Evaluation of Mix Properties of Cold In-Place Recycled Mixes

TODD SCHOLZ, DAVID F. ROGGE, R. GARY HICKS, AND DALE ALLEN

Oregon has used cold in-place recycling (CIR) techniques since 1984 as one alternative to conventional asphalt concrete pavement rehabilitation practices. The initial success of the early CIR projects (1984 and 1985) prompted a joint research effort in 1986 between the Oregon State Highway Division and Oregon State University. This effort, continued in 1988, has focused on developing improved mix design procedures and construction guidelines for cold in-place recycling. One of the goals of the study was to develop a sample preparation procedure for cold recycled mixtures; the samples were to be used for mix design purposes. To validate the procedure, selected mix properties of field cores were compared with those of laboratory-prepared samples. The field and laboratory studies, their results, and a comparison of their results are described. Also, the CIR mix properties are compared with those of conventional hot mixes. Significant findings include (a) laboratory samples can be prepared at void contents similar to those found in the field; (b) laboratory sample mix property test results generally compare well with those of the field cores; and (c) limited comparisons showed that cold in-place recycled mixtures generally have greater moduli and fatigue lives than conventional hot mixes at similar void contents.

Since 1984, Oregon has used cold in-place recycling (CIR) techniques as one alternative to conventional practices for the rehabilitation of asphalt concrete pavements. Experienced paving personnel constructed the 1984 projects using trial-and-error procedures. In 1985 Oregon first attempted a formal mix design for the cold recycled mixtures. Because of the initial success of these early projects, Oregon State University (OSU) and the Oregon State Highway Division (OSHD) initiated a study in 1986 to develop an improved mix design procedure and construction guidelines for cold in-place recycling (*1*). Ths study was continued in 1988.

One of the purposes of the study was to develop a sample preparation procedure for cold recycled mixtures with the intent of using the samples for mix design purposes. To validate the procedure, selected mix properties of field cores were compared with those of laboratory-prepared samples. To accomplish this, two of the seven CIR projects selected for the 1986 field study were also selected for the laboratory study. At the time of construction of these two projects, laboratory samples were prepared from the millings. These samples, along with field cores from the two projects, were tested for mix properties (modulus, fatigue, and stability) 3, 15, 27, and 48 months after construction.

T. Scholz, D. F. Rogge, and R. G. Hicks, Department of Civil Engineering, Oregon State University, Corvallis, Oreg. 97331. D. Allen, Oregon Department of Transportation, Bend, Oreg. 97708.

The laboratory and field studies are described and the mix property test results are presented for two of the seven CIR projects included in the 1986 construction season. A comparison between laboratory and field test results from 1986 to 1990 is given, as well as a comparison between CIR field mixes and conventional hot mixes. Also included are significant conclusions resulting from this test program.

FIELD STUDY

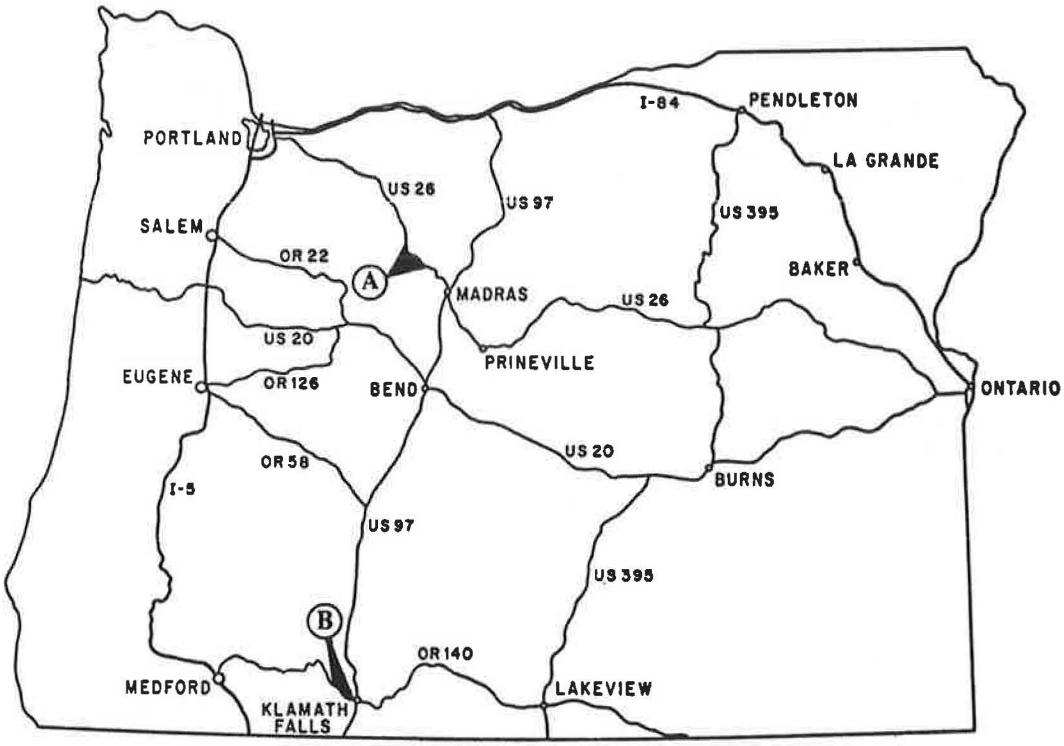
This section presents the results of the field study on two of the seven test sections evaluated in the 1986 OSU/OSHD study. Figure 1 shows location and construction information for the two projects (Warm Springs and Lake of the Woods). Both projects are on two-lane, medium-volume highways (1,750 to 2,850 average daily traffic). The Warm Springs test section had an average to soft (15 to 90 penetration at 77°F) asphalt before the CIR; the Lake of the Woods secton had a very hard and oxidized asphalt (4 to 5 penetration at 77°F). Field cores from the recycled projects were used for the field study, and recycled asphalt pavement (RAP) millings from the distressed pavement were used for the laboratory study.

Description of Field Study

Field cores were obtained from the Warm Springs and Lake of the Woods test sections in fall 1986, 1987, 1988, and 1989 (approximately 3, 15, 27, and 39 months after construction). Six 4-in. cores were extracted from each project. (The field cores were cut dry using air because use of cooling water tends to reemulsify the emulsified asphalt in the recycled cores, causing the core to soften and break down.) Three of the cores from each project were used for resilient modulus (ASTM D4123) and fatigue tests (*2*); the three remaining cores were used to test Marshall stability and flow (ASTM D1559).

Test Results

The results of mix property tests performed on the field cores from the two projects are summarized in Table 1. All results represent the average of three tests. The resilient modulus tests were conducted at 23°C (73°F), at a dynamic loading frequency of 1 Hz, at a dynamic load duration of 0.1 sec, and at a tensile strain of 100 microstrain ($\mu\varepsilon$). The fatigue tests were performed using the same loading conditions as for the



Unit	Project	Length (mi.)	Depth of CIR (in.)	Surface Treatment
A	MP 79.2-Wasco Co. Line (Warm Springs Hwy)	17.3	2-4	Polymer Chip Seal
B	Lakeshore Dr.-Greensprings Jct. (Lake of the Woods Hwy)	6.36	2.5-4	Chip Seal

FIGURE 1 Project location and construction information.

TABLE 1 SUMMARY OF FIELD CORE TEST RESULTS

Emulsion/ Water Content (%)	Test Period	Percent Voids	Average Resilient Modulus (ksi)	Average Fatigue Life (reps)	Average Marshall Stability (lb)	Average Flow (in./100)
a) MP 79.2-Wasco Co. Line (Warm Springs)						
1.0/2.4	Fall 1986	12.8	305 (243)	11,030 (5,053)	694 (80)	59 (5.7)
	Fall 1987	7.4	242 (15)	50,010 (17,709)	861 (81)	19 (3.0)
	Fall 1988	11.7	377 (30)	53,965 (12,800)	1,110 (22)	21 (1.5)
	Summer 1990	7.4	526 (8)	150,000+	1,811 (71)	17 (2.1)
b) Lakeshore Dr.-Greensprings Jct. (Lake of the Woods)						
1.8/1.6	Fall 1986	10.9	513 (107)	5,863 (4,354)	605 (100)	29 (13)
	Fall 1987	15.7	504 (62)	34,261 (5,536)	614 (27)	19 (0.6)
	Fall 1988	14.6	530 (16)	78,731 (13,847)	1,170 (43)	24 (3.8)
	Summer 1990	13.0	727 (58)	250,000+	1,597 (134)	17 (1.2)

Note: Parentheses contain standard deviation

resilient modulus tests, with an initial tensile strain of 100 $\mu\varepsilon$. Marshall stability tests were performed at 60°C (140°F) and at a load rate of 2 in./min.

The results indicate that the modulus, although initially remaining relatively constant, increased substantially after 3 years for both test sections, as shown in Figure 2a. Fatigue values, although initially very low for both sections, increased significantly over time (Figure 2b). This increase in fatigue resistance is attributed to improved cohesive properties of the asphalt cement due to additional curing over time.

As shown in Figure 3a, the stabilities increased over time for both test sections: the Warm Springs section shows a rel-

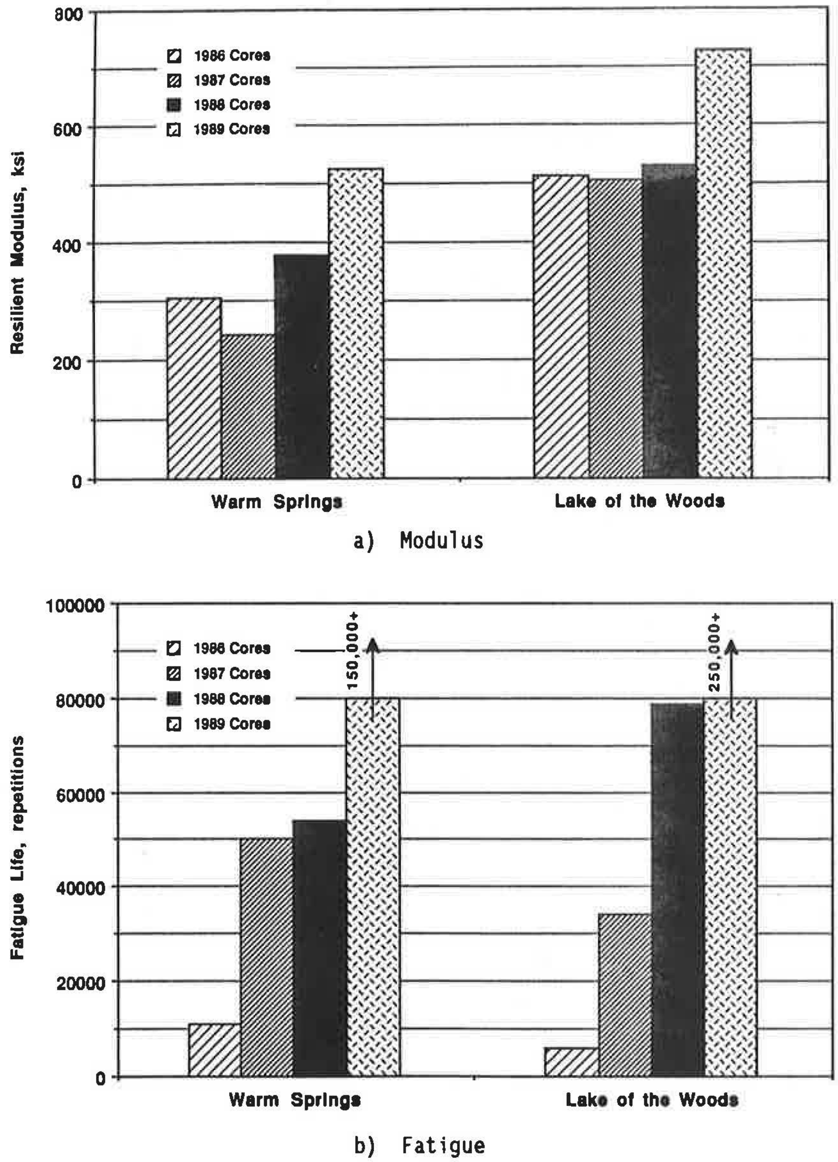


FIGURE 2 Modulus and fatigue results for field samples.

atively constant increase over time, and the stabilities for the Lake of the Woods section initially remained the same and then increased significantly. The flow values for the Warm Springs section were initially very high but leveled off to a relatively constant value; the values for the Lake of the Woods section decreased slightly or remained relatively constant over time (Figure 3b). Again, the increases in stabilities and decreases in flow values are attributed to improved cohesive properties of the asphalt cement due to additional curing of the recycled mix.

LABORATORY STUDY

This section presents the results of the laboratory study on the Warm Springs and Lake of the Woods test sections. The laboratory study is described and the mix property test results are summarized.

Description of Laboratory Study

A laboratory study program was undertaken on materials taken from the test sections on the Warm Springs and the Lake of the Woods highways in order to investigate the effects of emulsion content, curing time, and compactive effort. The recycled materials were collected and compacted at the same time as the cold recycling construction (July 1986 for Lake of the Woods, August 1986 for Warm Springs), which ensured a RAP gradation and existing asphalt content as in the in situ recycled pavement (Table 2).

The design emulsion content used to fabricate the 2.5-in.-thick by 4-in.-diameter briquets was the same as that used in the field during construction (1 percent for Warm Springs, 1.9 percent for Lake of the Woods). Additional samples were fabricated with the design emulsion content, the design minus 0.5 percent, and the design plus 0.5 percent. Thus, for the Warm Springs section, which had a design emulsion content

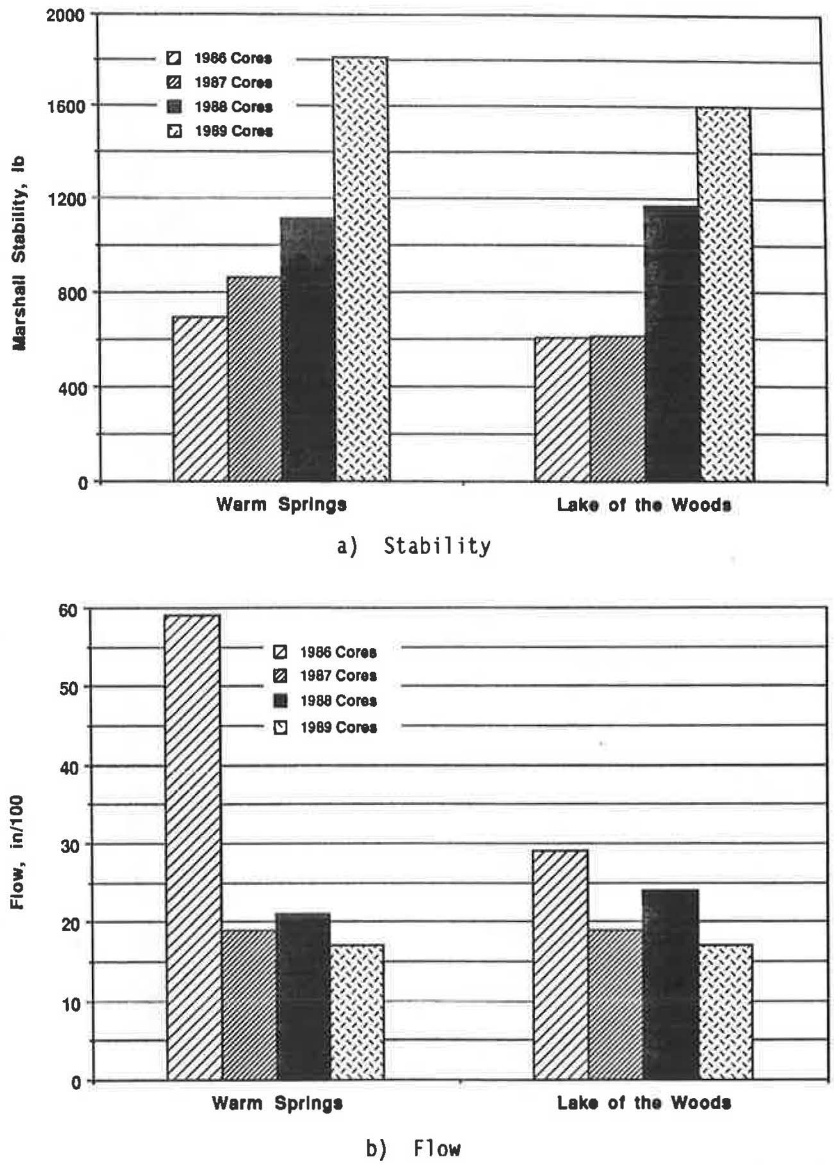


FIGURE 3 Marshall stability and flow results for the field cores.

of 1.0 percent, briquets were fabricated with 0.5 percent, 1.0 percent, and 1.5 percent added emulsion. Similarly, for the Lake of the Woods section, briquets were fabricated with 1.4 percent, 1.9 percent, and 2.4 percent added emulsion, with the design content being 1.9 percent.

The total liquids (emulsion and water) for all briquets fabricated with RAP from the Warm Springs section was held constant at 4.0 percent. Thus, for example, if the added emulsion content was 1.0 percent, the added water content was 3.0 percent. This same criterion was attempted for the Lake of the Woods section. However, during the preparation of samples with 1.4 percent emulsion, using 2.6 percent water produced a dry mix. To mitigate this problem, the total liquid content was increased to 4.5 percent, resulting in more workable and better-adhering mixtures. The total liquid content is the minimum quantity of liquids required for adequate dispersion of emulsion; insufficient liquid content results in a dry, unworkable mixture, and a total liquid content that is too high results in instability during compaction. Thus, once prescribed, the total liquid content was held constant to avoid problems during sample preparation. Incidentally, this philosophy is used in actual field construction.

Table 3 summarizes the number of samples prepared for each emulsion content; the mix property tests for the fall 1986, 1987, 1988, and summer 1990 test periods; and the schedule for each test period. Twelve samples per emulsion content were required for the remaining mix property tests (three samples per test period) because the fatigue and stability tests are destructive.

The procedure used to fabricate the samples is shown in Table 4. All mixing, curing, and compaction are performed at 60°C (140°F). A total compactive effort of 2,250 ft-lb is used during compaction (i.e., 150 blows using a 10-lb hammer with an 18-in. freefall). This relatively low compactive effort was necessary to achieve air void levels similar to those of CIR pavements in the field. Following specimen fabrication,

TABLE 2 RAP GRADATIONS AND ASPHALT CONTENTS

	MP 79.2-Wasco Co. Line (Warm Springs)			Lakeshore Dr.-Greensprings Jct. (Lake of the Woods)			
	1	2	Avg.	1	2	3	Avg.
% Passing							
1 in.	96	94	95	98	84	93	92
3/4 in.	88	90	89	96	81	90	89
1/2 in.	75	77	76	89	74	83	82
3/8 in.	61	62	62	79	65	74	73
1/4 in.	44	46	45	61	50	57	56
#4	33	36	34	48	40	46	45
#10	11	3	7	21	18	21	20
#40	1.7	2.2	2.0	6	6	7	6
#200	0.4	0.6	0.5	2.0	2.0	1.8	1.9
Extracted Asphalt Properties							
Content, %	5.4	5.7	5.6	4.6	4.4	5.1	4.7
Penetration @ 77°F, dmm	15	90	52	4	4	5	4
Viscosity @ 140°F, p.	18,067	2,693	10,380	100,000+	100,000+	100,000+	100,000+
Viscosity @ 25°F, cS	852	374	613	2,572	2,920	1,987	2,493

TABLE 3 NUMBER OF SAMPLES PREPARED AND TEST SCHEDULE FOR LABORATORY STUDY

Project Name	Emulsion/Water Content (%)	Resilient Modulus and Fatigue	Marshall Stability and Flow
a) Number of Samples Prepared			
MP 79.2- Wasco Co. Line (Warm Springs)	0.5/3.5 1.0/3.0 1.5/2.5	12 12 12	9 9 9
Lakeshore Dr.- Greensprings Jct. (Lake of the Woods)	1.4/2.6 1.4/3.1 1.9/2.6 2.4/2.1	12 12 12 12	9 9 9 9
b) Test Schedule Per Test Period*			
MP 79.2- Wasco Co. Line (Warm Springs)	0.5/3.5 1.0/3.0 1.5/2.5	3 3 3	3 3 3
Lakeshore Dr.- Greensprings Jct. (Lake of the Woods)	1.4/2.6 1.4/3.1 1.9/2.6 2.4/2.1	3 3 3 3	3 3 3 3

*Four Test Periods: Fall 1986, 1987, 1988, and Summer 1990

TABLE 4 SAMPLE PREPARATION PROCEDURE USED TO FABRICATE TEST SPECIMENS FOR LABORATORY STUDY

1	Split the millings into approximately 3500 gram batches. This size of sample makes three to four 2.5-in. high by 4.0-in. diameter specimens.	
2	Screen the sample over a 1-in. sieve. Reduce all material retained on the 1-in. sieve using a hammer or chisel such that 100% passes the 1-in. sieve.	
3	Heat the samples and emulsion to 60 ± 1°C (140 ± 1.8°F) for 1 hour prior to mixing.	
4	Add water to the millings in the appropriate portion based on the air dry weight of the millings (e.g., % water = % total liquids - % added emulsion). Thoroughly mix the water into the millings by hand.	
5	Add the emulsion to the pre-moistened millings using the recommended content (the added emulsion is based on the air dry weight of mill-ings). Thoroughly mix the emulsion into the millings by hand.	
6	Spread the material in a 305 x 432 mm (12 x 17-in.) baking pan and cure for 1 hour at 60 ± 1°C (140 ± 1.8°F) to simulate the average time elapsed between paver laydown and initial compaction during actual construction.	
7	Mold the samples using the standard Marshall procedure (ASTM D-1559) to produce 64 mm (2.5-in.) high briquets as described below.	
	a	Preheat molds to 60 ± 1°C (140 ± 1.8°F).
	b	Compact the mixture with 50 blows per side using a 44 N (10 lb) hammer having a 457 mm (18-in.) freefall.
	c	Remove the filter papers from each side of the briquets.
	d	Cure overnight at 60 ± 1°C (140 ± 1.8°F) and recompact with 25 blows per side using the 44 N (10 lb) hammer.
	e	Lay the molds on their end and cure the briquets for 24 hours at 60 ± 1°C (140 ± 1.8°F) prior to extrusion.
	f	Extrude the briquets with a compression testing machine.
	g	Lay the briquets on their side to maximize surface exposure and cure for 72 hours at room temperature prior to testing.

the samples were stored at 25±2°C in the laboratory before testing.

Test Results

Tests were performed on two groups of the laboratory-prepared samples as follows: (a) resilient modulus and fatigue samples, and (b) Marshall stability and flow samples.

Resilient Modulus and Fatigue Samples

For each test period (fall 1986, 1987, 1988, and summer 1990) resilient modulus tests were performed on three samples of each emulsion content. Fatigue tests were performed on these samples during the first three test periods. Modulus and fatigue tests were conducted under the same conditions as those used for the field cores.

The results of the modulus and fatigue tests are summarized in Table 5. All results represent the average of the three samples tested for each emulsion content. The maximum modulus for the Warm Springs section occurs at the design emulsion content of 1.0 percent, except for the first year's test results. Similarly, the maximum modulus for the Lake of the Woods section occurs at the design emulsion content of 1.9 percent, as well as at design minus 0.5 percent with the total liquids of 4.5 percent (i.e., 1.4/3.1 percent). For both

TABLE 5 SUMMARY OF LABORATORY SAMPLE TEST RESULTS

Project	Emulsion/ Water Content (%)	Test Period	Air Voids (%)	Average Resilient Modulus (ksi)	Average Fatigue Life	Average Marshall Stability (lbs)	Average Flow (in./100)
MP 79.2- Wasco Co. Line (Warm Springs)	0.5/3.5	Fall 1986	14.4	528	33,560	409	25
MP 79.2- Wasco Co. Line (Warm Springs)	0.5/3.5	Fall 1987	11.5	319	33,080	441	27
MP 79.2- Wasco Co. Line (Warm Springs)	0.5/3.5	Fall 1988	14.8	203	24,811	526	50
MP 79.2- Wasco Co. Line (Warm Springs)	0.5/3.5	Summer 1990	17.1	219	*	515	27
MP 79.2- Wasco Co. Line (Warm Springs)	1.0/3.0	Fall 1986	11.8	374 (60)	18,673 (7,015)	612 (?)	59 (?)
MP 79.2- Wasco Co. Line (Warm Springs)	1.0/3.0	Fall 1987	11.2	346 (99)	31,780 (2,653)	694 (98)	24 (4.5)
MP 79.2- Wasco Co. Line (Warm Springs)	1.0/3.0	Fall 1988	9.7	221 (28)	30,373 (9,330)	1,116 (144)	23 (3.6)
MP 79.2- Wasco Co. Line (Warm Springs)	1.0/3.0	Summer 1990	12.7	473 (55)	*	1,173 (24)	23 (5.1)
MP 79.2- Wasco Co. Line (Warm Springs)	1.5/2.5	Fall 1986	11.7	260	23,530	518	24
MP 79.2- Wasco Co. Line (Warm Springs)	1.5/2.5	Fall 1987	12.3	299	30,102	585	35
MP 79.2- Wasco Co. Line (Warm Springs)	1.5/2.5	Fall 1988	9.6	237	28,730	531	18
MP 79.2- Wasco Co. Line (Warm Springs)	1.5/2.5	Summer 1990	14.6	409	*	847	34
Lakeshore Dr.- Greensprings Jct. (Lake of the Woods)	1.4/2.6	Fall 1986	18.7	383	35,540	409	20
Lakeshore Dr.- Greensprings Jct. (Lake of the Woods)	1.4/2.6	Fall 1987	19.3	511	21,958	511	25
Lakeshore Dr.- Greensprings Jct. (Lake of the Woods)	1.4/2.6	Fall 1988	17.2	324	43,985	758	29
Lakeshore Dr.- Greensprings Jct. (Lake of the Woods)	1.4/2.6	Summer 1990	15.9	375	*	955	19
Lakeshore Dr.- Greensprings Jct. (Lake of the Woods)	1.4/3.1	Fall 1986	17.6	466	91,260	681	18
Lakeshore Dr.- Greensprings Jct. (Lake of the Woods)	1.4/3.1	Fall 1987	16.0	604	61,337	1,160	22
Lakeshore Dr.- Greensprings Jct. (Lake of the Woods)	1.4/3.1	Fall 1988	17.8	426	81,223	1,190	30
Lakeshore Dr.- Greensprings Jct. (Lake of the Woods)	1.4/3.1	Summer 1990	18.2	555	*	1,446	27
Lakeshore Dr.- Greensprings Jct. (Lake of the Woods)	1.9/2.6	Fall 1986	17.7	457 (98)	39,333 (10,874)	928 (?)	57 (?)
Lakeshore Dr.- Greensprings Jct. (Lake of the Woods)	1.9/2.6	Fall 1987	17.0	603 (74)	59,269 (25,899)	861 (17)	32 (1.2)
Lakeshore Dr.- Greensprings Jct. (Lake of the Woods)	1.9/2.6	Fall 1988	15.2	412 (56)	82,059 (19,597)	1,307 (228)	17 (1.5)
Lakeshore Dr.- Greensprings Jct. (Lake of the Woods)	1.9/2.6	Summer 1990	17.4	780 (33)	*	1,236 (285)	26 (7.2)
Lakeshore Dr.- Greensprings Jct. (Lake of the Woods)	2.4/2.1	Fall 1986	19.6	408	117,320	613	40
Lakeshore Dr.- Greensprings Jct. (Lake of the Woods)	2.4/2.1	Fall 1987	19.2	437	58,158	451	32
Lakeshore Dr.- Greensprings Jct. (Lake of the Woods)	2.4/2.1	Fall 1988	19.0	289	69,046	758	18
Lakeshore Dr.- Greensprings Jct. (Lake of the Woods)	2.4/2.1	Summer 1990	22.9	492	*	1,038	24

*Fatigue tests were not performed on the laboratory samples in Summer 1990
Note: Parentheses contain standard deviations

sections, the modulus decreased slightly or remained about the same when the emulsion content was increased or decreased from the design content (see Figure 4a). This finding is true of all four test periods except for the first year's results for the 0.5 percent emulsion content on the Warm Springs section. The unexpected drop in moduli within each emulsion content between 1987 and 1988 test periods is unexplained; possible reasons include operator or measurement error and variability in the mix.

As shown in Figure 4b, the fatigue life of the samples from the Warm Springs section remained relatively constant over the first three test periods (fatigue tests were not conducted during the fourth test period). Consequently, there is no definite trend that shows which emulsion content provides the best fatigue resistance. The fatigue results for the Lake of the Woods section show considerable variation within each emulsion content as well as between emulsion contents. However, it is evident that the 1.4/3.1 percent emulsion/water content provides better fatigue resistance than does the 1.4/2.6 percent emulsion/water content. That is, the mix having more water had better fatigue resistance. This finding may indicate that the greater amount of water provided a more thorough dispersion of the emulsion throughout the mixture.

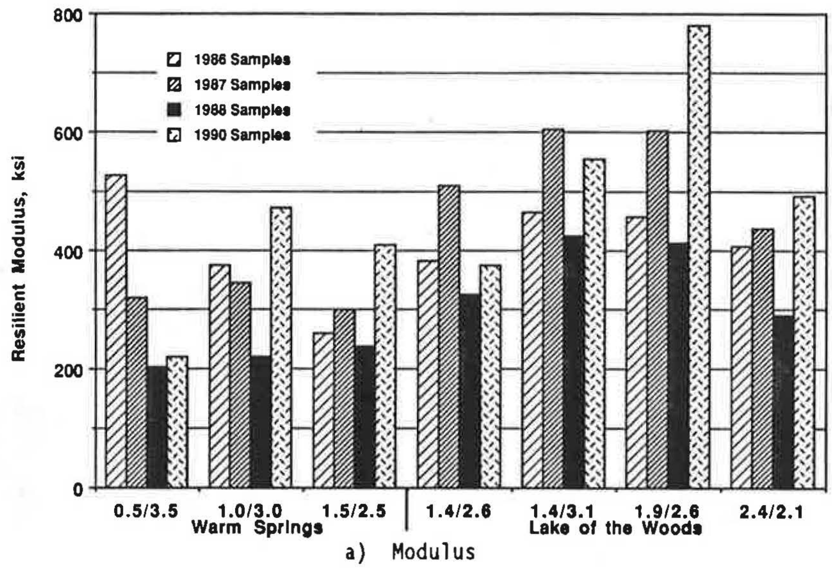
Marshall Stability and Flow Samples

During each test period, three samples from each emulsion content were tested for Marshall stability under the same conditions as those of the field core tests. The results of these tests are shown in Table 5. All results represent the average of the three samples. As shown in Figure 5a, the maximum stability occurs at the design emulsion content for the Warm Springs section for each test period. The maximum stability of the Lake of the Woods section occurs at the design emulsion content for three of the four test periods; the exception was the 1987 results in which the maximum stability occurred at the 1.4/3.1 percent emulsion/water content (design minus 0.5 percent).

The flow values generally reflect the stability values for the Warm Springs section in that low flows generally occur at the design emulsion content (see Figure 5b). However, for the Lake of the Woods section, trends in the flow values are indiscernible due to the erratic nature of the results.

COMPARISON OF RESULTS: LABORATORY VERSUS FIELD

A major purpose of this study was to compare selected mix properties of the field cores with those of the laboratory-prepared samples in order to develop a procedure for preparing laboratory samples. Because both the field cores and laboratory samples were from the same RAP, the significant differences between the two are the method of compaction, temperature during cure, moisture during cure, and traffic densification. The actual age of the two mixes (field cores versus laboratory specimens) differs by approximately 1 month: the field cores were tested 3, 15, 27, and 48 months after construction, and the laboratory samples were prepared im-



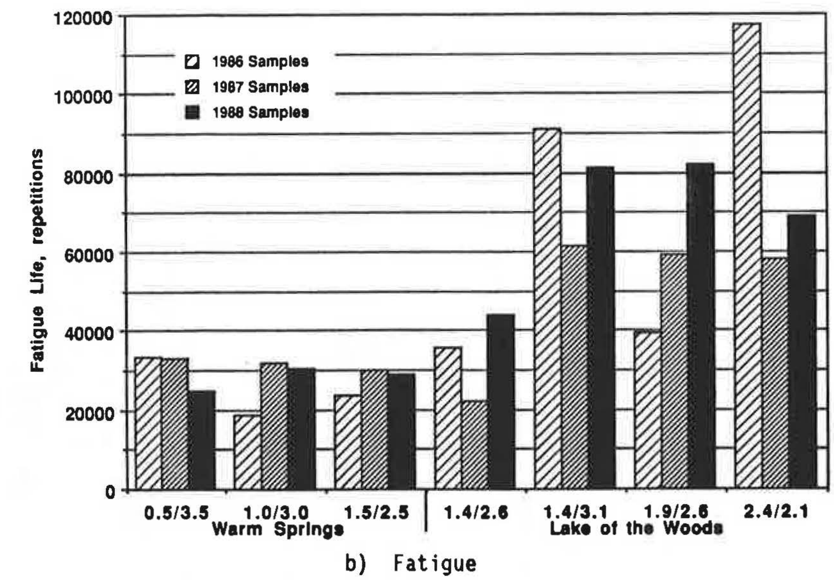


FIGURE 4 Modulus and fatigue results for laboratory samples.

mediately after the pavement was recycled and were tested 4, 16, 28, and 49 months after fabrication using an ambient cure condition (i.e., 25±2°C). The reason for the difference in ages is that the testing of the field cores required 1 month to complete.

Summary of Results

The results of tests made on both field cores and laboratory-prepared samples are summarized in Table 6. The results for the laboratory samples are those with the design emulsion contents (1.0 percent for Warm Springs, 1.9 percent for Lake of the Woods). Figures 6–8 compare test results for field core versus laboratory samples for percent voids, modulus, fatigue, Marshall stability, and flow.

To compare the results, statistical analyses were performed on the data obtained from each test method to determine, at a 5 percent significance level ($\alpha = 0.05$), whether the mean of the laboratory test results was equal to the mean of the field core test results (null hypothesis), with the alternative hypothesis being that the means are not equal. These analyses are summarized in Table 7. As indicated, the means were not found to be significantly different for the modulus and Marshall stability tests; the means for the fatigue and flow test results were found to be significantly different at the 5 percent significance level.

Discussion of Results

The comparison of test results for field cores versus laboratory samples generally indicate the following:

1. The voids of the laboratory-prepared samples are about the same as or slightly higher than those of the field cores

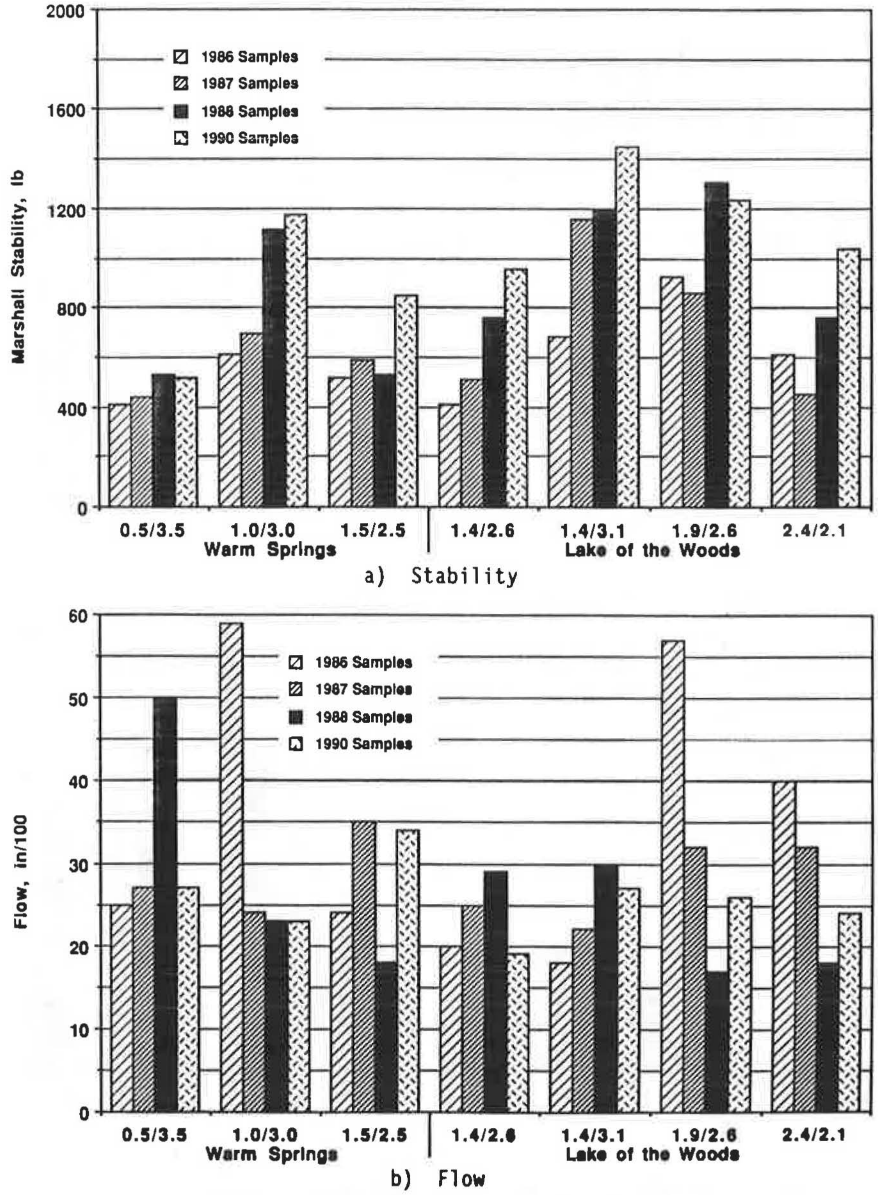


FIGURE 5 Marshall stability and flow results for laboratory samples.

(Figure 6). The air void contents for the laboratory samples would be expected to remain essentially equal over time, while those for the field cores would be expected to decline. The erratic nature of the results suggests errors in measurement or variability of the mix. Nevertheless, the compactive effort used in preparation of the laboratory samples appears to be at about the correct level.

2. The laboratory-prepared sample modulus values are not significantly different from those of the field core modulus values at the 5 percent significance level (see Figure 7a).

3. In general, the comparison of fatigue lives between field cores and laboratory samples is, at best, fair (the means are significantly different at a 5 percent significance level but not at a 1 percent significance level). The fatigue lives of the Warm Springs field cores are generally greater (except initially) than those of the laboratory samples, as shown in Figure 7b. The opposite is true of the results for the Lake of the Woods section; the fatigue lives of the laboratory samples are greater than those of the field cores, except for the 1988 test results in which the fatigue lives are essentially equal. The differences in fatigue lives between field cores and laboratory samples may be due to the significant differences in curing temperatures.

4. The comparison of Marshall stabilities between field cores and laboratory samples are, in general, good (the means are not significantly different at the 5 percent significance level). As shown in Figure 8a, the stabilities of the laboratory samples for the Warm Springs section compare well with those of the field cores. The stabilities of the laboratory samples for the Lake of the Woods section, however, are generally greater than those of the field cores.

5. Except for the first year's test results, the flow values of the laboratory samples compare well with those of the field

TABLE 6 SUMMARY OF TEST RESULTS (LABORATORY VERSUS FIELD)

Specimen Type	Emulsion/ Water Content (%)	Test Period	Percent Voids (%)	Average Resilient Modulus (ksi)	Average Fatigue Life (reps)	Average Marshall Stability (lb)	Average Flow (in./100)
a) MP 79.2-Wasco Co. Line (Warm Springs)							
Laboratory Sample	1.0/3.0	Fall 1986	11.8	374 (60)	18,673 (7,015)	612 (?)	59 (?)
		Fall 1987	11.2	346 (99)	31,780 (2,653)	694 (98)	24 (4.5)
		Fall 1988	9.7	221 (28)	30,373 (9,330)	1,116 (144)	23 (3.6)
		Summer 1990	12.7	473 (55)	*	1,173 (24)	23 (5.1)
Field Core	1.0/2.4	Fall 1986	12.8	305 (243)	11,030 (5,053)	694 (80)	59 (5.7)
		Fall 1987	7.4	242 (15)	50,010 (17,709)	861 (81)	19 (3.0)
		Fall 1988	11.7	377 (30)	53,965 (12,800)	1,106 (22)	21 (1.5)
		Summer 1990	7.4	527 (8)	150,000+	1,811 (71)	17 (2.1)
b) Lakeshore Dr.-Greensprings Jct. (Lake of the Woods)							
Laboratory Sample	1.9/2.6	Fall 1986	17.7	457 (98)	39,333 (10,874)	928 (?)	57 (?)
		Fall 1987	17.0	603 (74)	59,269 (25,899)	861 (17)	32 (1.2)
		Fall 1988	15.2	412 (56)	82,059 (19,597)	1,307 (228)	17 (1.5)
		Summer 1990	17.4	780 (33)	*	1,236 (285)	26 (7.2)
Field Core	1.8/1.6	Fall 1986	10.9	513 (107)	5,863 (4,354)	605 (100)	29 (13)
		Fall 1987	15.7	504 (62)	34,261 (5,536)	614 (27)	19 (0.6)
		Fall 1988	14.6	530 (16)	78,731 (13,847)	1,171 (43)	24 (3.8)
		Summer 1990	13.0	727 (58)	250,000+	1,597 (134)	17 (1.2)

*Fatigue tests were not performed on the laboratory samples in Summer 1990
Note: Parentheses contain standard deviations

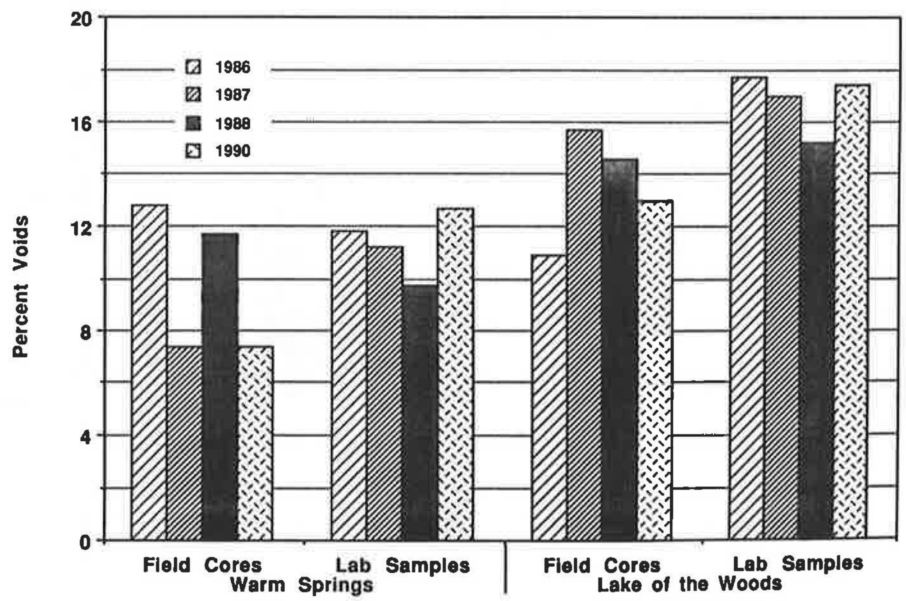


FIGURE 6 Comparison of void contents—field cores versus laboratory samples.

cores for both sections (Figure 8b). However, overall, the means were found to be significantly different at the 5 percent significance level.

COMPARISON OF CIR VERSUS CONVENTIONAL HOT MIXES

This secton compares the resilient modulus and fatigue of CIR mixtures and conventional hot mixes. The results of tests performed on cores from the Warm Springs and Lake of the Woods sections are shown in Table 8 along with results of tests performed on conventional hot mixes (*3,4*). The hot mixes are a Class B mix (*5*), with 5 to 6 percent asphalt intentionally compacted to acquire high air void contents. The results of tests performed on these mixes were chosen for the comparison because these mixes have void contents similar to those of the CIR mixes and were tested under similar conditions. The results in Table 8 are shown graphically in Figure 9.

The CIR mixes, which typically have high voids, show little change in mix properties with significant changes in void contents. Figure 9a clearly shows that significant changes in void content (up to 5.4 percent) have little effect on the modulus of either CIR project. Similarly, Figure 9b shows that, for the Warm Springs project, the fatigue life can be essentially

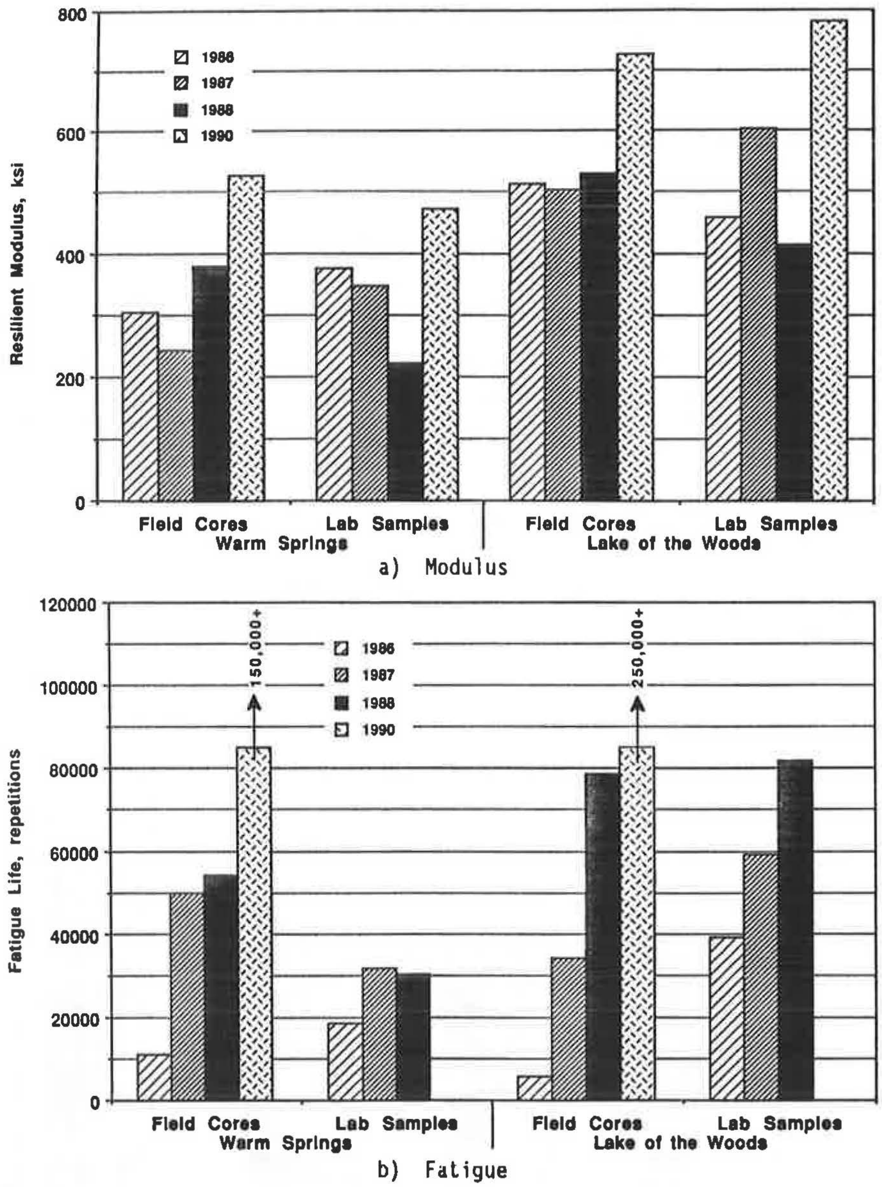


FIGURE 7 Comparison of modulus and fatigue results—field cores versus laboratory samples.

equal at significantly different void contents *or* significantly different at nearly equal void contents. The latter finding also holds true for the Lake of the Woods section. The significant increases in fatigue life are more likely caused by long-term softening of the original binder in the pavements than by increases or decreases in void content.

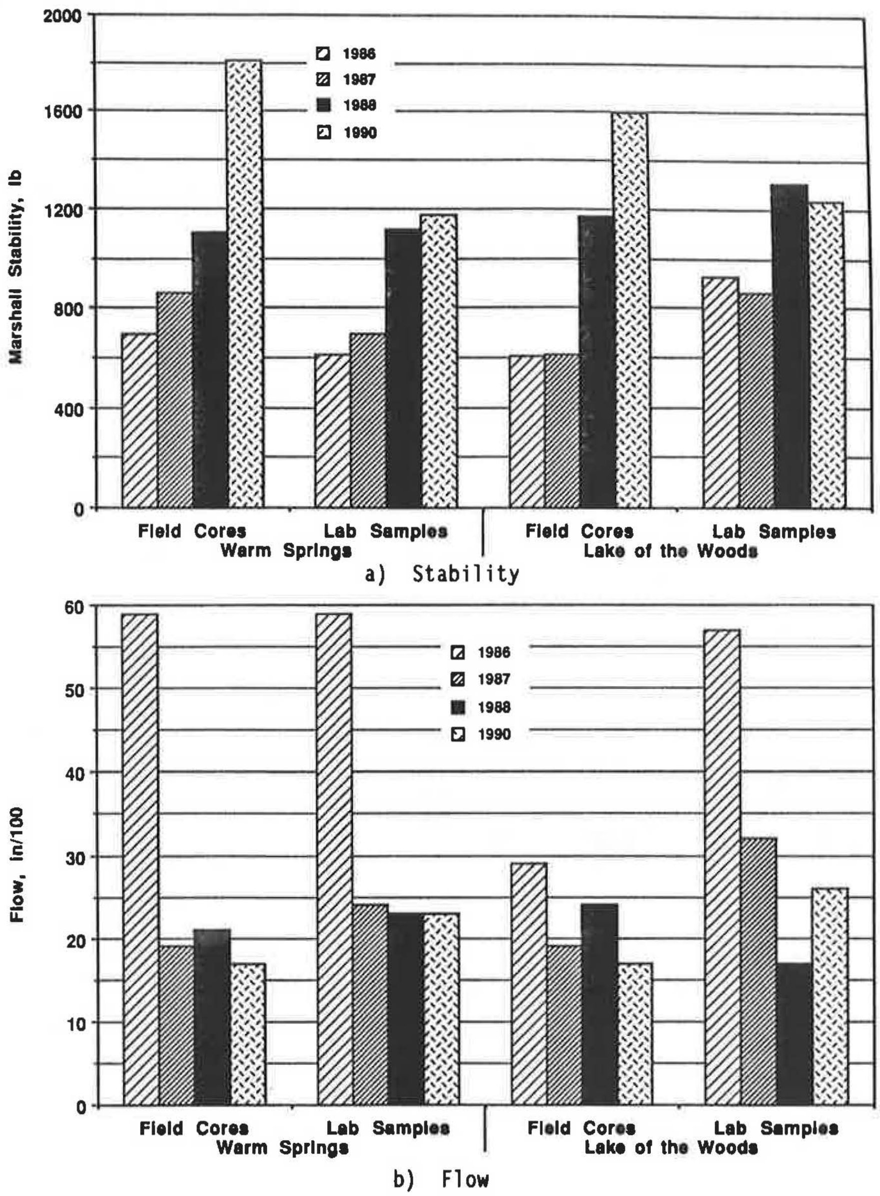
The void content of the hot mixes, however, has a clear and significant effect on the mix properties. As shown in Figure 9a, the modulus decreases appreciably with increased void content. Figure 9b shows the same trends for fatigue—decreased fatigue with increased void content—but the effect is not as dramatic as with the modulus.

These plots indicate that the CIR mixes generally have slightly higher modulus values and significantly greater fatigue lives relative to the hot mixes at similar void contents. This finding may indicate that CIR mixes behave more like open-graded mixes than dense-graded mixes.

CONCLUSIONS

The following conclusions appear to be warranted from this study:

1. The sample preparation procedure that was developed allows fabrication of specimens from RAP that closely simulate the void content of the pavements in the field.
2. Moderate deviations (± 0.5 percent) from the design emulsion content generally have little effect on the modulus of laboratory-prepared specimens. This finding is also true of



a) Stability

b) Flow

FIGURE 8 Comparison of Marshall stability and flow values—field cores versus laboratory samples.

TABLE 7 SUMMARY OF STATISTICAL ANALYSIS (LABORATORY VERSUS FIELD)

Test	Section	F	$F_{crit.}$ $\alpha = 0.05$	Significant Difference ?	P-value
Modulus	Warm Springs	0.066	4.49	No	P > 0.05
	Lake of the Woods	0.039	4.49	No	P > 0.05
Fatigue	Warm Springs	5.403	4.75	Yes	0.01 > P > 0.05
	Lake of the Woods	8.102	4.75	Yes	0.01 > P > 0.05
Marshall Stability	Warm Springs	1.897	4.75	No	P > 0.05
	Lake of the Woods	0.008	4.75	No	P > 0.05
Flow	Warm Springs	7.048	4.75	Yes	0.01 > P > 0.05
	Lake of the Woods	10.227	4.75	Yes	0.001 > P > 0.01

TABLE 8 CIR VERSUS HOT-MIX TEST RESULTS

Mix Type	Project	% Voids	Resilient Modulus (ksi)	Fatigue Life
CIR	Warm Springs	7.4	242	50,010
		11.7	377	53,965
		12.8	305	11,030
	Lake of the Woods	10.9	513	5,860
		14.6	530	78,731
		15.7	504	34,261
Hot Mix	Castle Rock-Cedar Creek	8.2	466	44,209
		13.2	238	10,426
		14.4	163	6,853
	Warren-Scappoose	8.0	736	9,166
		11.6	265	8,366

the Warm Springs fatigue specimens. However, for the Lake of the Woods section, the emulsion content significantly affected the fatigue life of the laboratory specimens. The effect of emulsion content is clearly indicated by the Marshall stabilities although no clear trends are evident by the flow values. Thus, from these observations, the Marshall stability appears to be the best test for design purposes.

3. The modulus and fatigue results from the fall 1986 test period (3 to 4 months after the pavements were constructed), when used as mix design criteria, predict an initial emulsion content of 0.5 percent for the Warm Springs section and 1.4 percent for the Lake of the Woods section. The fall 1986 Marshall stability test results predict 1.0 percent and 1.9 percent emulsion contents (those used in the field) for the Warm Springs and Lake of the Woods sections, respectively. When

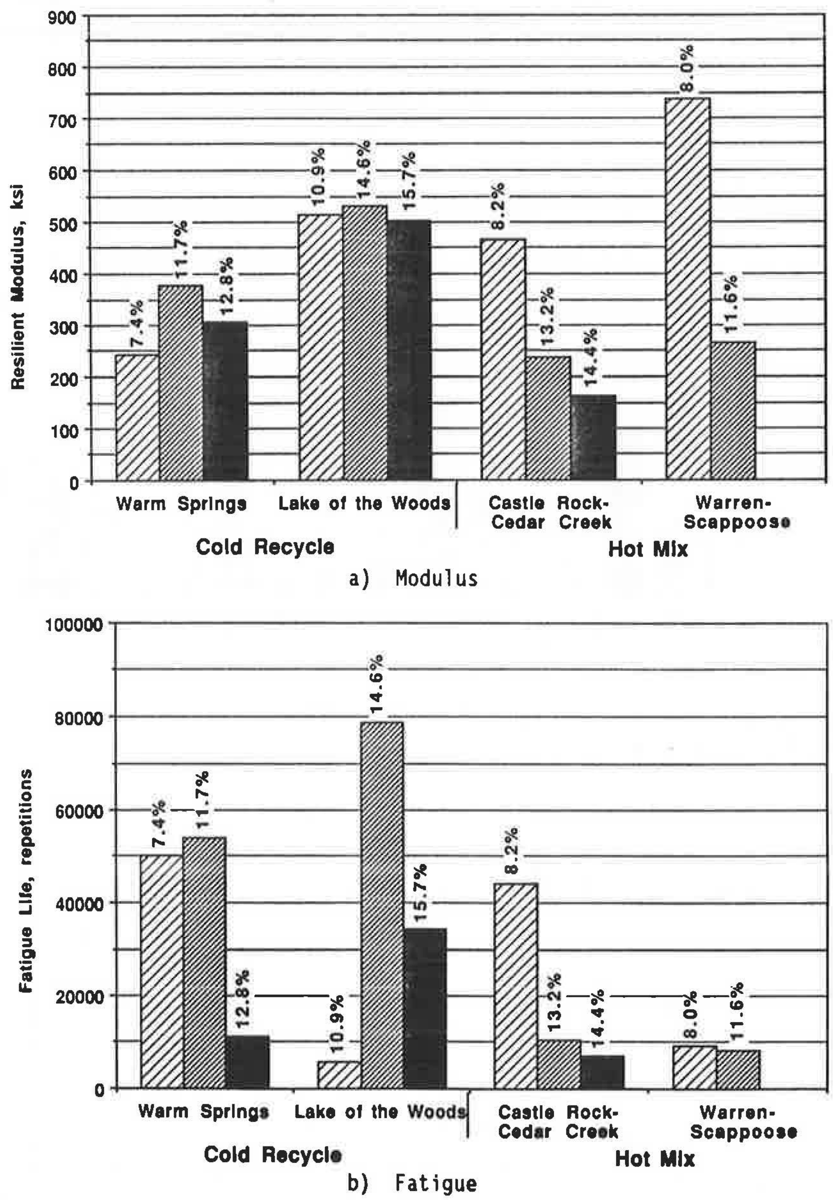


FIGURE 9 Comparison of CIR versus hot-mix modulus and fatigue test results (percentages are air void contents).

consideration is given to stabilities and flow values together, a 1.4 percent emulsion content might be used for the Lake of the Woods section. In short, only the Marshall stability predicted the emulsion content that was used in the field.

4. In general, the mix property test results of laboratory-prepared samples compare well with those of the field cores. In particular, the modulus and Marshall stability results show a good comparison, while the comparison of the fatigue and flow results is, at best, fair.

5. At similar void contents, CIR mixes generally have slightly greater modulus values and significantly greater fatigue lives relative to conventional hot mixes intentionally compacted to acquire high air void contents. This finding indicates that CIR mixes can provide a significant contribution to the pavement structure.

6. Total liquids content must be adequate to disperse the emulsion throughout the mix. There was an adverse effect on material properties (Figures 4 and 5) when Lake of the Woods specimens were prepared with insufficient addition of water (4 percent total liquids).

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