A	864	A	756	A
	Cond.	526	B	648	B	283	A	765	B	857	A	324	B	714	A	597	B
OBC	Uncond.	1341	A	944	A	834	A	1036	A	1251	A	967	A	857	A	864	A
	Cond.	1084	A	678	B	455	B	981	A	1100	A	521	B	847	A	898	A
OBC +0.5	Uncond.	926	A	1180	A	891	A	1387	A	1091	A	1132	A	1070	A	903	A
	Cond.	770	A	955	B	721	A	1057	B	1034	B	620	B	969	B	838	A
Comparision between different asphalt contents																	
OBC -0.5	Uncond.	783	A	969	A	540	A	1020	A	1018	A	756	A	864	A	756	A
OBC	Uncond.	1341	B	944	A	834	B	1036	A	1251	A	967	B	857	A	864	B
OBC +0.5	Uncond.	926	C	1180	B	891	B	1387	B	1091	A	1132	B	1070	BA	903	AB
OBC -0.5	Cond.	526	A	648	A	283	A	765	A	857	A	324	A	714	A	597	A
OBC	Cond.	1084	B	678	A	455	B	981	B	1100	B	521	B	847	A	898	B
OBC +0.5	Cond.	770	C	955	B	721	C	1057	B	1034	B	620	B	969	B	838	B

[a]Values are in kilopascals (1 psi = 6.89 kPa)

[b]Groups having different designations indicate significant differences.

[c]Percentage in parentheses indicates the lime content.

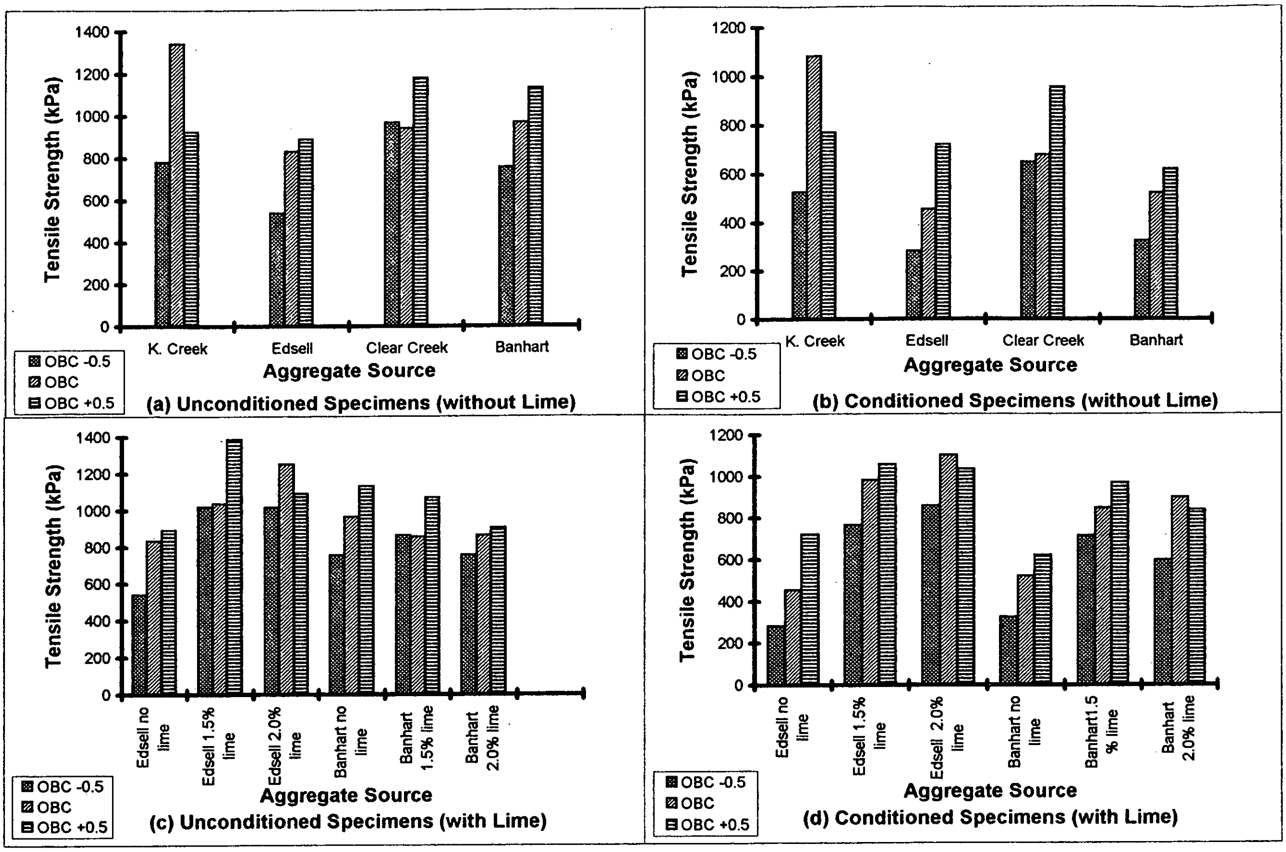

FIGURE 1 Tensile strength as a function of aggregate source and binder content.

cent and 2.0 percent lime contents, respectively. At OBC the improvements were 63 percent and 72 percent for lime contents of 1.5 percent and 2.0 percent, respectively. At OBC +0.5 there were improvements for both Banhart and Edsell but they were not as great as they were at the other asphalt contents. This shows that lime is most effective in increasing strength, especially at the lower asphalt contents where the potential for moisture sensitivity is higher.

Table 5 shows the results of the *t*-test comparing strength values at different lime contents. The table compares the strength values for Edsell and Banhart before and after lime treatment. These results show that there are significant differences between the strengths before and after lime treatment for both levels of lime content. However, there are no significant differences between strength values at 1.5 percent lime content and 2.0 percent lime content, even though the SIs for the 2.0 percent lime content were generally higher than those for the 1.5 percent lime content.

Edsell exhibited lower strength values than Banhart at OBC −0.5 and OBC, but higher strength at OBC +0.5 for the conditioned specimens. After lime treatment, Edsell exhibited higher strength values at all asphalt contents.

Table 6 shows the effect of lime treatment on the TSR values in terms of tensile strength ratio improvements (TSRIs), which were computed according to the following formula:

$$TSRI = [(TSR_{AL} - TSR_{BL})/TSR_{BL}] \times 100\%$$

where

$TSRI$ = tensile strength ratio improvement (%),
TSR_{BL} = tensile strength ratio before lime treatment, and
TSR_{AL} = tensile strength ratio after lime treatment.

Both Edsell and Banhart showed improvements. Banhart showed higher TSRI than Edsell. The TSRIs at OBC −0.5 and OBC were 44 percent and 73 percent for Edsell, and 98 percent and 83 percent for Banhart at 1.5 percent lime content, respectively. At these asphalt contents the addition of lime caused improvements in TSR. Similar patterns, with higher TSRIs, are exhibited for the 2.0 percent lime content. At OBC +0.5 the improvements were not consistent. At this asphalt content, the TSRIs for Edsell were −6 percent (no improvement) and 17 percent for the 1.5 percent and 2.0 percent lime contents, respectively, and the TSRI for the Banhart were 65 percent and 69 percent for the 1.5 percent and 2.0 percent lime contents, respectively. This supports the previous conclusion that lime treatment was most effective at lower asphalt contents.

This analysis makes it clear that treating aggregates with lime before mixing with asphalt increases the strength and the TSR. Also, because the SI and TSRI parameters give a measure of the effect of treatments such as lime, they should be used along with the TSR in moisture-sensitivity evaluation.

Effect of Air Voids on Tensile Strength and TSR

The analysis presented above was conducted at 95 percent relative compaction, at which level each mixture had a unique OBC with a

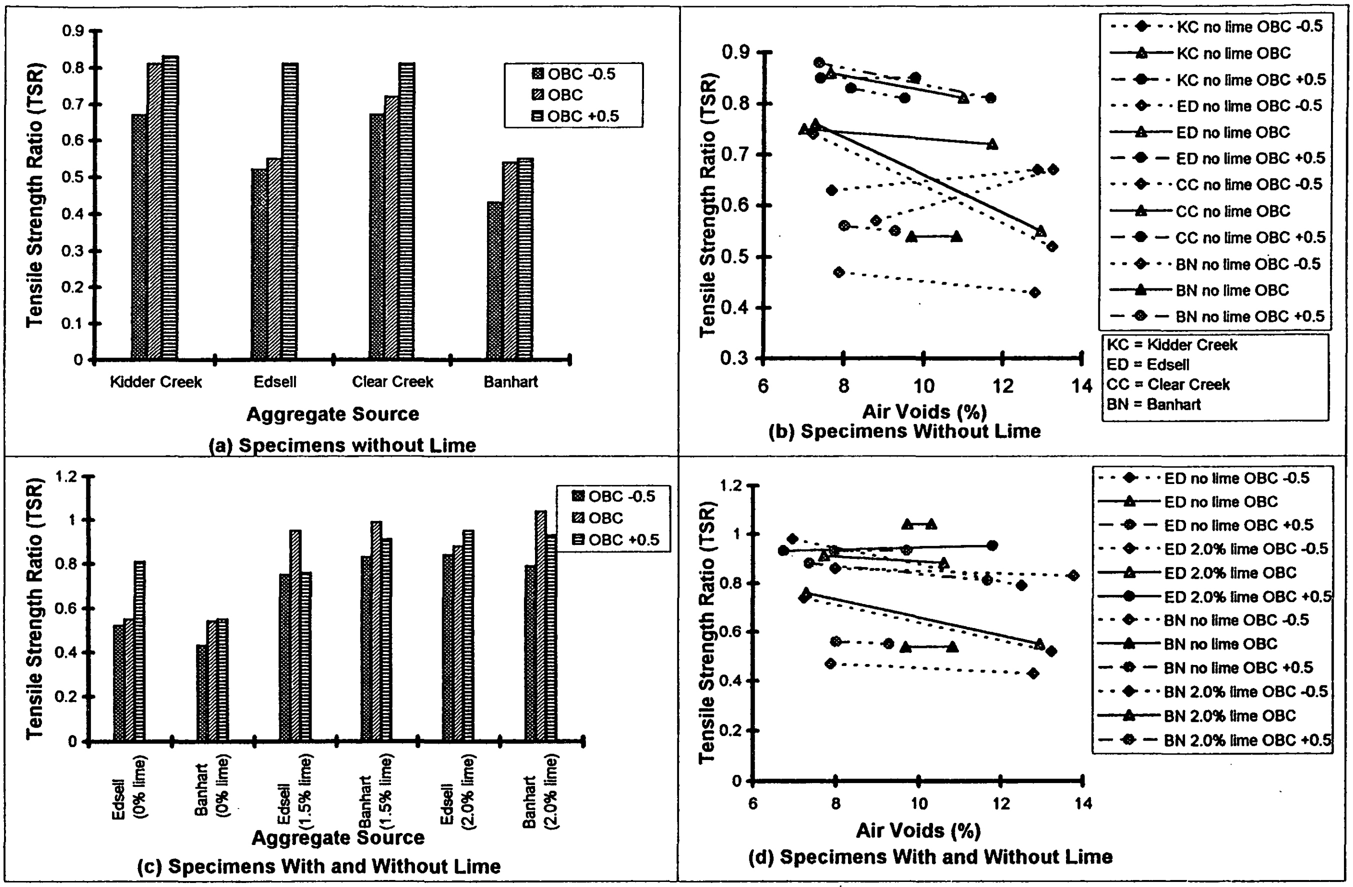

FIGURE 2 TSR as a function of aggregate source, lime content, binder content, and air voids.

unique air-void level. The variations from the OBCs also produced different levels of air voids. Therefore, the evaluated data showed a combined effect of air voids and asphalt content. These variations reflect what happens in practice in California. Other tests were conducted at different air-void levels (Table 2). Figures 2 and 3 show the effect of air voids on TSR and tensile strength. The figures show that air voids have a significant effect on tensile strength. As air voids increase, tensile strength decreases significantly. There were some decreases in the TSRs corresponding to the increases in air voids.

Effect of Using Asphalt-Rubber Binder on Tensile Strength and TSR

Table 7 contains a summary of AASHTO T283 results for the asphalt-rubber mixtures along with the conventional dense-graded asphalt-concrete (DGAC) mixtures at 95 percent relative compaction. These mixtures were compared at their OBCs. The table shows that tensile strength values for the ARHM-DG were almost equal to the DGAC mixture for Kidder Creek, and higher than the DGAC for Banhart. The strength values for ARHM-GG were significantly lower than those for DGAC and ARHM-DG mixtures. The table also shows low TSR values for the asphalt-rubber mixtures even for the non–moisture-sensitive Kidder Creek aggregate. These results indicate that there could be moisture-damage problems associated with the asphalt-rubber mixtures. However, other types of tests should be conducted to verify these findings. Tests that need to be considered include the simple shear and controlled-strain fatigue beam test (SHRP A-003A). These tests, along with field experience, will show the applicability of the AASHTO T283 test in the evaluation of the moisture sensitivity of asphalt-rubber mixes.

Evaluation of the Controlled-Strain Fatigue Beam Test

Table 8 shows the normalized results of the controlled-strain flexural beam test for different strain levels. The table shows that for the specimens that were not treated with lime, conditioning reduced both flexural stiffness and fatigue life and generally increased the phase angle. On the other hand, the lime-treated specimens showed no significant reductions in stiffness, had remarkable increases in fatigue life and exhibited reductions in phase angle as a result of conditioning. These changes indicate that when lime was present, a reaction occurred during conditioning that resulted in strengthening the binder-aggregate bond. Therefore, conditioning of the lime-treated specimens resulted in a stronger bond, instead of the weaker bond experienced with the untreated specimens. More research is needed to confirm this finding.

Table 9 shows the effect of lime on the FSR and the FLR. The table shows that for Banhart, the average FSR increased from 0.61 to 0.97 and the average FLR increased from 0.49 to 3.06 as a result

TABLE 5 Tensile Strength Data: *t*-Test Groupings Showing the Effect of Aggregate Source and Lime Content for Specific Binder Contents

Aggregate	Mean(kPa)[a]	T-Grouping[b]	Mean(kPa)	T-Grouping	Mean(kPa)	T-Grouping
	OBC -0.5		OBC		OBC +0.5	
Unconditioned Specimens without Lime						
Kidder Creek	783	A	1341	A	926	A
Edsell	540	B	834	B	891	A
Clear Creek	969	C	944	CB	1180	AB
Banhart	756	D	967	DB	1132	AB
Conditioned Specimens without Lime						
Kidder Creek	526	A	1084	A	770	A
Edsell	283	B	455	B	721	AB
Clear Creek	648	A	678	C	955	AC
Banhart	324	B	521	DB	620	ABC
Edsell Specimens with and without Lime (Unconditioned)						
Edsell no lime	540	A	834	A	891	A
Edsell 1.5% lime	1020	B	1036	B	1387	B
Edsell 2.0% lime	1018	B	1251	AB	1091	C
Edsell Specimens with and without Lime (Conditioned)						
Edsell no lime	283	A	455	A	721	A
Edsell 1.5% lime	765	B	981	B	1057	B
Edsell 2.0% lime	967	B	1100	B	1034	B
Banhart Specimens with and without Lime (Unconditioned)						
Banhart no lime	756	A	967	A	1132	A
Banhart 1.5% lime	864	B	857	A	1070	A
Banhart 2.0% lime	756	AB	864	BA	903	A
Banhart Specimens with and without Lime (Conditioned)						
Banhart no lime	324	A	521	A	620	A
Banhart 1.5% lime	714	B	847	B	969	B
Banhart 2.0% lime	597	B	898	B	838	B

[a]1 psi = 6.89 kPa

[b]Groups having different designations indicate significant differences.

TABLE 6 Tensile Strength and TSR Improvement due to the Addition of Lime for Conditioned Specimens

Asphalt Content	SI(%)	TSRI(%)	SI(%)	TSRI(%)
	Edsell with 1.5% Lime		Edsell with 2.0% Lime	
OBC -0.5	171	44	243	62
OBC	116	73	142	60
OBC +0.5	46	-6	43	17
	Banhart with 1.5% Lime		Banhart with 2.0% Lime	
OBC -0.5	120	98	84	84
OBC	63	83	72	93
OBC +0.5	56	65	35	69

of lime treatment. The table also shows that the FSRs and TSRs had similar trends in terms of their ranking of the various mixes. The strongest trends are associated with the 200-microstrain results. The FLRs were significantly lower than the FSRs and TSRs except for the lime-treated specimens. The average FLRs can be considered shift factors for the purposes of pavement modeling. The measurement of flexural stiffness before and after conditioning can be used in pavement analysis.

The strain-fatigue life relations were plotted in Figure 4 for two strain levels (200 and 300 microstrains). The figure indicates that moisture conditioning decreases fatigue life (except for the lime treated specimens) and that the mixtures at OBC −0.5 were more moisture sensitive than those at OBC.

Although the data were limited, the results indicate that the controlled-strain fatigue beam test has a potential use in moisture-sensitivity evaluation of binder-aggregate mixtures. This test mea-

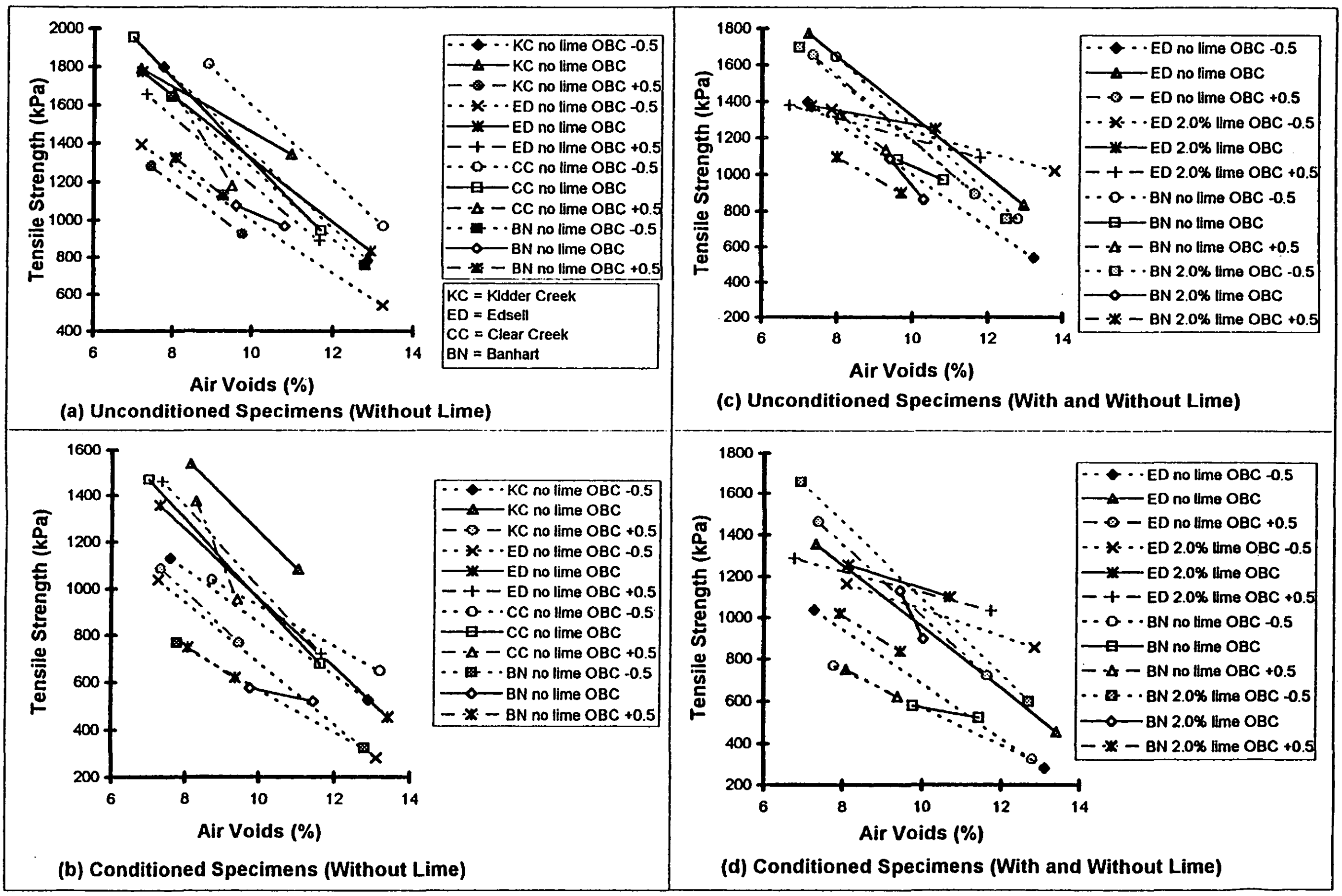

FIGURE 3 Tensile strength as a function of air voids for various aggregates.

TABLE 7 Summary of AASHTO T283 Moisture Damage Test Results for Asphalt-Rubber Mixes

Aggregate Source		Unconditioned Air Voids (%)	Unconditioned TS[a] kPa[b]	Conditioned Air Voids (%)	Conditioned TS kPa	Average TSR[c]
Kidder Creek						
DGAC		10.75	1536	10.72	1137	
		10.79	1323	10.79	1116	
		11.42	1164	11.57	999	0.81
	Mean	**10.99**	**1341**	**11.03**	**1084**	
	Std. Dev.	**0.38**	**187**	**0.47**	**74**	
ARHM DG		7.90	1392	6.74	668	
		6.60	1385	5.80	978	
		5.70	1268	5.70	785	0.60
	Mean	**6.73**	**1348**	**6.08**	**811**	
	Std. Dev.	**1.11**	**70**	**0.57**	**157**	
ARHM GG		6.30	1054	6.40	448	
		6.19	958	6.28	717	
		6.84	965	6.39	971	0.72
	Mean	**6.44**	**992**	**6.36**	**712**	
	Std. Dev.	**0.35**	**54**	**0.07**	**262**	
Banhart						
DGAC		10.99	978	10.88	593	
		11.17	965	11.95	427	
		10.33	958	11.50	544	0.54
	Mean	**10.83**	**967**	**11.44**	**521**	
	Std. Dev.	**0.44**	**11**	**0.54**	**85**	
ARHM DG		7.30	1137	7.80	503	
		7.40	1096	6.90	758	
		7.20	1123	6.90	758	0.60
	Mean	**7.30**	**1118**	**7.20**	**673**	
	Std. Dev.	**0.10**	**21**	**0.52**	**147**	
ARHM GG		6.14	861	6.14	331	
		6.66	834	5.62	537	
		6.19	847	6.91	345	0.48
	Mean	**6.33**	**847**	**6.22**	**404**	
	Std. Dev.	**0.29**	**14**	**0.65**	**116**	

[a]TS = Tensile Strength.
[b]1 psi = 6.89 kPa (kilopascals).
[c]TSR = Tensile Strength Ratio.

sures engineering properties that can be used in pavement analysis. Also, this test is an appropriate tool for moisture-sensitivity evaluation since the tension properties that relate to the binder-aggregate bond are evaluated under cyclic loading. Further evaluation and refinement of this test for moisture-sensitivity evaluation are necessary.

CONCLUSIONS

1. The modified Lottman test (AASHTO T283) appears to differentiate non–moisture-sensitive from moisture-sensitive asphalt-concrete mixtures.

2. Hydrated lime in a slurry form can be effective in increasing the moisture-damage resistance of moisture-sensitive asphalt-concrete mixtures.

3. A reduction in the binder content from the optimum by 0.5 percent may have a detrimental effect on the moisture-damage resistance of otherwise non–moisture-sensitive mixtures, and can be detrimental for moisture-sensitive mixtures.

4. Lime treatment may decrease the moisture sensitivity of asphalt-concrete mixtures that is caused by variations from the OBC.

5. Lime treatment is most effective in increasing tensile strength below the OBC where the potential for moisture sensitivity is greater.

TABLE 8 Summary of Controlled-Strain Fatigue Beam Test Results at 95 Percent Relative Compaction

Aggregate Source	Specimen Condition	Strain (μ-strain)	N_f (Cycle)	Stiffness (kPa)[a]	Phase Angle
Kidder Creek					
OBC -0.5	Unconditioned	200	69,288	4,184,490	22.76
OBC -0.5	Conditioned	200	14,214	3,013,569	27.55
OBC -0.5	Unconditioned	300	8,538	3,193,239	27.30
OBC -0.5	Conditioned	300	3,242	2,773,590	26.66
OBC	Unconditioned	200	189,481	6,791,914	21.23
OBC	Conditioned	200	54,620	5,721,300	22.64
OBC	Unconditioned	300	23,664	6,395,711	23.60
OBC	Conditioned	300	8,292	5,307,706	24.23
Banhart					
OBC -0.5	Unconditioned	200	162,846	4,920,487	20.46
OBC -0.5	Conditioned	200	30,619	2,679,190	21.82
OBC -0.5	Unconditioned	300	16,658	4,267,432	20.46
OBC -0.5	Conditioned	300	5,103	1,142,238	22.00
OBC	Unconditioned	200	110,042	5,554,236	23.28
OBC	Conditioned	200	77,417	2,734,117	27.02
OBC	Unconditioned	300	21,845	5,610,052	22.63
OBC	Conditioned	300	6,190	4,120,390	24.18
Banhart with 1.5% Lime					
OBC	Unconditioned	200	239,443	7,013,337	20.00
OBC	Conditioned	200	721,636	7,107,916	18.54
OBC	Unconditioned	300	58,877	6,885,218	20.75
OBC	Conditioned	300	182,576	6,411,558	20.22

[a]1 psi = 6.89 kPa (kilopascals).

6. In moisture-sensitivity evaluation, tensile strength, tensile SI and TSRI caused by additives should be considered as well as TSR.
7. High air voids can result in a reduction in tensile strength and TSR.
8. The controlled-strain fatigue beam test has a potential use in moisture-sensitivity evaluation. The stiffness ratio and FLR are potential parameters.
9. Asphalt-rubber mixtures (ARHM-GG and ARHM-DG) may be more moisture-sensitive than conventional dense-graded mixtures containing the same aggregate. Other tests are needed to verify this finding.

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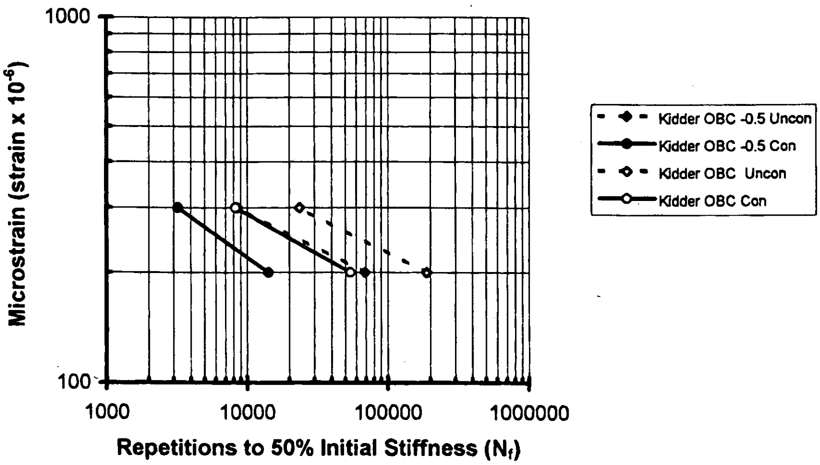
TABLE 9 Moisture-Damage Parameters: TSR, FSR, and FLR

Aggregate Source	Tensile Strength Ratio	Flexural Stiffness Ratio			Fatigue Life Ratio		
		200 μ-strain	300 μ-strain	Average	200 μ-strain	300 μ-strain	Average
Kidder Creek-OBC -0.5	0.67	0.72	0.86	0.79	0.21	0.38	0.30
Kidder Creek-OBC	0.81	0.84	0.83	0.84	0.29	0.35	0.32
Banhart-OBC -0.5	0.43	0.54	0.27	0.41	0.19	0.31	0.25
Banhart-OBC	0.54	0.49	0.73	0.61	0.70	0.28	0.49
Banhart-OBC with Lime	0.99	1.01	0.93	0.97	3.01	3.10	3.06



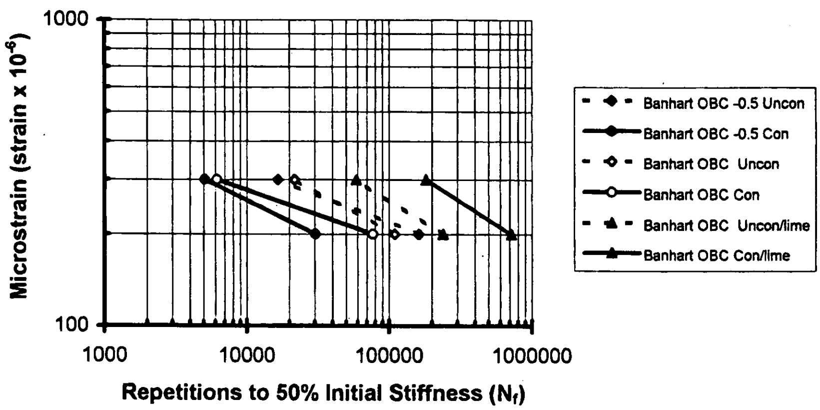


FIGURE 4 Strain-fatigue life relation at 20°C.

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REFERENCES

1. Shatnawi, S R., and J. Van Kirk. Premature Asphalt Concrete Pavement Distress Caused by Moisture Induced Damage. In *Transportation Research Record 1417,* TRB, National Research Council, Washington, D.C., 1993, pp. 168–177.
2. Shatnawi, S. R. *Premature AC Pavement Distress—District 2 Investigation.* Report FHWA-CA/TL-92-07 (CALTRANS-F91TL07). California Department of Transportation, Sacramento, 1992.
3. Harvey, J., and C. L. Monismith. Effects of Laboratory Asphalt Concrete Specimen Preparation Variables on Fatigue and Permanent Deformation Results Using Strategic Highway Research Program A-003A Proposed Testing Equipment. In *Transportation Research Record 1417,* TRB, National Research Council, Washington, D.C., 1993, pp. 38–48.
4. Terrel, R. L., and S. Al-Swailmi. *Water Sensitivity of Asphalt-Aggregate Mixtures Test Development.* SHRP, National Research Council, Washington, D.C., 1992.
5. Lottman, R. P. Laboratory Test Method for Predicting Moisture Induced Damage to Asphalt Concrete. In *Transportation Research Record 843,* TRB, National Research Council, Washington, D.C., 1982, pp. 88–95.
6. Tayebali, A. A., J. A. Deacan, J. S. Coplantz, J. T. Harvey, and C. L. Monismith. Mixtures and Mode-of-Loading Effects on Fatigue Response of Asphalt-Aggregate Mixtures. *Proc., AAPT* March 1994.

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