D.Y. Lee
July 1985

Field Demonstration and Laboratory Evaluation of Foamed Asphalts—Muscatine County

Submitted to Highway Division, Iowa Department of Transportation and the Iowa Highway Research Board

Iowa Department of Transportation

Final report

College of Engineering
Iowa State University

Iowa DOT Project HR-233
ERI Project 1526
ISU-ERI-Ames-86083

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1. INTRODUCTION

The objective of the research project HR-212, "Treating Iowa's Marginal Aggregates and Soils by Foamix Process," was to explore the possibilities of using local aggregates--which normally do not meet specifications for hot mix designs--in a foamed asphalt mix to stabilize local roads. The results of HR-212, completed in 1980, indicated the following [5]:

- The Marshall stability results were quite good with a majority of the foamed mixes. Six of the eight aggregates can be designed by the foamed asphalt process to meet either Hubbard-Field or Marshall criteria as suggested by Professor Csanyi.
- In eight of eleven comparable mixes, including pit-run sand, fine sands, and blends of the pit-run sand and loess, foamed mixes had equal or higher Marshall stabilities than corresponding hot mixes of the same aggregate, asphalt type, and content.
- Soils and aggregates tested successfully with the Csanyi steam-foaming process twenty years ago can be utilized the same way by the Mobil/Conoco cold-water foaming process.
- Foamed mix design procedure and criteria should be locally based. These design criteria can best be established on the basis of laboratory-field correlations obtained from field trials.

In view of the energy, environmental, and above all, economic advantages of the foamed asphalt process using local materials in cold mixes (5-9, 11-16), and the encouraging results obtained in the laboratory phase of the study, field demonstration of foamed mixes was recommended and proposed. Subsequently research project HR-233, "Field Demonstration and Evaluation of Foamed Asphalt" was approved by the Iowa Highway Research Board and Iowa DOT for the purpose of constructing and evaluating a foamed asphalt project in Shelby County as a joint effort undertaken by Shelby County, the Iowa DOT, and Iowa State University. HR-233 commenced on May 1, 1981, and was to be completed on July 31, 1984. The proposed field test would consist of six half-mile sections of 6-inch foamed mixes using existing road surface material and an AC-5 foamed asphalt. The six sections would allow evaluation of two levels of mixing and compaction moisture contents (75% and 90% of optimum AASHTO T-99) and three levels of surface treatments (no surface treatment, single chip seal, and double or fog seal).

Extensive laboratory testing and evaluation of repeated in-place samples was undertaken between May and July 1981. A major problem was the excessive fines in the soil sample (49% to 65% passing No. 200 sieve). Based on the laboratory results, it was recommended that either 20%-30% of sand be blended with the in-place soil or the asphalt content be increased to 5%-6%. Unfortunately, either option would exceed the original budget, and the Shelby County construction project did not materialize.

In early 1983, at least three counties (Buchanan, Linn, and Muscatine) were interested in constructing foamed asphalt demonstration projects similar to those proposed for Shelby County, using local materials. Ultimately, a proposal and funding request for the construction of a demonstration project was submitted by Muscatine County and approved as Iowa Highway Research Board project HR-257. A modification of HR-233 was also approved in April 1983 to cover the testing, evaluation, and design of foamed mixes from materials submitted by Muscatine county and field evaluations of the demonstration project.

A progress report presenting the results of laboratory tests leading to the field job mix formulas eventually used in the nine test sections was submitted in January 1984 [7]. A construction report documenting the construction phase of the Muscatine foamed asphalt demonstration project was presented by Robert K. Simmering, Muscatine County Engineer, and Kevin Jones, Office of Materials, Iowa Department of Transportation [14]. This report presents the results of extensive laboratory evaluation of the five plant mixes used in the test sections, plus core samples taken for a period of up to 15 months and a number of special studies not included in the original proposal, from testing of over 1500 samples.

2. *OBJECTIVES*

The objectives of the field demonstration and evaluation project were:

- To evaluate the performance of the foamed asphalt mixes using locally available 3/8-inch limestone tailings and pit-run sand as bases.

- To evaluate and/or generate construction and inspection tests and specifications.
- To correlate field strength characteristics and performance of foamed mixes with laboratory strength and other properties as functions of curing conditions, time, and cured moisture content.
- To identify and document foamed asphalt construction techniques and problems.
- To establish locally based foamed asphalt mix design criteria.

3. DEMONSTRATION PROJECT DESCRIPTION

A 4.2-mile section of Muscatine County Road A-91 was selected for the project. The road is located along the base of a bluff above the Mississippi River flood plain. The left portion of the road is in a cut section, and the right portion of the road is in a fill section. The structure of the existing roadbed was a 1½-inch built-up seal coat over a 1½-inch limestone base. Average traffic is 230 to 240 vehicles per day.

Nine foamed asphalt base test sections were planned and constructed. The base is 4-inch thick and 22-feet wide. The test sections as constructed allow the evaluation of two levels of mixing and compaction moisture content (75% and 90% of optimum AASHTO T-99), three levels of surface treatment (fog seal, single chip seal, and double chip seal), two levels of foamed asphalt content, and the effects of foaming agents (Test Section 9). The test section arrangement is given in Table 1.

Table 1. Test section factorial arrangements.

Sta. to Sta.	Section No.	Asphalt Content (%)	Moisture (% of Optimum)	Surface Treatment
139 to 165	1	4.5	75	fog seal
165 to 180	2	4.5	90	fog seal
180 to 194	3	4.5	90	double chip seal
194 to 220	4	5.5	90	double chip seal
220 to 246	5	5.5	75	double chip seal
246 to 278	6	4.5	75	single chip seal
278 to 309	7	4.5	90	single chip seal
309 to 338	8	4.5	90	single chip seal
338 to 365	9	4.5 (high foam)	75	single chip seal

The construction of foamed asphalt base sections began on August 25 and was completed on September 29, 1983, with the exception of surface treatments. A detailed description of the construction procedures, problems encountered, post-construction testing, and an excellent set of recommended changes for control and construction of foamed asphalt mixes was reported by Simmering and James [14].

4. MATERIALS AND PROCEDURES

4.1. Job Mix Design

Three project aggregates were received on August 12, 1983. They were: 3/8-inch crushed stone (5TH3-44), 10 bags; a fine sand (5TH3-45), 5 bags; and a concrete sand (5TH3-46), 5 bags. The gradations of these materials are given in Table 2. It is to be noted that, although the Special Provision 494 requires the percent passing the No. 200 sieve to be 16%-30%, the 3/8-inch aggregate contained only 13% passing the No. 200 sieve.

Based on gradations of blending trials, it was decided to evaluate foamed mixes based on two combinations of materials (44/45 and 44/46) each at two blending ratios: 50% crushed stone/50% sand, as stipulated in the Special Provision; and 70% crushed stone/30% sand for a denser mix and a more desirable percent passing No. 200 sieve of 9%-10%. The gradations, optimum moisture contents, and maximum dry densities of these four blends are given in Table 3.

Table 2. Aggregate properties.

Designation	5TH3-44 3/8-in. crushed Limestone	5TH3-45 Fine Sand	5TH3-46 Concrete Sand
Gradation		Percent Passing	
3/8 in.	100	-	100
No. 4	80	-	99
No. 8	57	100	93
No. 16	42	99	93
No. 30	32	93	82
No. 50	25	56	49
No. 100	19	9	9
No. 200	13	2	1
Bulk sp.gr.	2.578	2.649	2.670

Table 3. Gradation of aggregate blends--laboratory.

Designation	55	53	65	63
Aggregate, %				
44	50	70	50	70
45	50	30	-	-
46	-	-	50	30
Gradation		Percent passing		
3/8 in.	100	100	100	100
No. 4	93	90	93	90
No. 8	79	70	76	68
No. 16	71	59	62	54
No. 30	63	50	41	37
No. 50	41	35	18	21
No. 100	15	16	14	15
No. 200	7	10	7	9
Bulk sp.gr.	2.613	2.599	2.623	2.604
Optimum m.c.%	9.4	8.8	9.4	8.8
Max. dry density, pcf	126.8	129.7	126.8	129.7

Between August 13 and August 22, 1983, when the construction was scheduled to start, four series of foamed mixes were prepared and tested using the four aggregate combinations and a 120-150 pen asphalt cement from Cenex Refinery available in the Bituminous Research Laboratory. Two additional series of foamed mixes were prepared and evaluated between September 6 and September 13, 1983, while the construction of test sections was in progress, using project asphalt cement (AC-5) received on August 19, 1983. The properties of the project asphalt cement are given in Table 4. The laboratory foaming characteristics of the asphalt cement are given in Table 5.

Foamed asphalt was produced by a foaming unit built by Conoco, Inc. Foamed asphalt mixes were prepared at premix aggregate moisture contents of either 75% or 90% of optimum moisture contents determined by AASHTO T-99 and at a range of asphalt contents (3%-6.5%). The mixes, 4000 grams per mix, were prepared in a C100 Hobart planetary mixer. The aggregates were weighed into the tarred mixing bowl according to the desired blending ratios of either 50/50 or 70/30. Water needed for the predetermined moisture level was added and mixed until homogeneous. The moist aggregate at room temperature was mixed while the foamed asphalt was being introduced through the nozzle of the foaming unit. Mixing was accomplished by mechanical mixing for three minutes (except in Series 5 mixes, where mixing time was varied) followed by hand mixing for one minute. The required amount of asphalt was added through a calibrated timer. The moisture content sample was spread on a filter paper to about one particle thick and cured in ovens at 140° F over-

Table 4. Properties of asphalt cement.

	Original	Plant	ISU Lab
Viscosity, 140° F, p	376	533	474
Viscosity, 275° F, cs	--	--	186
Penetration, 77/100/5	204	145	175
Softening point, °F	--	--	109
Specific gravity	1.022	--	1.012
Flash point, °F	410	--	--
Soluble in trichloroethylene, %	99.85	99.67	--
Thin film oven test residue			
Penetration, 77/100/5	67	71	--
Viscosity, 140° F, p	1510	1450	--
Ductility, 77° F, cm	120+	120+	--

Table 5. Foaming characteristics of asphalt cement.

Temperature, °F	% Water by wt of A.C.	Half Life, sec	Foam Ratio
	1.0	31.0	8.3
315	1.5	21.5	12.1
	2.0	17.0	15.1
	1.0	28.5	8.4
325	1.5	19.0	12.3
	2.0	15.5	15.6

night for visual examination of asphalt distribution and particle coating. Three to six Marshall specimens per mix were compacted at room temperature immediately following mixing in accordance with standard procedure (50 blows per side). The molded specimens were cured in ovens at 120° F and/or 140° F for three days and tested for cured moisture content, bulk specific gravity, and standard Marshall stability and flow at 140° F (wet).

4.2. Laboratory Test Program Using Plant Mixes

For the purpose of mix characterization and laboratory-field performance correlation, five plant mixes were taken at the project and delivered to the Bituminous Research Laboratory, Iowa State University, in 4 to 11 plastic-lined and sealed bags between September 15, 1983 and October 8, 1983. The identification of these mixes is given in Table 6.

From each mix, 15 Marshall specimens were molded and cured under each of 15 curing (treatment) conditions as shown in Table 7. After curing, these specimens were tested in five series (three specimens per series) as shown in Fig. 1. For comparison, laboratory foamed mixes and conventional hot mixes corresponding to Plant Mix No. 1 (4.5% AC) were also prepared and tested. They were designated as Mix 7 and Mix 6, respectively. A three-digit system was used to designate each sample. For example, sample 1-E-3 refers to Mix No. 1, Treatment Type E (1 day at 77° F), and Sample No. 3.

Table 6. Mix designation for laboratory evaluation program.*

Moisture Content (% of OMC)	A.C. Content, % 4.5	5.5	4.5 (high foam)
75	1 (Sec. 1,6)	2 (Sec. 5)	5 (Sec. 9)
90	3 (Sec. 2,3,7,8)	4 (Sec. 4)	

*Mix 6: Lab prepared hot mix, similar to Mix 1.
Mix 7: Lab prepared cold mix, similar to Mix 1.

Table 7. Laboratory curing condition designations.

Curing Time Days	Humidity Room (Sealed)	77° F	104° F	120° F	140° F
1	A	E	I	L	N
3	B	F	J	M	O
7	C	G	K		
28	D	H			

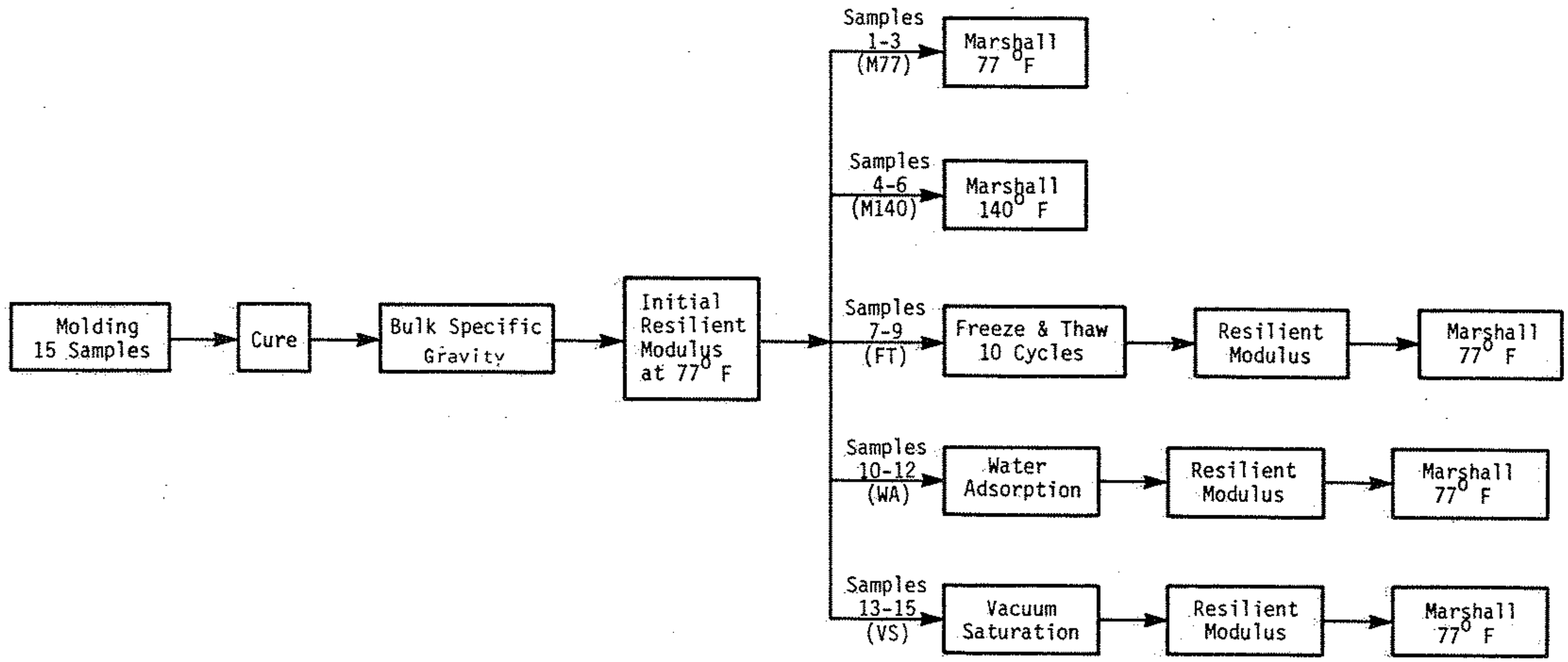


Figure 1. Laboratory testing program.

In addition, 2-inch by 2-inch Proctor density specimens were prepared from Mixes 1, 3, and 7 following the procedure developed at Iowa State University [17]. The specimens were cured at conditions E to O (Table 7) and tested for cured moisture content and unconfined compressive strength.

To evaluate and compare foam mix properties with those recommended for design of emulsified asphalt mixes, three sets of specimens were prepared and tested from Mix 3, following compaction, curing, and testing procedures recommended by the University of Illinois, the University of Mississippi, and the Asphalt Institute [4,10].

4.3. Core Samples

For the purpose of comparing field curing and strength-gain characteristics with those of the laboratory cured samples, field core samples were periodically taken. A total of 83 cores was taken at 1 to 15 months. These are identified in Table 8. Core samples were sawed and tested for moisture content, bulk specific gravity, resilient modulus and Marshall stability and flow at 77° F. Each core sample, after being sawed into 2-inch thick lifts, was identified by a 4-digit number. For example, sample 1-4-3-T refers to the top lift of Core Number 3, Test Section 4, taken one month after construction.

Table 8. Core sample identifications.

Date	Oct. 7, 1983	Oct. 19, 1983	May 11, 1984	Dec. 28, 1984
Section		No. of Core Samples		
1	4	4	6	6
2	0	0	1	0
3	0	1	0	0
4	4	3	6	6
5	0	2	6	6
6	0	5	5	0
7	0	4	0	6
8	0	6	0	0
9	0	2	0	0
Total	8	27	24	24

Table 9. Properties of recommended foamed asphalt mixes.

Mix No.	53		53C		53D	
Asphalt cement	AC-5 (H.L. = 20 sec.; F.R. = 11.3)					
% A.C. by wt of mix*	4.2		4.2		5.6	
% Moisture by wt of agg.*	6.8		8.0		7.3	
(as % of optimum)	(77)		(91)		(83)	
No. of Marshall blows	50		50		50	
Curing temp. (3 days), °F	120	140	120	140	120	140
Cured m.c. %	0.15	0.08	0.40	0.40	0.08	0.08
Marshall stability, lbs	698	650	555	620	425	452
Marshall flow, 0.01 in.	5	6	8	9	7	7
Bulk sp.gr., cured	2.03	2.02	2.04	2.03	2.02	2.02
Bulk sp.gr., dry	2.03	2.02	2.03	2.02	2.02	2.02
Voids, %	16.8	17.1	16.8	17.0	15.7	15.7
Test sections	1,6,9		2,3,7,8		4,5	

*Recommendations: 6.8% and 8.0% moisture, 4.5% and 5.5% asphalt cement.

5. RESULTS AND DISCUSSION

5.1. Job Mix Design

Mixes consisting of 70% limestone (45) and 30% fine sand (45) at 6.8% and 8.0% moisture and 4.5% and 5.5% foamed asphalt contents were recommended, as based on the results of six series of the 24 trial mixes prepared and tested in the laboratory and on the overall evaluation of particle coating, workability, percent passing No. 200 sieve, costs, density, and Marshall properties. These mixes were eventually used in the field test sections and are represented by Mixes 53, 53C and 53D, (Table 9). Detailed documentation of the properties of the 24 trial mixes were presented in a progress report submitted in January 1984 [7]. There were evidences from these laboratory trials that (1) increased laboratory mixing time and (2) increased foam half-life due to use of foam-aid enhanced particle coating and asphalt distribution. These evidences lead to the later requirements of plant modifications to increase the mixing time and the inclusion of an additional mix with Foam-aid at 75% moisture content and 4.5% asphalt (Mix No. 5) in the field.

5.2. Laboratory Evaluation of Plant Mixes

Fifteen Marshall specimens were prepared for each of the fifteen curing conditions for each of the five plant mixes. Samples were compacted at room temperature and as-received moisture content following standard Marshall procedure (50 blows per side). Moisture contents were taken each time the specimens were compacted. As to be expected from field samples, moisture variation existed from sample bag to sample bag and within each bag. As shown in Table 10, the results of 10 randomly sampled moisture contents of the mixes were 0.7% to 1.8% lower than target values. The standard deviations of the moisture contents ran between 0.6% to 1.0%. After curing, the samples were tested in five groups for cured moisture content, bulk specific gravity, resilient modulus before treatment (MRB), Marshall stability at 77° F, Marshall stability at 140° F, and resilient modulus, Marshall stability at 77° F and moisture increase after freeze-thaw (10 cycles), water absorption (from 1 hr. to 4 days) and vacuum-saturation treatments (Fig. 1).

The results of tests on the five plant mixes are given in Appendix A in the five groups: Marshall 77 (Table A1), Marshall 140 (Table A2), freeze and thaw (Table A3), water absorption (Table A4), and vacuum saturation (Table A5). A summary of average moisture content, asphalt content, and compacted density of the five mixes as compared to average field data and target values is given in Table 11. A typical field-obtained gradation of the combined aggregate is given in Table 12.

Because of the sample-to-sample variability within a given mix (especially moisture content), the data on the compacted density, cured moisture content, and therefore, other properties showed considerable scatter. While interpretation of large amounts of data with built-in variation calls for caution, the extensive data obtained did provide answers to questions needed for evaluation regarding foamed mixes, which were the major objectives of this study.

Table 10. Moisture contents of plant mixes.

Mix No.	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
MC 1	5.48	6.07	7.34	7.27	5.46
MC 2	6.43	5.43	8.34	6.8	5.9
MC 3	6.37	4.86	6.53	6.67	5.96
MC 4	5.11	4.94	5.15	6.66	6.03
MC 5	5.66	4.63	6.42	6.57	8.66
MC 6	5.44	4.44	6.77	6.85	6
MC 7	6.67	5.45	7.26	5.48	5.58
MC 8	5.6	5.35	6.38	7.02	5.96
MC 9	6.98	4.37	5.54	7.77	5.07
MC 10	7.07	4.42	7.77	6.38	6.39
Average	6.081	4.996	6.75	6.747	6.101
STDEV	0.70	0.56	0.97	0.59	0.97
Target	6.8	6.8	8	8	6.8
Difference	0.719	1.804	1.25	1.253	0.699

Table 12. Typical combined aggregate gradation--field.

Sieve Size	Percent Passing
3/8 in.	99
No. 4	80
No. 8	61
No. 16	49
No. 30	40
No. 50	28
No. 100	17
No. 200	12

Table 11. Moisture content, asphalt content, and dry density--field vs laboratory.

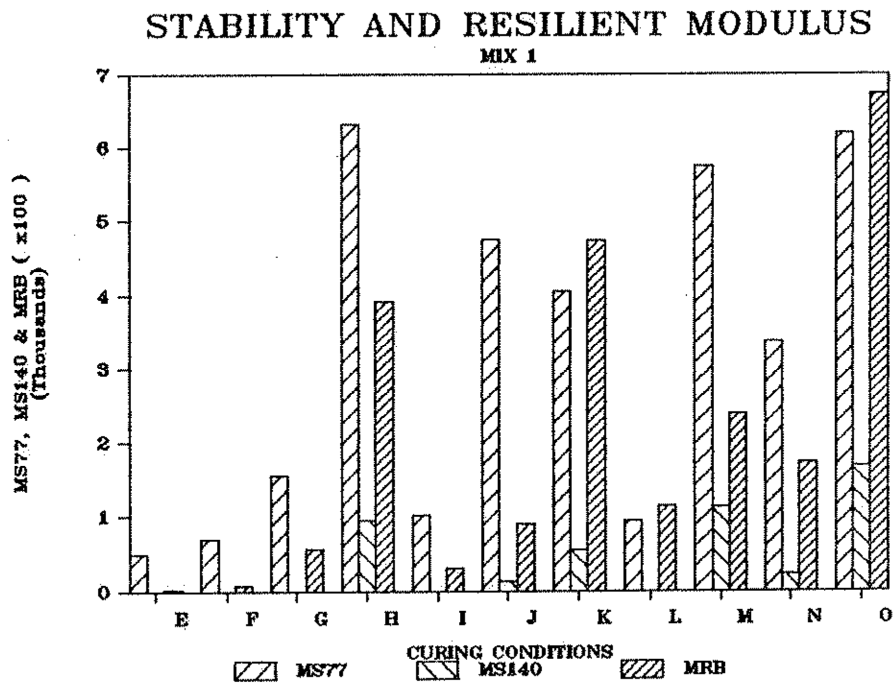
Section	1	2	3	4	5	6	7	8	9
Mix No.	1	3	3	4	2	1	3	3	5
A.C., %									
Target	4.5	4.5	4.5	5.5	5.5	4.5	4.5	4.5	4.5
Field	4.7	7.8	3.6	6.1	5.2	4.9	-	5.1	-
ISU Lab	4.7	4.6	4.6	5.6	4.7	4.7	4.6	4.6	4.7
M.C., %									
Target	6.8	8.0	8.0	8.0	6.8	6.8	8.0	8.0	6.8
Field	5.0	7.4	11.6	10.5	6.4	6.6	7.9	9.2	7.4
Lab	6.1	6.7	6.7	6.7	5.0	6.1	6.7	6.7	6.1
Dry density, pcf									
Field	133.0	136.8	137.0	132.1	131.5	126.9	128.6	134.2	121.1
Lab	129.1	128.3	128.3	126.3	127.5	129.1	128.3	128.3	129.3

5.2.1. Effect of Curing Conditions

A major question in foamed asphalt mix design is that of selecting laboratory curing conditions that simulate strength development under field conditions. To evaluate the effect of curing conditions on foamed mix properties was one of the main thrusts of this study. Of the 15 curing conditions evaluated (Table 7), conditions F (3 days at 77° F) and M (3 days at 120° F) correspond to that used by Csanyi [5,6]. Condition O (3 days at 140° F) corresponds to that used by Mobil Australia [1]; conditions E (1 day at 77° F), I (1 day at 104° F), and J (3 days at 104° F) correspond to the initial, intermediate, and final cure conditions recommended by Ruckel et al. [12].

Average Marshall stability at 77° F, stability at 140° F, and resilient modulus at 77° F before treatments are shown in Fig. 2 for Mixes 1 through 5, respectively. It can be observed that:

- Strength development depends greatly on the curing conditions, especially temperature.
- Although there is general strength increase from curing condition A to O, the specific strength depends on both mix type and properties measured. For example, for Mixes 1 and 3, the best condition for development of stability at 77° F was condition H, but for Mix 2, the best conditions were K and N; while the best condition for high stability at 140° F was condition O for other mixes, it was condition K for Mixes 2 and 3.
- While moisture loss has the most effect on mix strength, there is definite strength gain in compacted foamed mixes without



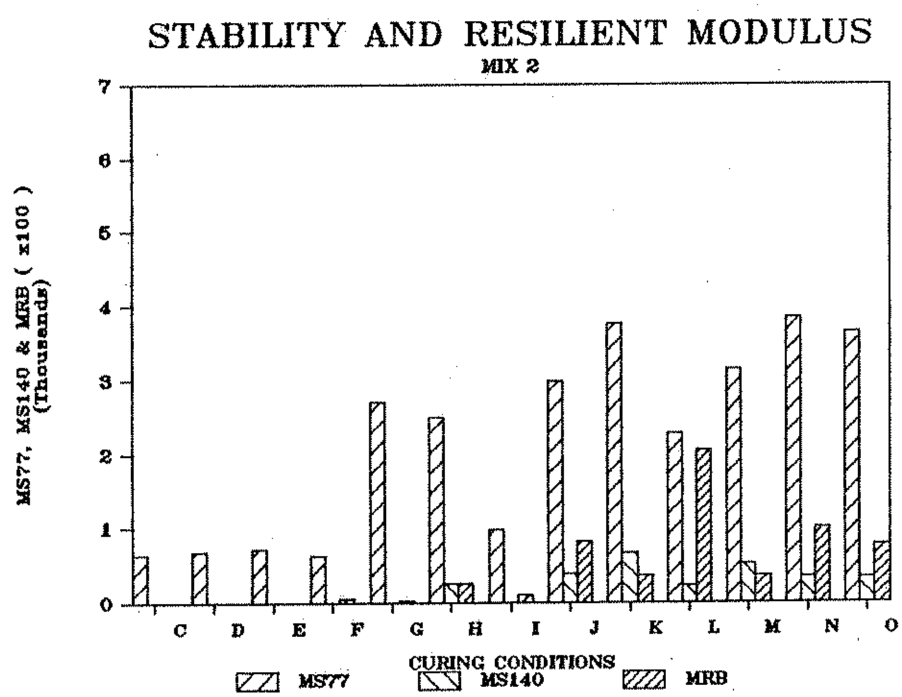
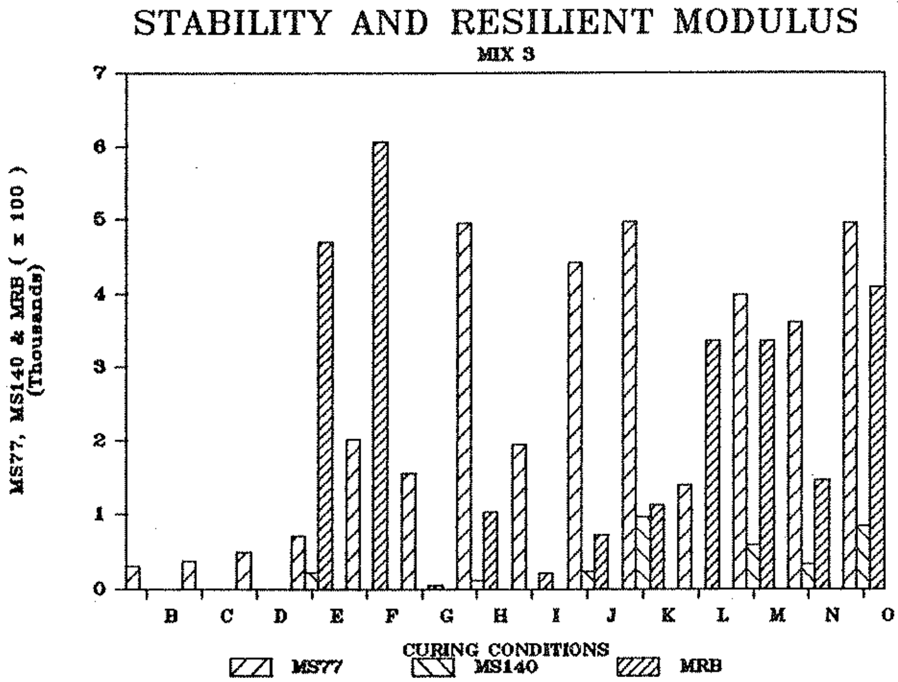


Fig. 2. Marshall stability at 77° F and 140° F and resilient modulus for Mix 1 to 5 cured at different conditions.


STABILITY AND RESILIENT MODULUS
MIX 3
MS77, MS140 & MRB (x 100)
(Thousands)
0
1
2
3
4
5
6
7
B C D E F G H I J K L M N O
CURING CONDITIONS
MS77
MS140
MRB

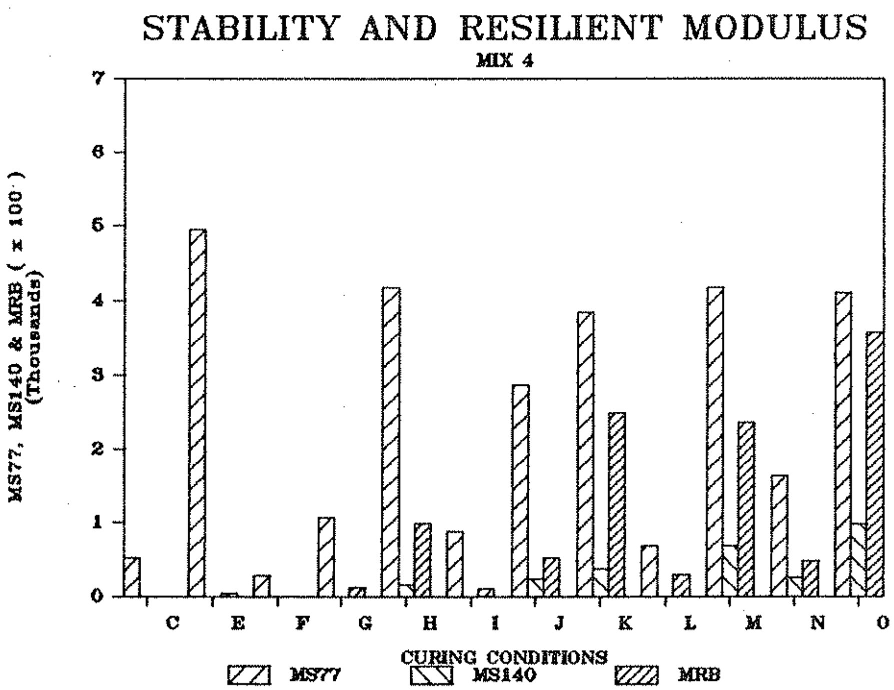

STABILITY AND RESILIENT MODULUS
MIX 4
MS77, MS140 & MRB (x 100)
(Thousands)
0
1
2
3
4
5
6
7
C E F G H I J K L M N O
CURING CONDITIONS
MS77
MS140
MRB

Fig. 2. Cont'd.

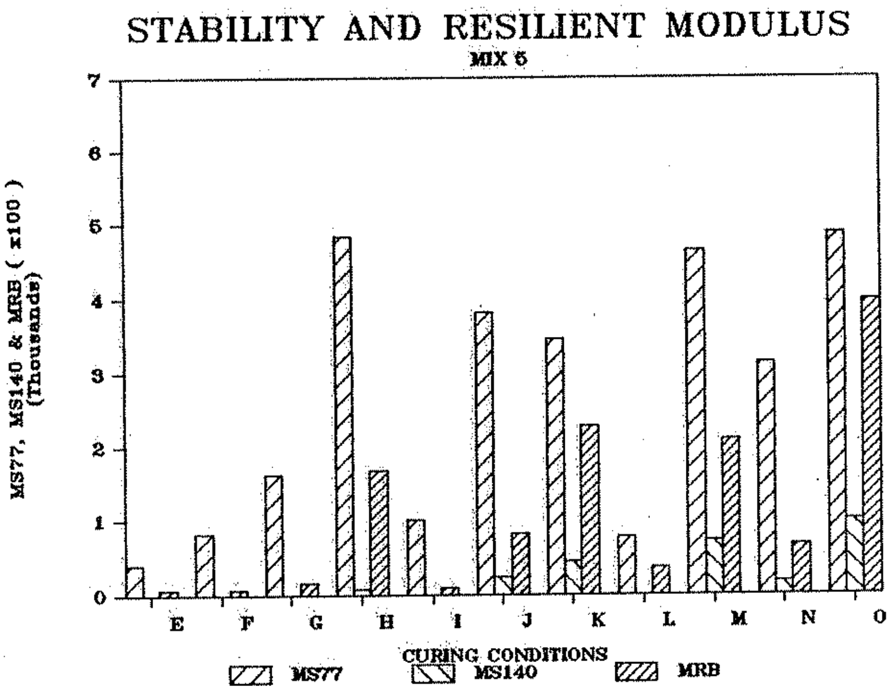

STABILITY AND RESILIENT MODULUS
MIX 6
MS77, MS140 & MRB (x100)
(Thousands)
0
1
2
3
4
5
6
7
E
F
G
H
I
J
K
L
M
N
O
CURING CONDITIONS
MS77
MS140
MRB

Fig. 2. Cont'd.

loss of moisture, as evidenced in conditions C and D for Mixes 2 and 3.

In Figs. 3 and 4, the water content of cured specimens was plotted against Marshall stability and resilient modulus. The correlation coefficients were -0.8472 and -0.7359, respectively; both were significant at the 0.01% level. However, the cured water content was a poor predictor for Marshall stability at 140° F (as shown in Fig. 5), the correlation coefficient being -0.1942. However, the poor correlation was partly due to the elimination of data points for specimens cured at conditions A through F with 3% to 6% cured moisture content and zero stability at 140° F.

Unconfined compressive strength, traditionally used to evaluate stabilized soil systems, was determined for Mixes 1, 3, and 7 after cured under conditions E through O. The average results of three 2-inch by 2-inch specimens for each condition are given in Table 13. The relationship between unconfined compressive strength and cured moisture content for Mixes 1, 3, and 7 is shown in Fig. 6. Linear regression analyses showed correlation coefficients between -0.94 to -0.98, all significant at 0.01%.

In an attempt to better describe curing conditions and to find alternative predictors for strength gain in foamed mixes (other than cured water content), two curing indices were defined. Curing Index 1 was defined as the product of curing temperature (°F) and time (days) and Curing Index 2 was defined as the product of curing temperature (°C) and time (days) divided by relative humidity. The unconfined compressive strength of the three mixes at various curing conditions

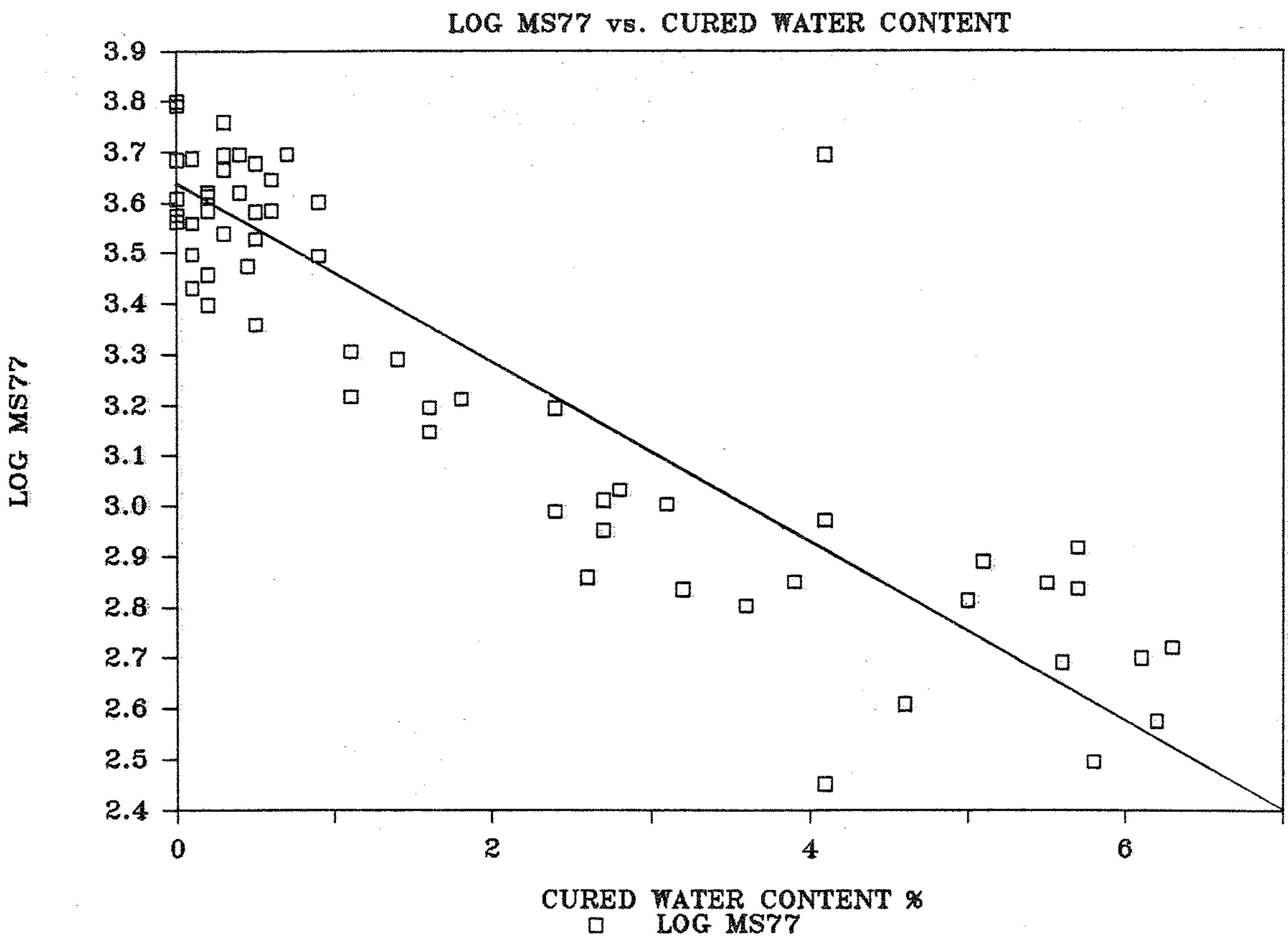


Fig. 3. Relationship between log Marshall stability at 77° F and cured water content.

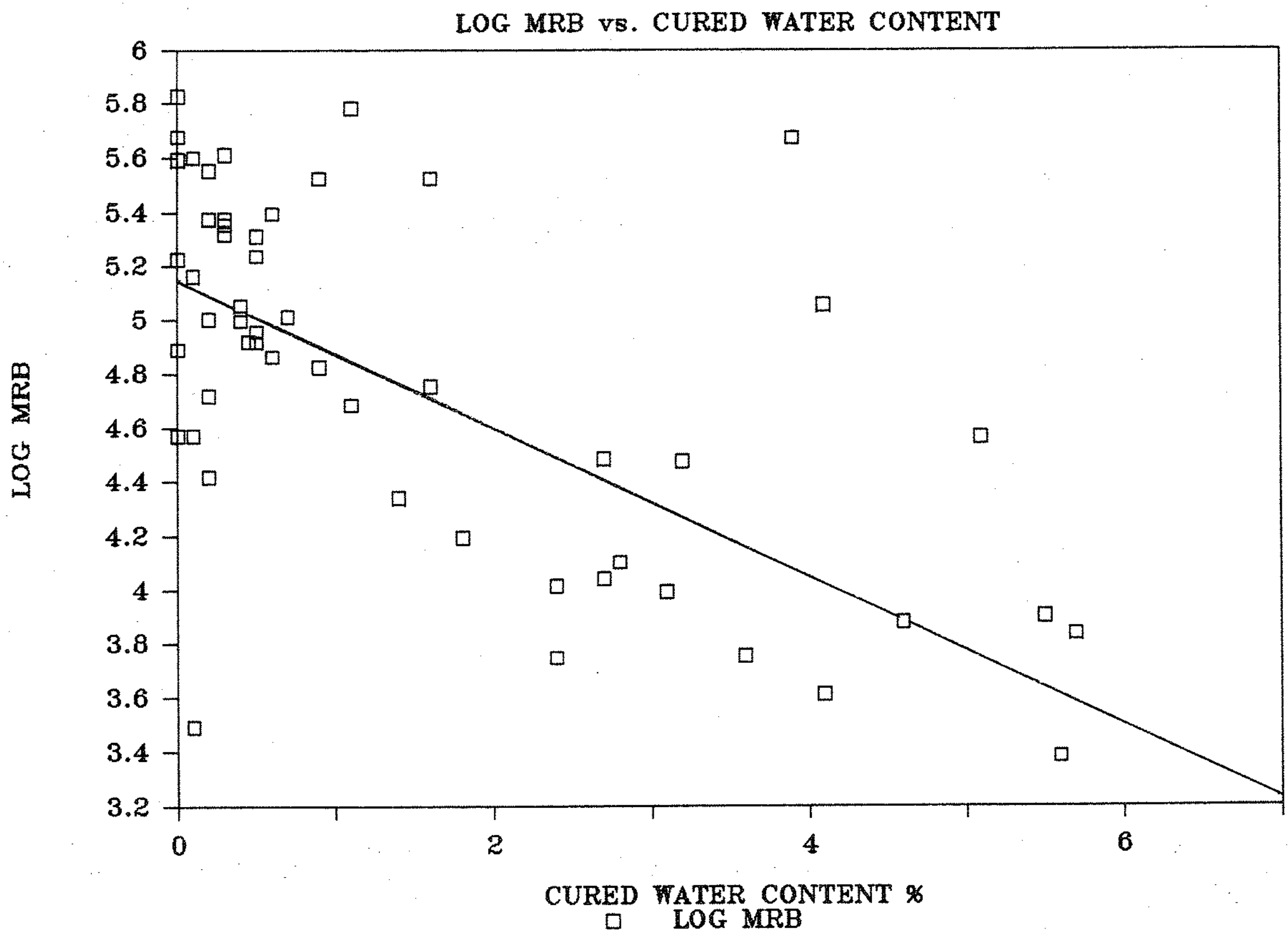


Fig. 4. Relationship between log resilient modulus and cured water content.

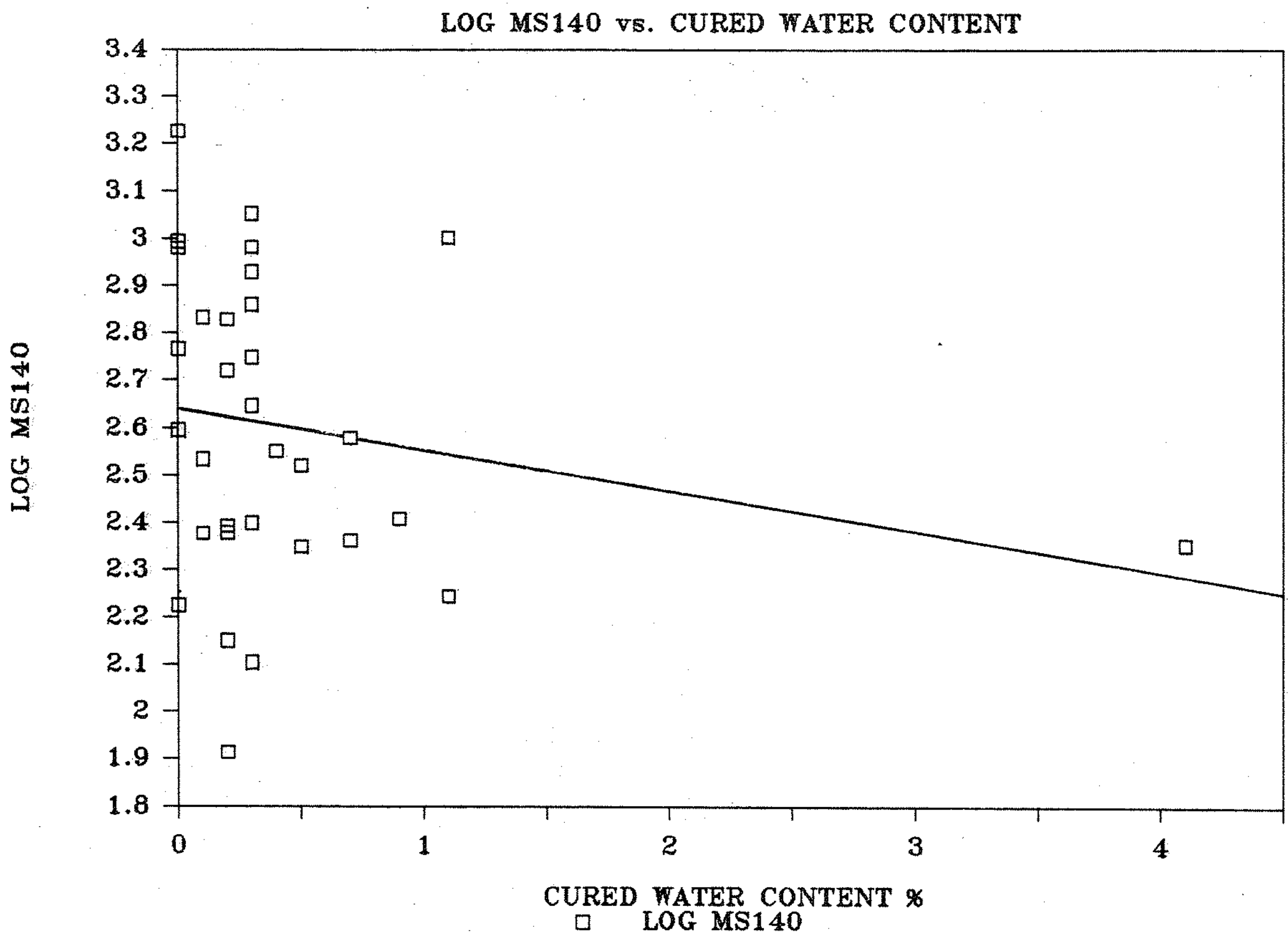


Fig. 5. Relationship between Marshall stability at 140° F and cured water content.

Table 13. Unconfined compressive strength of foamed mixes.

Mix No.	1		3		7	
M.C., %	5.43		8.35		6.52	
Dry density, pcf	117.3		111.4		118.3	
Curing Condition	Cured m.c., %	ucs, psi	Cured m.c. %	ucs, psi	Cured m.c., %	ucs, psi
E	3.09	16.8	6.46	5.8	4.49	5.7
F	0.47	69.6	2.27	24.7	1.00	37.2
G	0.13	80.3	0.30	80.2	0.42	56.1
I	0.03	86.1	1.68	29.7	0.21	42.4
J	0.08	104.8	0.00	71.2	0.17	45.1
K	0.11	92.6	0.10	55.2	0.11	47.6
L	0.27	79.7	0.39	77.3	0.28	48.9
M	0.06	71.9	0.21	84.8	0.64	62.5
N	0.14	105.5	0.09	81.6	0.25	42.6
O	0.20	113.5	0.17	101.9	0.47	72.9

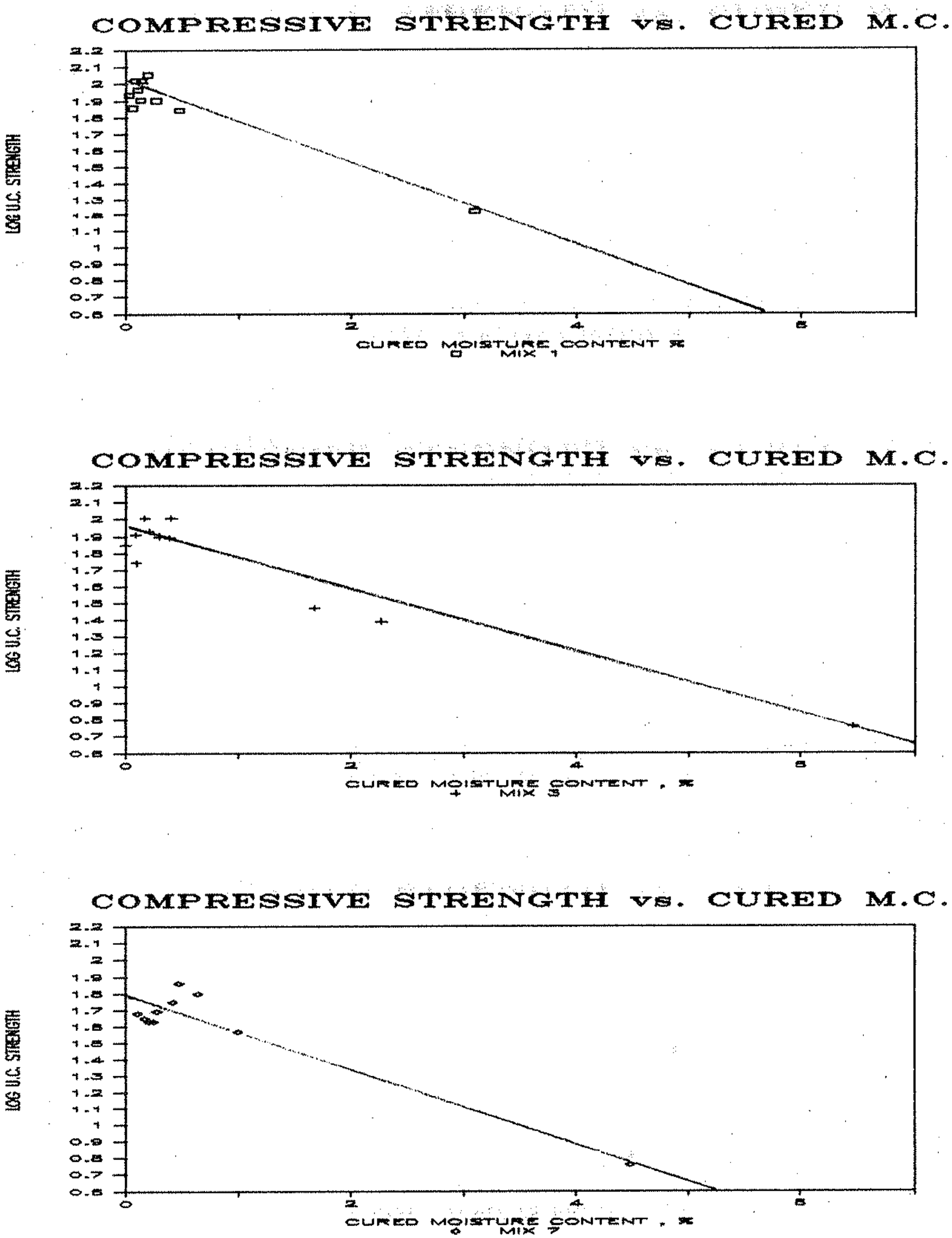


Fig. 6. Relationship between unconfined compressive strength and cured moisture content for Mixes 1, 3, and 7.

was plotted against Curing Index 1 (Fig. 7) and Curing Index 2 (Fig. 8). Although Curing Index 2 predicts the strength better than Curing Index 1, neither were good predictors for strength gain; the correlation coefficients ranged between 0.4 to 0.5 for Index 1 and 0.6 to 0.7 for Index 2.

Based on these data, it must be concluded that, while moisture loss and cured moisture content are the predominant factors and good predictors for strength gain in foamed asphalt mixes, there are factors other than curing time, temperature, humidity, and moisture loss that affect the strength development.

The effect of curing temperature and time on the strength development of the foamed mixes can be better described using a multilinear regression model. The following model was developed for Mix 3:

$$ucs = -60.42 + 1.05\ (T) + 3.15\ (t)$$

where:

ucs = unconfined compressive strength, psi

T = curing temperature, °F

t = curing time, days.

The model has a R value of 84% and is significant at better than 1%.

To compare the properties of hot mix and foamed mixes prepared both in the laboratory and from the plant at comparable compositions and with identical materials, Mix 6 (hot mix) and Mix 7 (foamed mix) were prepared in the laboratory and tested following the same procedures as with other plant mixes. The results are summarized in Table 14. For this particular set of materials and composition, the hot mix had

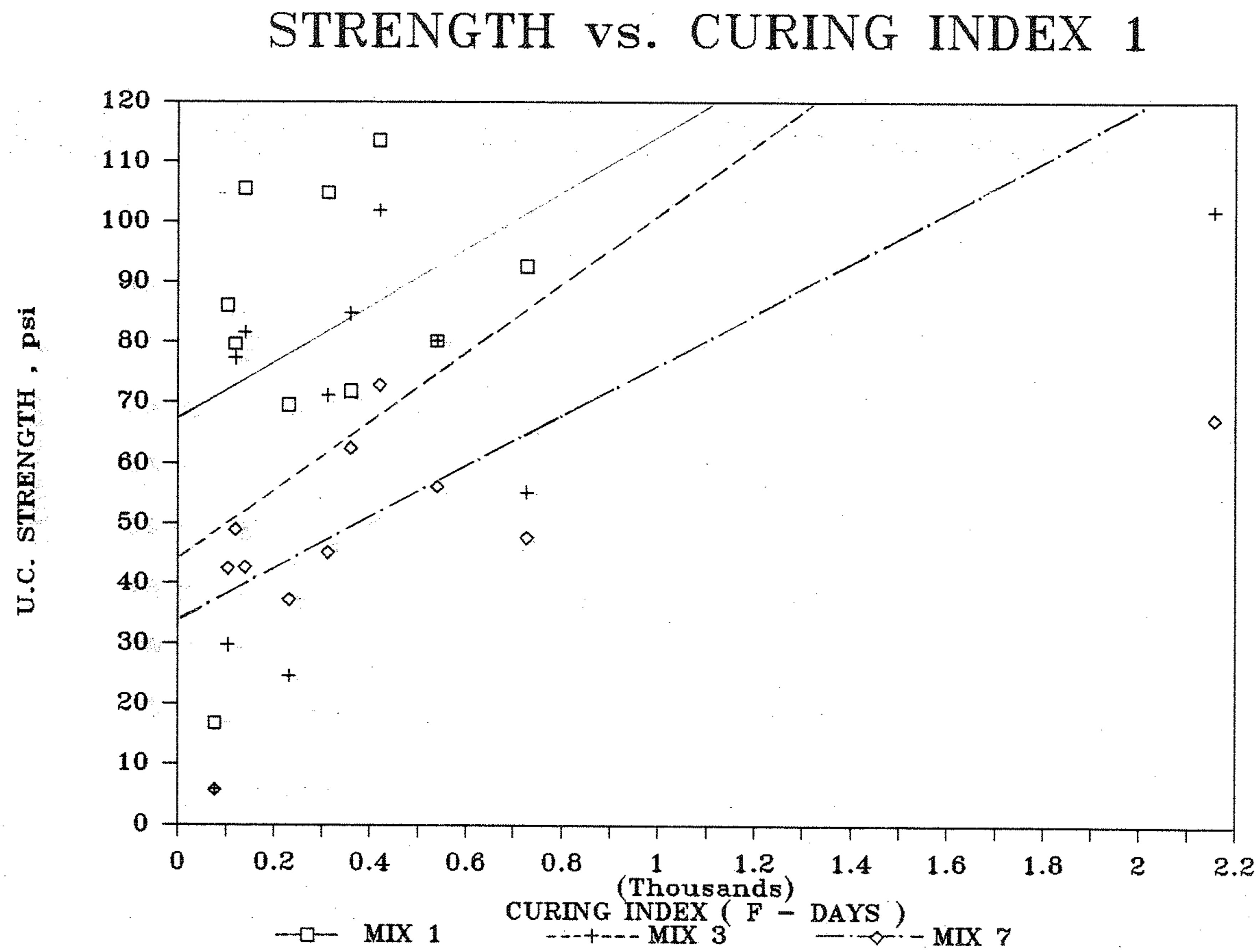


Fig. 7. Unconfined compressive strength vs. Curing Index 1.

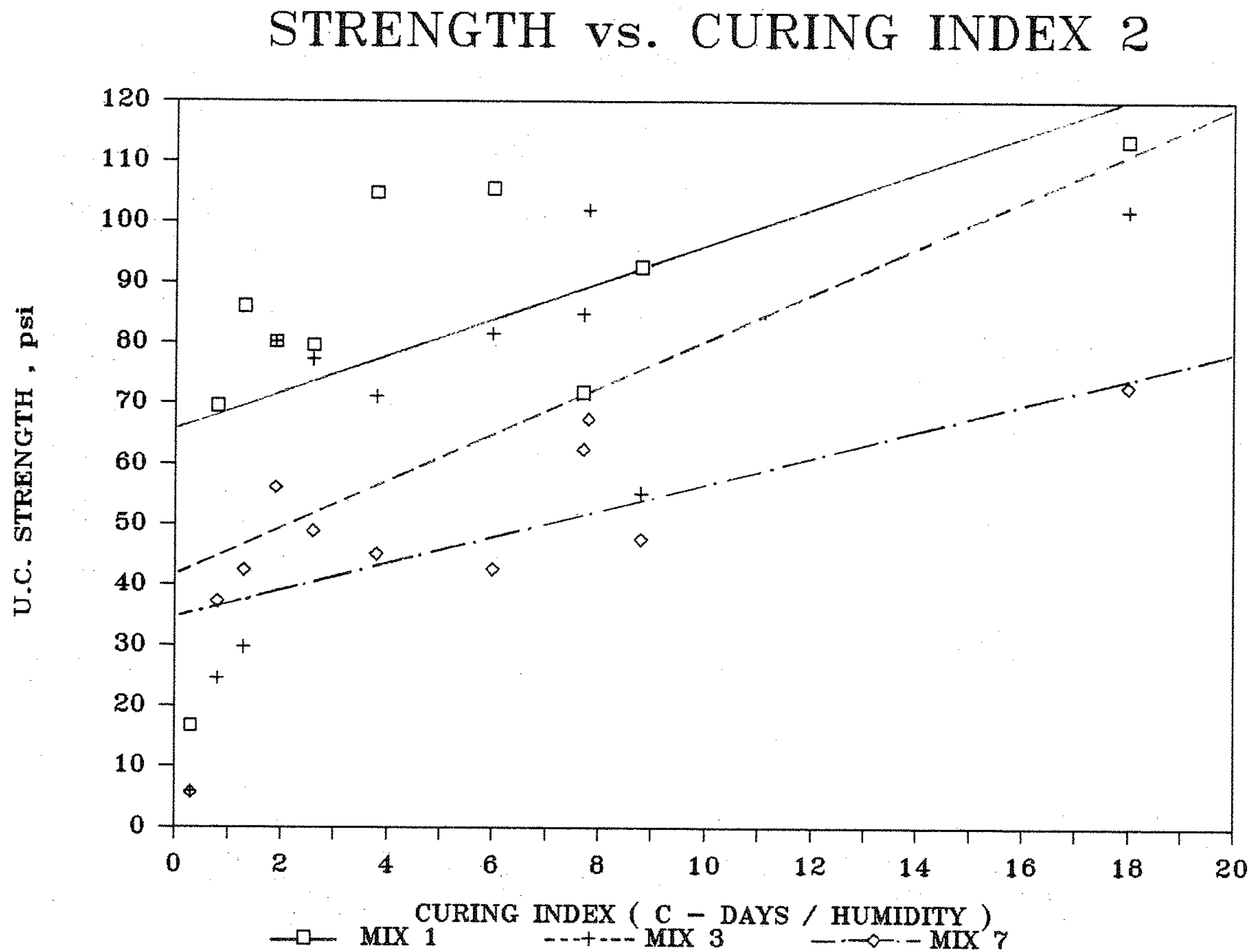


Fig. 8. Unconfined compressive strength vs. Curing Index 2.

Table 14. Comparison between hot mix and foam mixes cured at different conditions.

Mix Type	Plant Foam 1-M	1-O	Lab Foam 7-M	7-O	Lab Foam 7-A	7-D	Hot Mix 6
Percent A.C. by wt of mix	4.7	4.7	4.2	4.2	4.2	4.2	4.5
Curing							
Temperature, °F	120	140	120	140	moist cure*		-
Time, days	3	3	3	3	1	28	-
Cured m.c.%	0.24	0	0.08	0	5.99	5.94	-
Bulk sp. gr.	2.08	2.09	2.07	2.07	-	2.20	2.27
Marshall, 77° F							
Stability, lbs	5740	6190	3160	2990	420	540	9100
Flow, 0.01 in.	9	9	6	6	8	8	13
Marshall, 140° F							
Stability, lbs	1130	1680	-	-	-	-	2280
Flow, 0.01 in.	6	7	-	-	-	-	8
M_R,ksi	231	346	513	586	5.7	7.2	162

*Cured in humidity room, sealed.

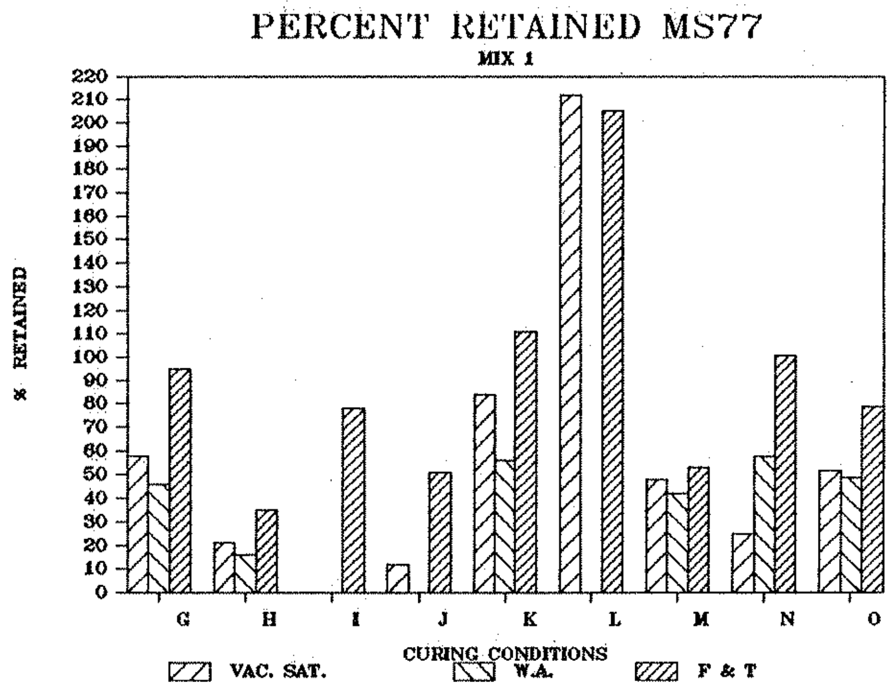
higher density and stability both at 77° F and 140° F than the comparable foamed mixes. However, the resilient modulus of the hot mix was lower than the foamed mixes when fully cured. It is also apparent, comparing Mixes 7A and 7D, which were cured without loss of moisture, that there was strength development in the foamed mix from sources other than the loss of moisture.

5.2.2. Moisture Susceptibility

The characteristics of foamed asphalt mixes (low asphalt content, high voids, incomplete coating of larger particles, and the need of moisture for mixing and compaction) all lead to concern for their moisture susceptibility [3,5,6,8].

Samples of the plant mixes cured at various conditions were exposed to three different moisture deterioration treatments: water soaking up to four days, vacuum-saturation at 100 mm Hg [10], and 10 cycles of freeze-thaw between 0° F and 40° F. Moisture increase, Marshall stability at 77° F, and resilient modulus were determined for samples that survived the treatments. Data are given in Appendix A. Moisture susceptibility was evaluated in terms of ratios of Marshall stability after and before treatment (retained stability), ratios of resilient modulus after and before treatment, and moisture increase during the treatments, as shown in Figs. 9, 10, and 11.

Again the degree of moisture deterioration depends on treatments, mix type, degree of curing, and properties measured. In general, all foamed mixes were susceptible to moisture attack, especially early cured mixes. The deterioration was more severe as measured by resilient modulus than by stability. Even fully cured mixes suffered 20% to 80%



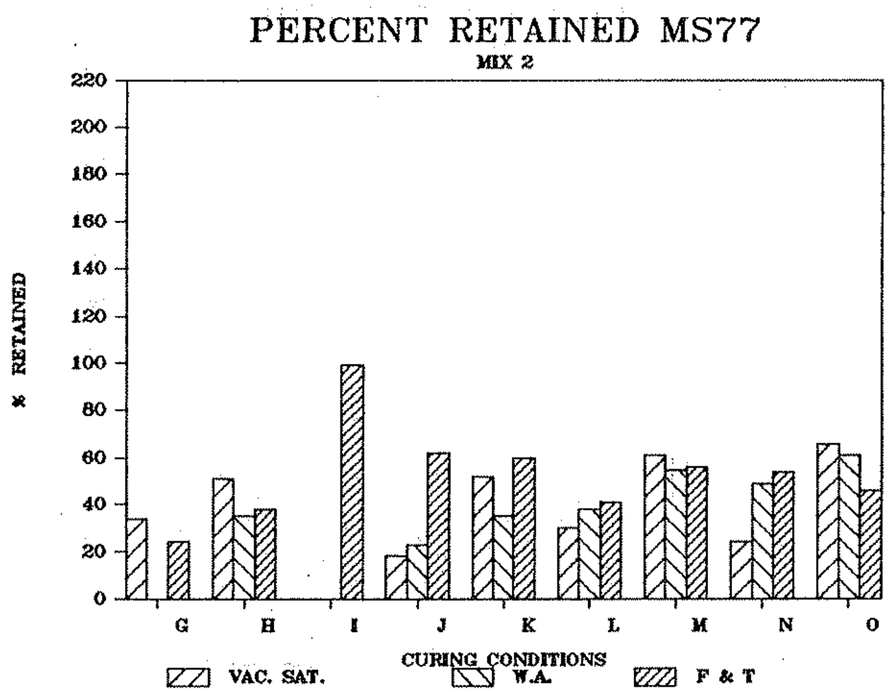
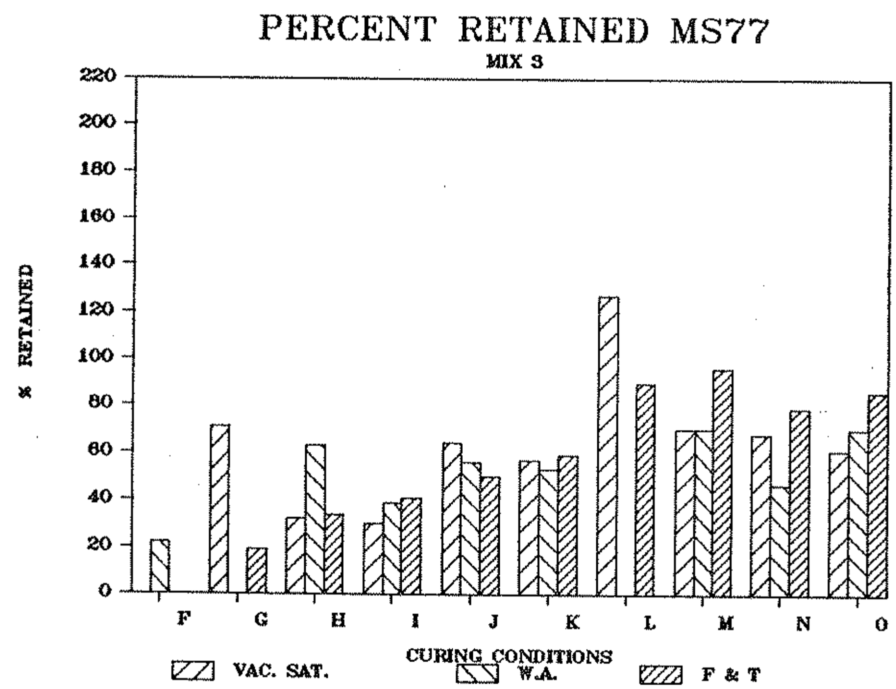


Fig. 9. Percent retained stability at 77° F after vacuum saturation, water absorption, and freeze-thaw treatments for Mix 1 to 5 cured at different conditions.


PERCENT RETAINED MS77
MIX 3
220
200
180
160
140
120
100
80
60
40
20
0
% RETAINED
F
G
H
I
J
K
L
M
N
O
CURING CONDITIONS
VAC. SAT.
W.A.
F & T

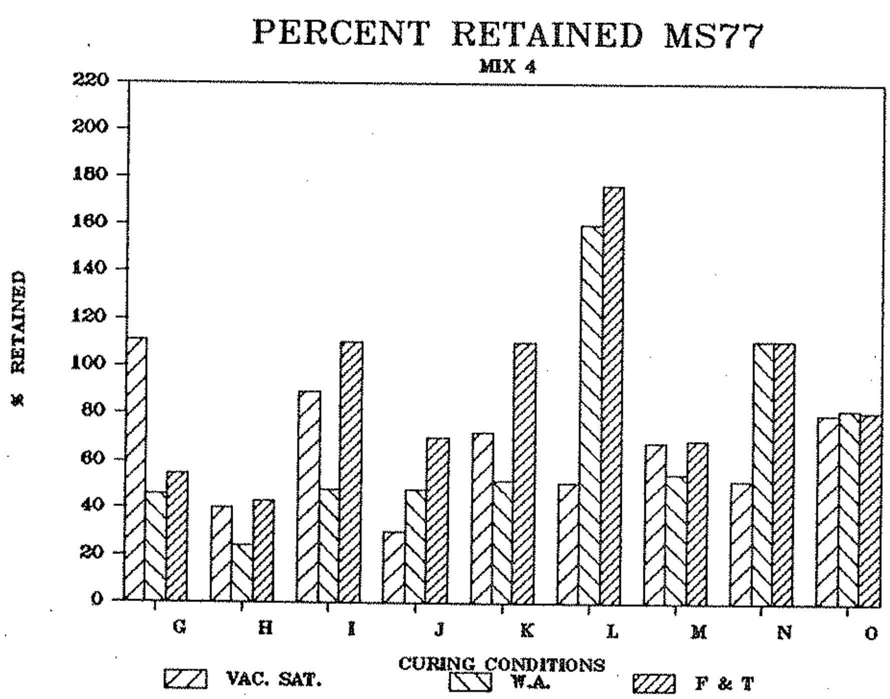
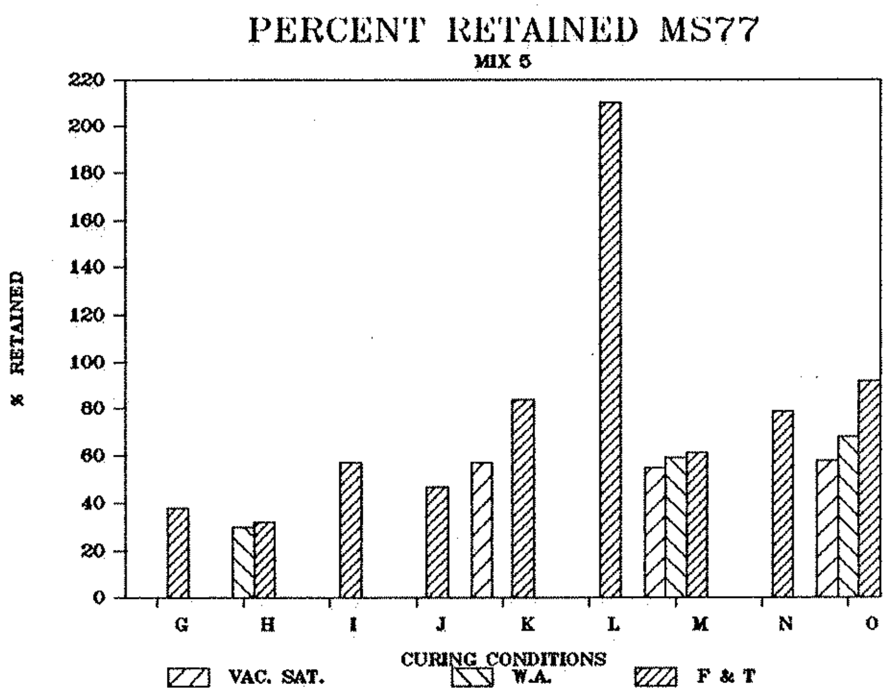

PERCENT RETAINED MS77
MIX 4
220
200
180
160
140
120
100
80
60
40
20
0
% RETAINED
G
H
I
J
K
L
M
N
O
CURING CONDITIONS
VAC. SAT.
W.A.
F & T

Fig. 9. Cont'd.


PERCENT RETAINED MS77
MIX 5
% RETAINED
220
200
180
160
140
120
100
80
60
40
20
0
G
H
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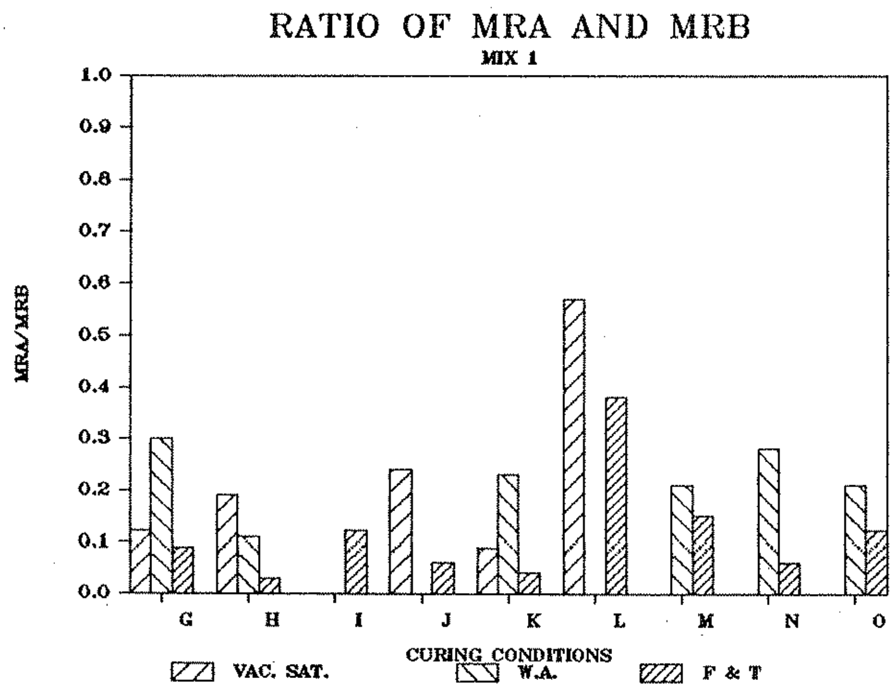
J
K
L
M
N
O
CURING CONDITIONS
VAC. SAT.
W.A.
F & T

Fig. 9. Cont'd.



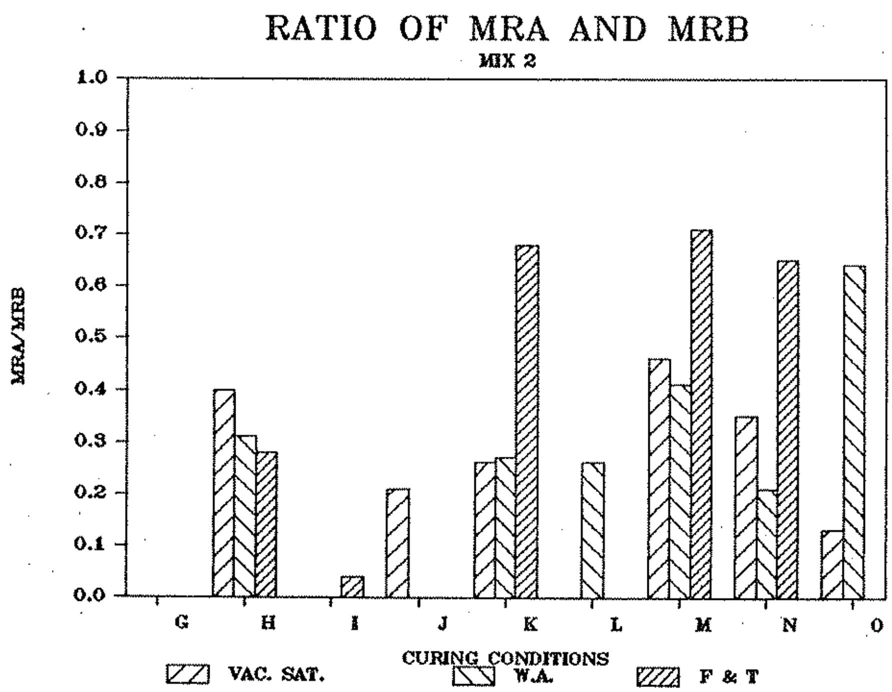
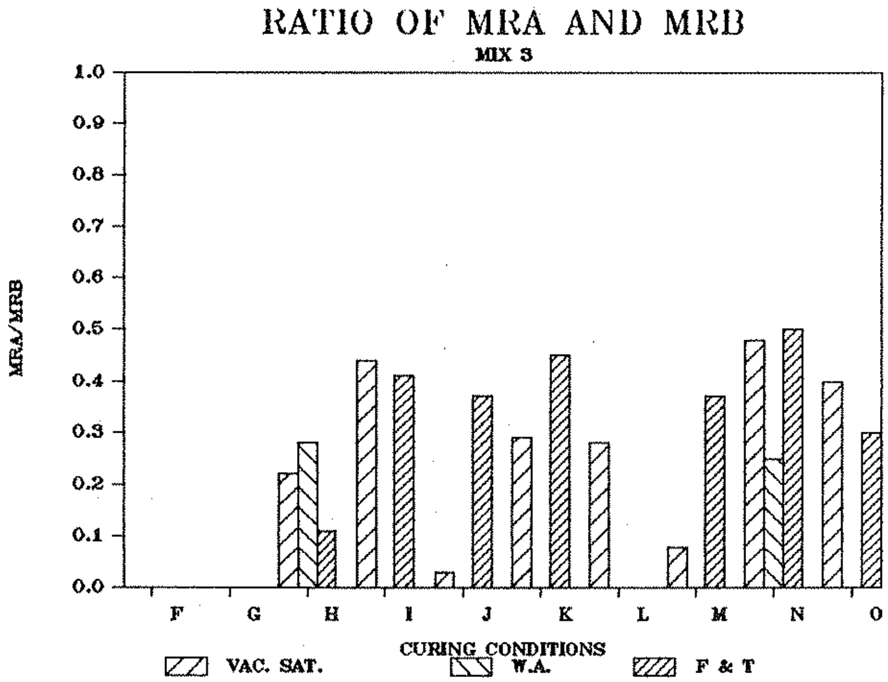


Fig. 10. Ratio of resilient moduli after and before vacuum saturation, water absorption, and freeze-thaw treatments for Mix 1 to 5 cured at different conditions.


RATIO OF MRA AND MRB
MIX 3
MRA/MRB
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
F
G
H
I
J
K
L
M
N
O
CURING CONDITIONS
VAC. SAT.
W.A.
F & T

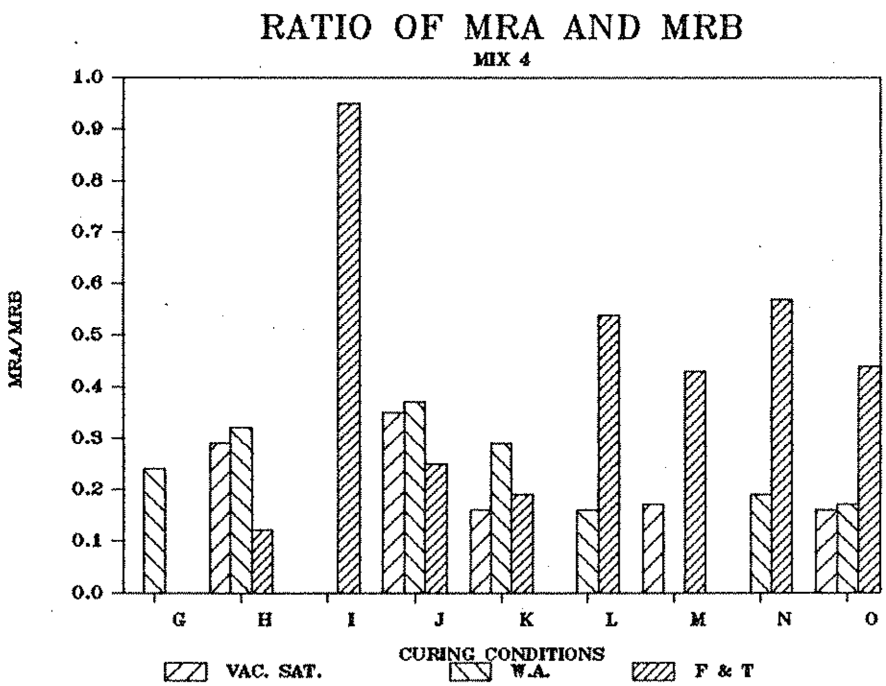
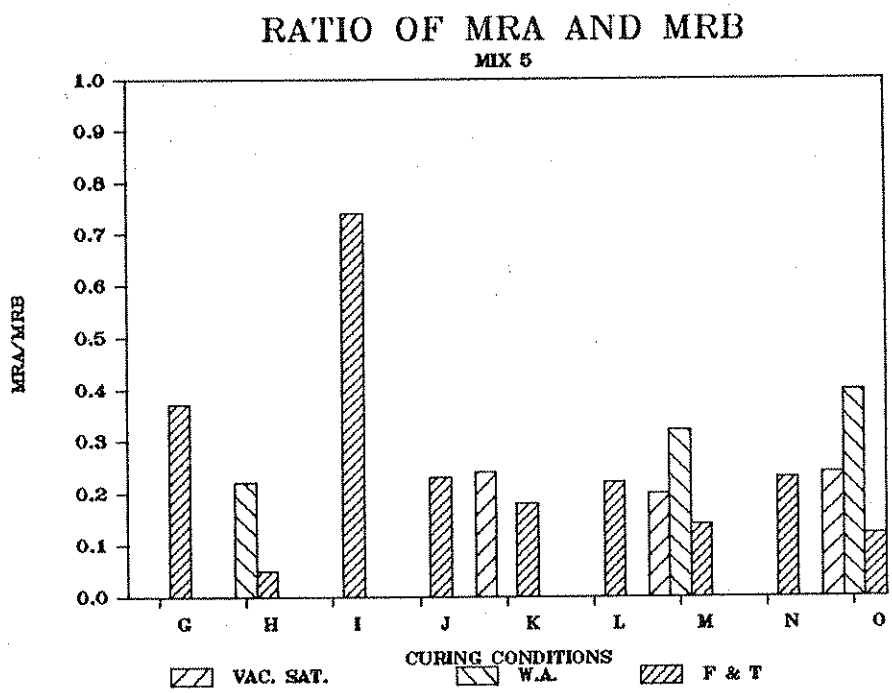

RATIO OF MRA AND MRB
MIX 4
MRA/MRB
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
G
H
I
J
K
L
M
N
O
CURING CONDITIONS
VAC. SAT.
W.A.
F & T

Fig. 10. Cont'd.


RATIO OF MRA AND MRB
MIX 5
MRA/MRB
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
G
H
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CURING CONDITIONS
VAC. SAT.
W.A.
F & T

Fig. 10. Cont'd.

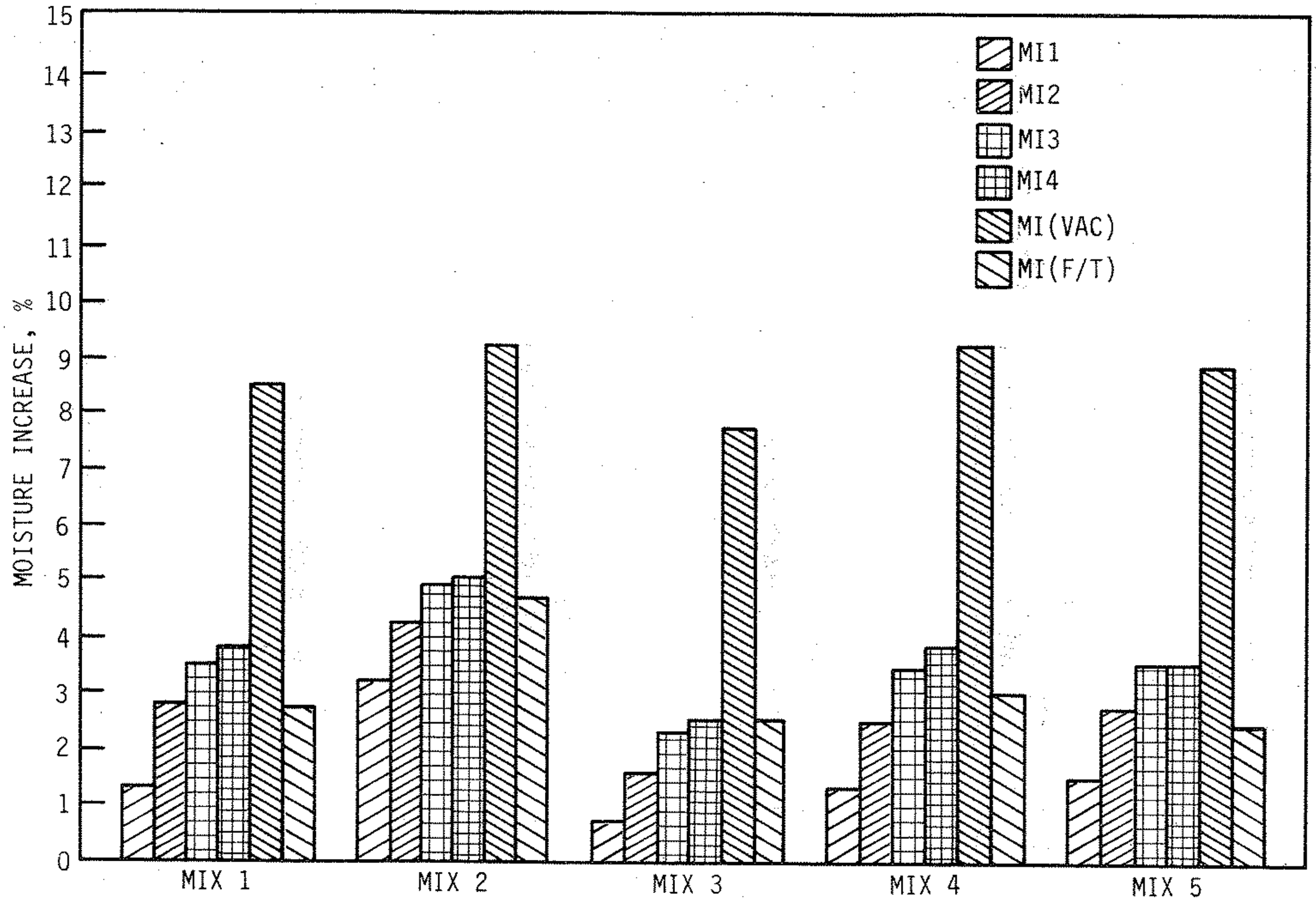

Fig. 11. Moisture increase after vacuum saturation, water absorption, and freeze-thaw treatments for fully cured mixes.

loss in stability and 30% to 100% loss in resilient modulus. High asphalt content mixes appeared to perform better under all curing conditions and moisture treatments. The use of foaming agents (Mix 5) seemed to have made the mix more susceptible to water soaking and vacuum saturation treatments, especially measured by stability loss. No other clear trends could be observed, except that foamed mixes were less susceptible to freeze-thaw treatment than either water soaking or vacuum saturation.

Vacuum saturation, in general, resulted in highest moisture increase, ranging from 2.5% for Mix 3 cured 3 days at 104° F to 10.2% for Mix 4, cured 1 day at 104° F; most samples were in the 8%-9% range. Four-day soaking resulted in an average of 4.8% moisture increase, ranging from 2.5% to 7.5%. Freeze-thaw treatments resulted in an average of 3.4% moisture increase, ranging from 1.8% to 5.7%. Although relatively low freeze-thaw moisture increases corresponded to low strength losses, the high moisture increase in vacuum saturation treatment did not always result in high strength loss.

Low asphalt content Mixes 1 and 3 had lower moisture increases at all curing conditions by all measurements than high asphalt content Mixes 2 and 4. Increased curing reduced moisture absorption.

Figure 11 compares moisture increase of the fully cured mixes during the three moisture treatments.

Linear regression analyses were performed between retained stability and moisture increase, and between retained resilient modulus and moisture increase for the three moisture treatments. The only relationships significant at better than 1% were those between retained stability and moisture increase during freeze-thaw treatment (R = -0.4505), retained stability and 1-hour absorption (R = -0.4278), and 4-day absorption (R = -0.5094) during water soaking treatment. There were no significant relationships between moisture increases during three treatments.

To determine whether the loss of strength is permanent, three specimens from Mix 3 cured 3 days at 120° F (3M) were subjected to water soaking and drying cycles (moisture cycling). Resilient modulus and moisture content were determined after each cycle. The results up to 21 cycles are shown in Fig. 12. Although there were two or three modulus values (e.g., cycles 9 and 15) open to question, there is evidence that the loss of strength due to moisture is recoverable once the foamed mix is dried.

Curing and moisture susceptibility are also of concern in the design and performance of the emulsified-asphalt paving mixtures. In order to evaluate the foamed mixes on the basis of established procedure and criteria for emulsified mixes, three sets of Marshall samples were prepared from Mix 3, following the University of Illinois [10], the University of Mississippi [4], and the Asphalt Institute [10] procedures of molding, curing, and moisture treatment testing. The results are presented in Table 15.

The recommended design criteria for emulsified-asphalt paving mixes by the Illinois procedure are as follows: (a) minimum Marshall stability at 77° F before moisture treatment of 500 lbs., (b) maximum stability loss due to treatment of 50%, and (c) maximum water absorption of 4%. The criteria by the Mississippi method differ slightly:

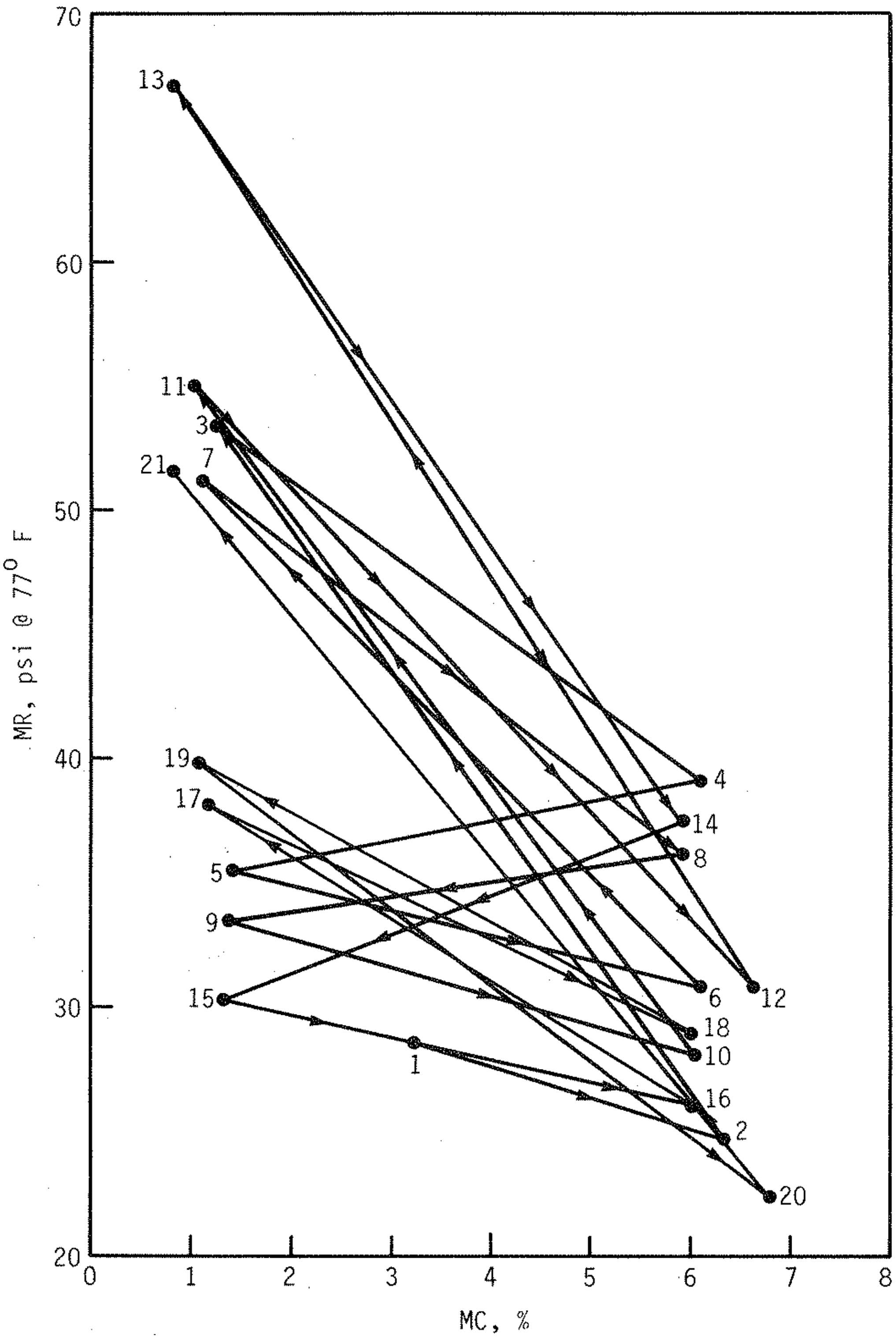

Fig. 12. Effect of moisture cycling on resilient modulus.

Table 15. Comparison between Univ. Ill., Univ. Miss., and the Asphalt Institute procedures (Mix 3).

Procedure	Cured m.c., %	Cured bulk sp.gr.	Marshall, 77° F Before Treatment Stability lbs	Marshall, 77° F Before Treatment Flow 0.01 in.	Absorption %	Marshall, 77° F After Treatment Stability lbs	Marshall, 77° F After Treatment Flow 0.01 in.
Illinois: Compaction: Marshall 75 blows; Curing: 3 days in mold at room temperature; Treatment: 4 days soaking in mold							
	4.73	2.204	442	11	1.60	249	9
Mississippi: Compaction: Marshall 50 blows; Curing: 7 days in mold at room temperature; Treatment: vacuum saturation, 2 hours							
	3.04	2.113	742	14	**	**	**
Asphalt Institute: Compaction: Marshall 50 blows; Curing: 1 day in mold at room temperature followed by 1 day at 100° F outside mold; Treatment: vacuum saturation, 2 hrs							
	1.99	2.030	1111	14	**	**	**

**Disintegrated during vacuum saturation

(a) minimum soaked stability at 77° F of 950 lbs., and (b) maximum water absorption of 8.5%. Professor L. H. Csanyi's criteria [6] for foamed mixes included: (a) minimum Marshall stability at 140° F of 500 lbs., and (b) maximum water absorption of 3%.

Examination of Table 15 shows that Mix 3 would not have been considered satisfactory based on the criteria set by the three procedures for emulsified mixes. Comparing the plant mix properties in Appendix A with these criteria revealed the following:

- Mixes 1H, 1K, 1M, 1O, 2H, 3H, 3J, 3K, 3M, 3N, 3O, and 4H met the Mississippi criteria
- Mixes 1K, 1M, 1O, 3K, 3M, 3O, 4M, 4O, 5M, and 5O met the Csanyi criteria
- Mixes 3K, 3M, 3O, 4O, 5M, and 5O met the Illinois criteria.

It is both interesting and important to note that only Mix 3 cured at conditions K, M, and O met all three sets of criteria and that Mix 2 (5.5% asphalt) met only the Mississippi criteria and only when cured at condition H (28 days at 77° F). It is obvious that these criteria must be validated in view of the long term performance of the test sections.

The moisture susceptibility of Mix 1 cured at conditions M and O is compared to the laboratory prepared comparable hot mix (No. 6) in Table 16. It again demonstrates the potentially more severe water damage to foamed mixes than to hot mix.

5.2.3. Effect of Mix Composition

Comparison between mixes is difficult because the large variation in moisture content within each mix and the properties depends greatly on moisture content (molding and cured) and curing condition. For a

Table 16. Moisture susceptibility, foam mix vs hot mix.

Mix		Moisture Increase, %		Properties	Marshall @ 77° F Stability lbs.	Flow 0.01 in	M_R, ksi
				Freeze thaw, 10 Cycles			
Foam mix, 1-M		2.93			3030	12	34.6
(% retained)					(52)		(15)
Foam mix, 1-O		2.66			4860	10	120
(% retained)					(79)		(35)
Hot mix, 6		1.18			9750	14	260
(% retained)					(107)		(160)
				Water absorption			
	1 hr	1 day	3 day	4 day			
Foam mix, 1-M	1.89	3.72	4.39	4.75	2461	10	17.7
(% retained)					(42)		(8)
Foam mix, 1-O	1.26	2.82	3.48	3.80	3034	11	157
(% retained)					(49)		(53)
Hot mix, 6	0.16	0.72	1.15	1.31	-	-	192
(% retained)							(119)
				Vacuum saturation			
Foam mix, 1-M		8.37			2730	11	68.6
(% retained)					(48)		(30)
Foam mix, 1-O		8.39			3240	8	102
(% retained)					(52)		(29)
Hot mix, 6		3.75			8260	15	145
(% retained)					(91)		(90)

given curing condition, it appeared that Mixes 1 and 3 had higher stability and resilient modulus values than corresponding Mixes 2 and 4 (higher asphalt content). The effect of mixing and molding moisture content was not obvious. While Mix 1 (lower moisture content) had higher stability and resilient modulus values than corresponding Mix 3 when fully cured, Mix 3 had better stability at early-cured conditions. There were no appreciable differences between Mixes 2 and 4. The addition of a foaming agent (Mix 5) seemed to have reduced the stability and resilient modulus values as compared to otherwise identical Mix 1.

While additional asphalt in Mix 4 improved the resistance to moisture deterioration in terms of retained Marshall stability as compared to Mix 3; the same cannot be said for Mix 2 as compared to Mix 1 (Fig. 9). Also, no benefits could be observed in the use of foaming agent (Mix 5) in terms of moisture susceptibility. Although not consistently true for all treatments and all curing conditions, additional asphalt (Mixes 2 and 4) and the use of foaming agent (Mix 5) seemed to have improved the moisture resistance in terms of retained resilient modulus (Fig. 10).

Contrary to original belief, additional asphalt (Mixes 2 and 4) did not decrease moisture pickup during moisture susceptibility treatments (Fig. 11).

The average dry densities of laboratory compacted specimens for Mixes 1 and 3 (129.3 and 128.3 pcf) were greater than the corresponding Mixes 2 and 4 at higher asphalt contents (127.5 and 126.3 pcf). At the same asphalt contents, mixes compacted at 75% of the optimum moisture content (Mixes 1 and 2) had higher densities than the corresponding

Mixes 3 and 4, compacted at 90% of the optimum. Addition of foaming agent (Mix 5) had little effect on the compacted density comparing to the otherwise identical Mix 1. These density differences, while small, could explain the differences in engineering properties between mixes observed earlier.

A stepwise multilinear regression technique was used to develop the relationships and relative effects of mix variables and curing conditions on Marshall stability at 77° F and resilient modulus. The significant (at 0.0001 level) relationships are:

$$MS77 = 3957 - 802\ (CWC)$$
$$MS77 = 573 - 849\ (CWC) + 546\ (MWC)$$
$$MS77 = 3755 - 453\ (AC) - 850\ (CWC) + 405\ (MWC)$$
$$MS77 = 4200 + 28\ (t) - 507\ (AC) - 807\ (CWC) + 344\ (MWC)$$
$$MS77 = 3312 + 23\ (T) + 54\ (t) - 517\ (AC) - 694\ (CWC) + 300\ (MWC)$$
$$MS77 = -1566 + 86\ (T) + 157\ (t)$$

where

MS77 = Marshall stability at 77° F, lbs.
CWC = cured water content, %
MWC = molding water content, %
t = curing time, days
T = curing temperature, °C
AC = asphalt content, %

The relationship between mix variables and curing conditions on resilient modulus before treatment (MRB) is less significant; the best fit was

$$MRB = 758861 - 108347\ (AC) - 39072\ (CWC),$$

significant at 0.0011.

It is significant to note that, while cured water content (CWC) was the most important factor that determined both Marshall stability and resilient modulus, the second most important factor for stability was molding moisture content, but for resilient modulus it was asphalt content.

5.3. Core Samples

Four sets of 83 cores were taken between one month and 15 months after project construction. In the laboratory they were sawed into 133 two-inch thick samples and tested for moisture content, bulk specific gravity, resilient modulus, and Marshall stability at 77° F. The results are presented in Appendix B.

Although the cured moisture contents of core samples are open to question as water was used both during field coring and laboratory sawing operations, the correlation between cured moisture content and stability at 77° F for core samples was surprisingly good (Fig. 13), having a correlation coefficient of -0.7139, which was significant at 0.0001.

Since cores were not taken consistently from all nine test sections, trends regarding core strength and pavement age were difficult to establish. Figures 14 and 15 show the Marshall stability and resilient modulus changes with time for Sections 1 (Mix 1), 4 (Mix 4), and 5 (Mix 2). While both density and moisture content affect stability and modulus values, the more rapid increases in stability and resilient modulus for Section 1 may be an indication of more rapid aging, because of low asphalt content in Mix 1 as compared to Mixes 2 and 4. More field testing and core data are needed to verify this hypothesis.

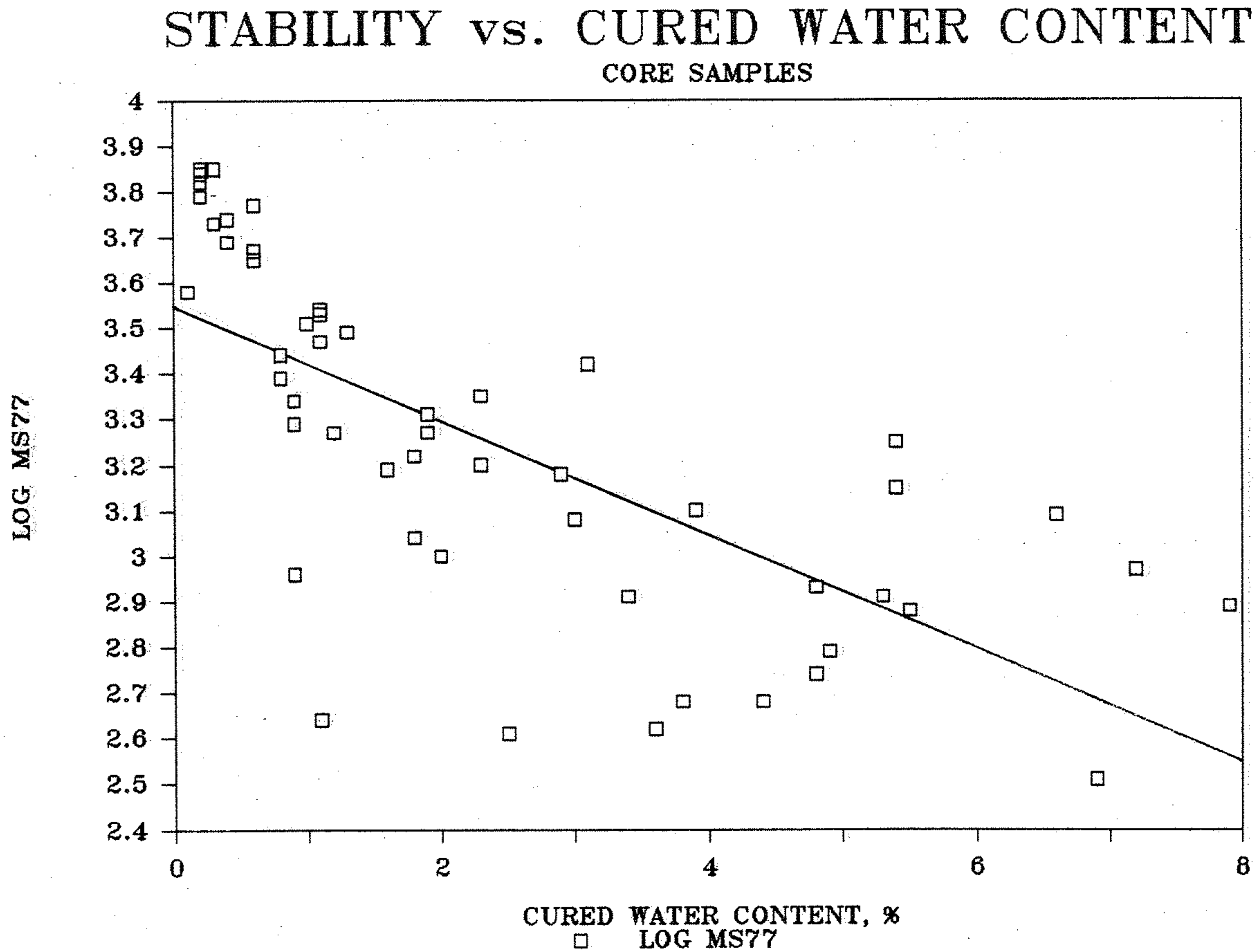

Fig. 13. Marshall stability at 77° F vs. cured water content for core samples.

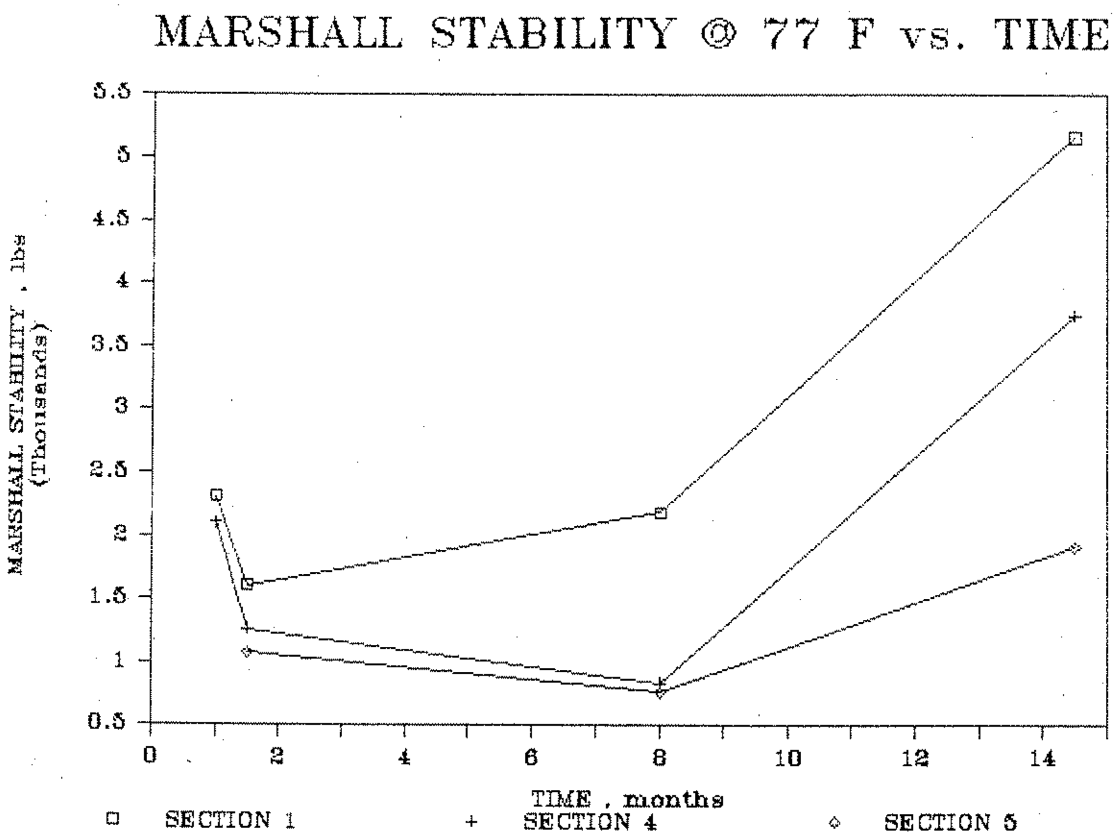

Fig. 14. Marshall stability at 77° F vs. time for Test Sections 1, 4, and 5.

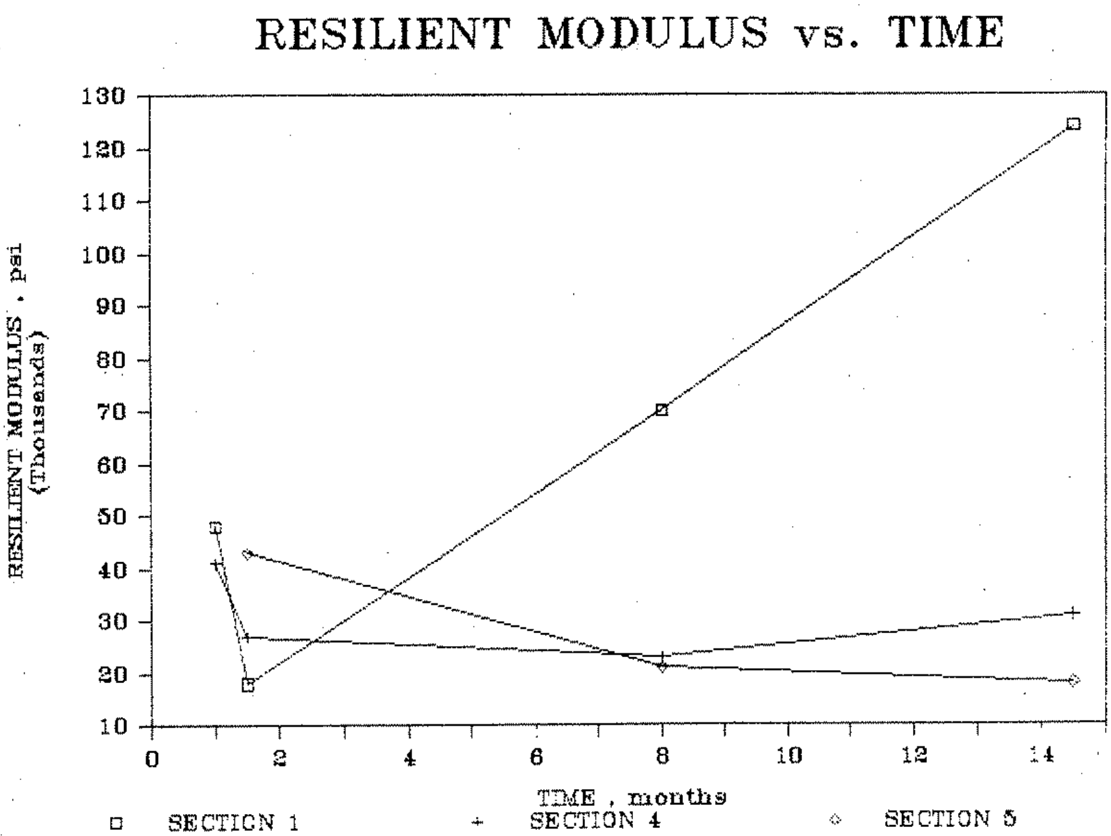

Fig. 15. Resilient modulus vs. time for Test Sections 1, 4, and 5.

The average bulk specific gravity for core samples taken 4 to 6 weeks after construction was about 5% higher than the average specific gravity of laboratory compacted specimens (2.179 vs 2.067).

5.4. Laboratory to Field Correlation

Because of the limited field data available and the multitude of variables involved in the field data, definitive correlations are not possible at this time. A cursory examination of core data (e.g., Fig. 14) shows that laboratory curing condition I seemed to produce foamed mix properties at an early-cured age of one month; laboratory curing conditions M, O, or H predict field mix properties at about 15 months.

Cured moisture contents were plotted against time for both laboratory and field curing time in Fig. 16. Laboratory curing condition E seemed to give reasonable estimates of field-cured moisture content at one day. Laboratory curing condition I approached approximately what was obtained in the field in a week.

Based on these observations, it seems justified, for foamed mix evaluation and design purposes, to use condition I (1 day at 104° F) to estimate foamed mix properties that can be expected in the field one week to one month after construction and to use condition M to estimate foamed mix properties when fully cured (3 days at 120° F). This is a compromise between curing conditions recommended by Ruckel et al. [12] and Professor Csanyi [5,6]. It is interesting to note that the Montana

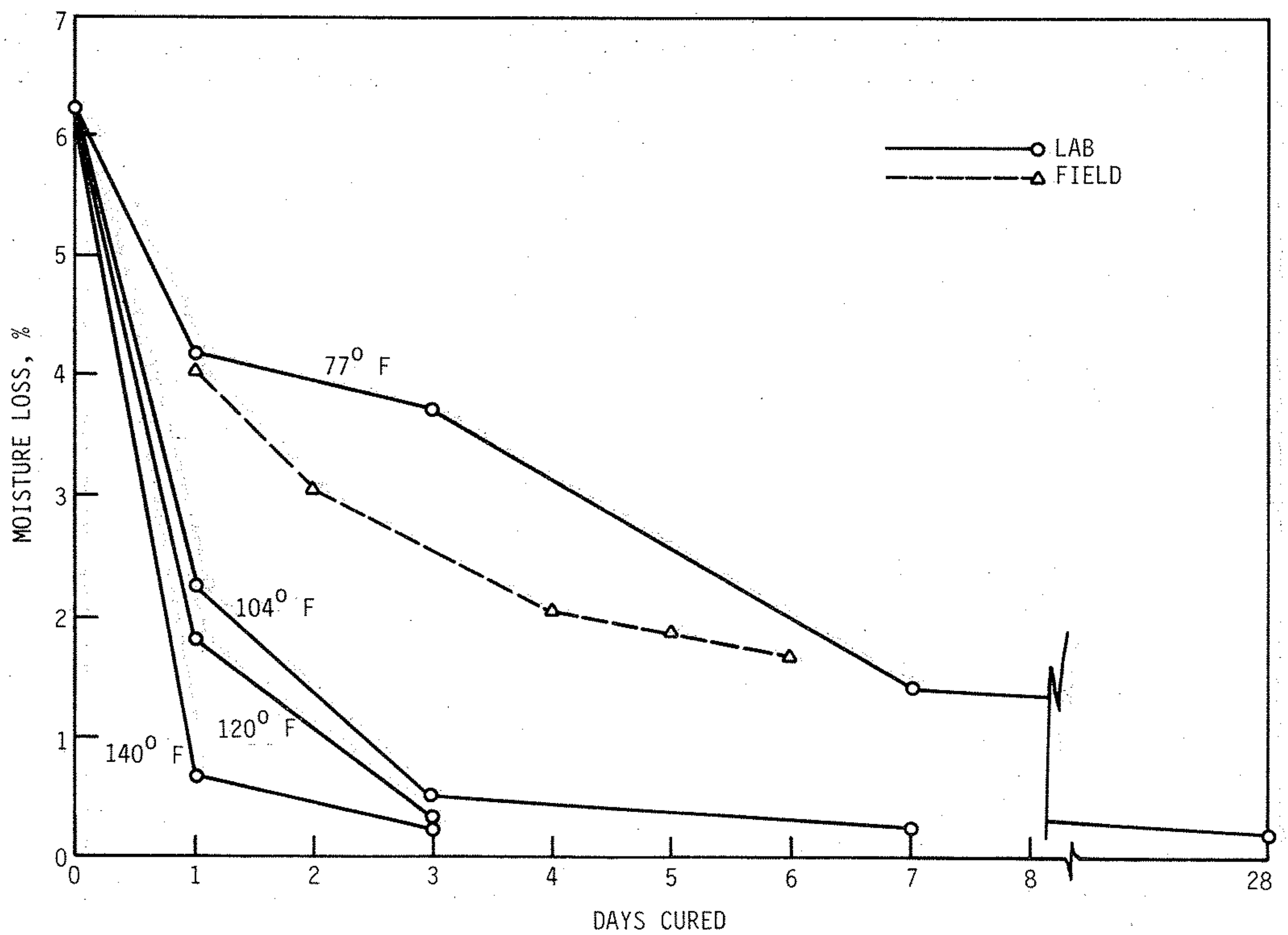

Fig. 16. Cured moisture content vs. curing time, laboratory vs. field conditions.

Department of Highways [9] uses curing conditions (3 days at 96° F) somewhere between conditions I and J for foamed asphalt mix evaluation.

Figure 17 compares the Marshall stability-cured moisture content relationships for core samples and for laboratory prepared plant mixes. Both correlations are significant at 0.0001. It is suggested that the relationship be used for mix design and field construction control purposes.

It is significant to note that the average field-achieved densities exceeded the corresponding laboratory Marshall (50 blows) densities in seven of the nine test sections. Field densities ranged from 94% to 107% laboratory densities.

5.5. Structural Evaluation of Foamed Asphalt Mixes

One of the problems with the use of foamed mixes, as with other new pavement materials, is the lack of information regarding the thickness equivalencies needed for thickness designs. Mixes 3 and 4 were evaluated in terms of their ability to perform as part of a structural pavement system.

The computer program DAMA [2] was used to model the pavement systems. The pavement system was simulated using a two-layer system of asphalt pavement material 4-inches thick (either foamed mix or high quality asphalt concrete) resting on top of an elastic subgrade. The computational points are specified within DAMA to evaluate the three critical responses: horizontal tensile strain at the bottom of the asphalt layer, vertical compressive strain at the top of the subgrade,

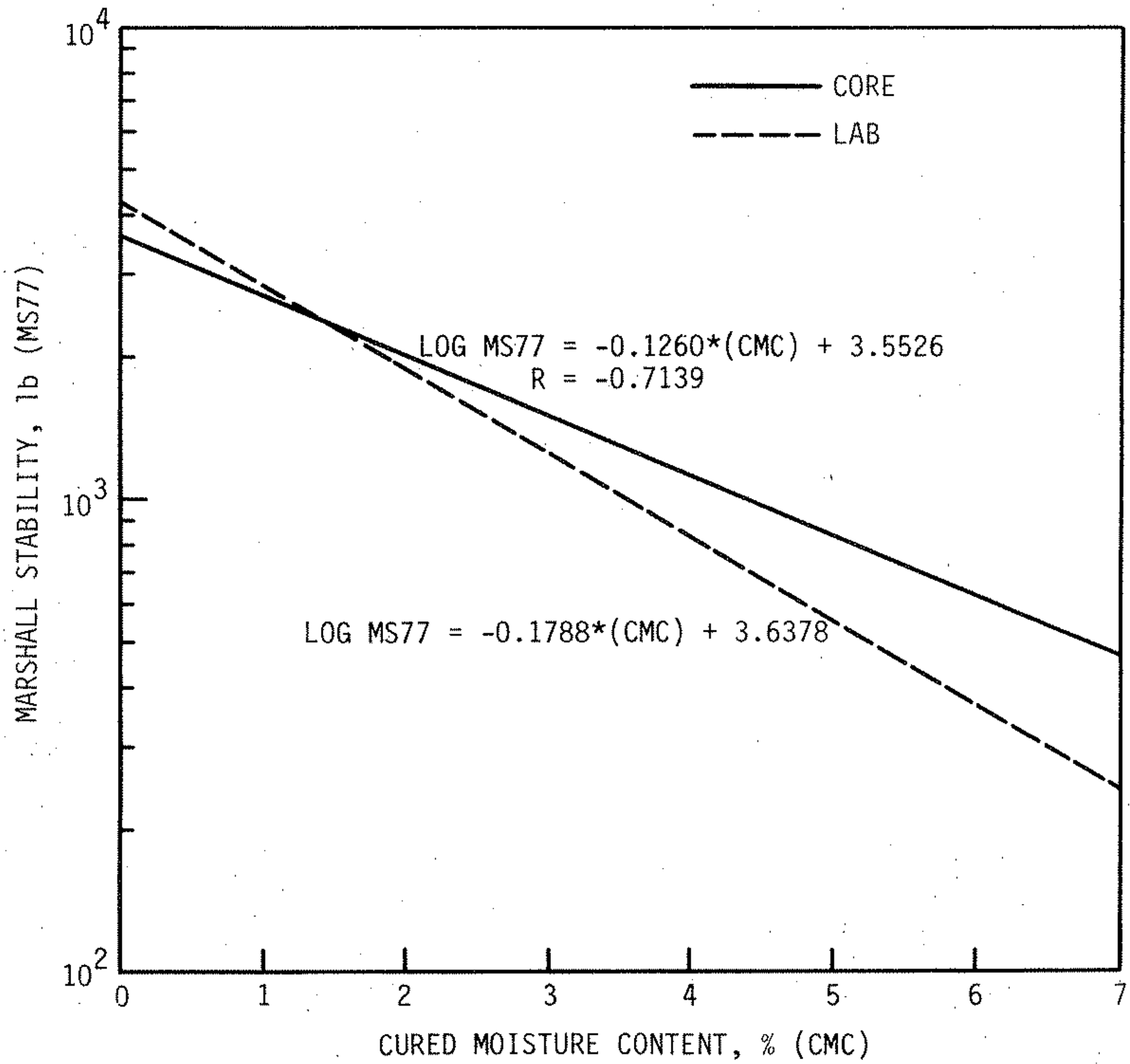

Fig. 17. Marshall stability vs. cured moisture content, laboratory vs. field conditions.

and surface deflection. These computational points are at the center of one tire (point 1), at the edge of one tire (point 2), and at the mid-point of the dual-tire system (point 3). For the purpose of this analysis, the load on each tire was assumed to be 4500 pounds, which is equivalent to an 18-kip single axle load (SAL). Tire pressure of 70 psi and distance between dual tires of 13.5-inches were also assumed. The environmental effects are represented by using the mean monthly air temperature (MMAT) of 60° F.

The structural responses of Mix 3 and Mix 4, each at three curing conditions (condition I for early-cured, condition J for intermediate-cured, and condition O for final-cured) were computed and compared to standard asphalt concrete with AC-5 asphalt cement [2] for single thickness of 4-inch, two subgrade soil moduli of 4500 psi and 12,000 psi (CBR of 3 and 8), and two levels of traffic (300 and 1000 SAL per month). A total of 28 computer runs were carried out as shown in Table 17.

The pavement performance was evaluated using the three critical responses and two distress criteria: number of 18-kip SAL load repetitions required to cause fatigue failure and number of 18-kip SAL repetitions to cause rutting failure. Appendix C gives a sample computer input and output for run No. 3 (Mix 3, final cured, on a subgrade of 4500 psi modulus with traffic of 300 loads per month). Table 18 summarizes the results of the computer analyses. Assuming <u>all</u> the assumptions were valid, the following general observations can be made:

- Before fully cured, foamed mixes are susceptible to load strains and both fatigue and rutting failures.

Table 17. Structural analysis by DAMA computer program.

Subgrade E, psi	4500		12000	
Traffic, SAL	300/mon	1000/mon	300/mon	1000/mon
Mix 3, E3i(EC), 22000 psi	1	8	15	22
E3j(IC), 73000 psi	2	9	16	23
E3o(FC), 410000 psi	3	10	17	24
Mix 4, E4i(EC), 11000 psi	4	11	18	25
E4j(IC), 52000 psi	5	12	19	26
E4o(FC), 357000 psi	6	13	20	27
Standard ACC	7	14	21	28

Note: EC = early-cured; IC = intermediate-cured; FC = final-cured.

Table 18. Results of computer analyses.

	Tensile Strain Microstrain		Comp. Strain Microstrain		Surface Defl. $\times 10^{-3}$ in.		No. Load to Cause Fatigue Failure $\times 10^3$		No. Load to Cause Rutting Failure $\times 10^3$	
Subgrade Modulus, ksi	4.5	12.0	4.5	12.0	4.5	12.0	4.5	12.0	4.5	12.0
Mix 3										
EC	1910	985	4290	2200	90	37	0.3	1.8	0.3	0.3
IC	1010	618	2380	1400	71	29	0.3	3.3	0.3	3.3
FC	330	230	880	570	47	20	4.4	15.2	16.6	140
Mix 4										
EC	2550	1170	5700	2660	104	44	0.3	3.3	0.3	0.3
IC	1240	730	2870	1600	77	31	0.3	3.6	0.3	0.6
FC	360	260	960	600	49	21	5.3	19.1	11.5	100
ACC	380	270	1000	640	50	22	170	610	22.0	100

Notes: EC = early-cured; IC = intermediate-cured; FC = final-cured
ACC = standard asphalt cement concrete

- When fully cured, foam mixes are comparable to asphalt concrete in structural responses but more susceptible to fatigue failure.

A more quantitative and rational approach to evaluate the structural performance of the foamed mixes is to compute the thickness equivalencies.

Before the thickness equivalency can be computed, a reference material must be selected. In this case it will be asphalt concrete. If D_f inches of foamed mix is required to give performance equivalent to that of D_a inches of asphalt concrete under identical loading, subgrade, and environmental conditions, the thickness equivalency of the foamed mix can be calculated as D_f/D_a. In this analysis, D_f was fixed at 4 inches, DAMA computer runs were repeated to determine thickness of asphalt concrete (D_a) to produce

- The same surface deflection
- The same horizontal strain at the bottom of the asphalt layer
- The same vertical compressive strain in the subgrade
- The same number of loads to cause fatigue failure
- The same number of loads to cause rutting failure.

The results of thickness equivalencies for foamed Mixes 3 and 4 at different curings and for two subgrades are given in Table 19.

It can be seen that the equivalency factors depend not only on the subgrade bearing capacity and degree of curing but also on the criteria used. For intermediately cured (3 days at 104° F) Mix 3, the equivalency factors for structural responses ranged between 1.07 to 4.44, averaging about 2.5. The average for Mix 4 at intermediate cure was 3.7. Based on structural responses, fully cured foamed mixes

Table 19. Thickness equivalencies for foamed mixes based on equal structural responses.

	Based on Tensile Strain		Based on Comp. Strain		Based on Surface Defl.		Based on No. Load to Cause Fatigue Failure		Based on No. Load to Cause Rutting Failure	
Subgrade Modulus, ksi	4.5	12.0	4.5	12.0	4.5	12.0	4.5	12.0	4.5	12.0
Mix 3										
EC	33.3	--	4.00	5.00	2.50	2.86	--	--	--	--
IC	3.03	4.44	2.00	2.22	1.67	1.74	--	--	--	--
FC	0.87	0.87	0.87	0.91	0.91	0.93	4.00	--	1.08	0.93
Mix 4										
EC	--	--	6.67	8.00	3.33	5.00	--	--	--	5.70
IC	5.00	8.00	2.50	2.67	1.89	2.00	--	--	--	4.00
FC	0.95	0.98	0.95	0.95	0.97	0.98	3.57	--	1.25	1.00
ACC	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Notes: EC = early-cured; IC = intermediate-cured; FC = final-cured
ACC = standard asphalt cement concrete

performed equally well or better than asphalt concrete. The thickness equivalency values for intermediate and fully cured mixes in Table 19 compared reasonably well with limited reported values of 1.3 to 3.4 [6, 8,15,16]. Again, the equivalency factors based on fatigue criteria were much higher than those based on rutting failure criteria, indicating that foamed mixes may have relatively short fatigue lives even fully cured. It must be stressed that these calculations hold only if layered elastic theory and DAMA assumptions are valid, and only applicable to 4 inches of foamed mixes and under assumed MMAT of 60° F. The verification of these calculations must come from the long term performance of the test sections.

6. SUMMARY AND CONCLUSIONS

In view of the energy, environmental, and economic advantages of the foamed asphalt process using local aggregates in cold mixes and the promising results from Research Project HR-212, a 4.2-mile section of county road in Muscatine County was built with foamed asphalt and local aggregates during August-September 1983. Extensive laboratory evaluation was carried out on five plant mixes representing foamed mixes used in the nine test sections, a laboratory prepared foamed mix, and a laboratory prepared hot mix similar to Plant Mix 1. The foamed mixes were compacted, cured under 15 curing conditions and tested for bulk specific gravity, Marshall stability at 77° F and at 140° F, cured moisture content, resilient modulus and effects of moisture damage due to freeze-thaw cycles, water soaking, and vacuum saturation. In addition, four sets of 83 core samples were taken at 1 to 15 months and tested for moisture content, specific gravity, Marshall stability, and resilient modulus.

Inherent in any field test program is the number of variables involved, some of which cannot be controlled. The more serious uncontrolled variables encountered in this project included the weather conditions during construction, the large variability in mixing moisture content, and the difficulties in getting the proper mix compositions based on designs. These factors made definitive correlations and conclusions difficult. Therefore, the conclusions that follow must be viewed as tentative. Further research and field tests are needed to verify and refine these conclusions.

1. Plant produced mixes varied in both asphalt content and moisture content, both from target values and within samples. Better moisture content control is needed in future foamed asphalt projects.

2. Higher density was achieved in the field than in the laboratory by Marshall compaction using 50 blows per side. On the average, the field compacted density was about 5% higher than the laboratory density.

3. Strength development in foamed mixes depends greatly on the curing conditions.

4. While moisture loss is the single most important factor for strength development in foamed mixes, there is strong evidence indicating strength gains without the loss of moisture.

5. Cured moisture content is a good predictor for strength development in foamed mixes, both in the laboratory and in the field.

6. Mix 3 had the best overall characteristics of the five plant mixes.

7. Foamed mixes are more susceptible to moisture deterioration than comparable hot mix; additional asphalt in Mixes 2 and 4 appeared to have improved the moisture resistance of foamed mixes.

8. Strength loss in foamed mixes due to moisture increase is recoverable when the moisture content is decreased.

9. Data on core samples up to 15 months showed more stability increase in Mix 1 (Section 1) than in Mixes 2 and 4 (Section 4 and 5), perhaps as a result of aging. Additional asphalt in Mixes 2 and 4 may prove to be beneficial in terms of resistance to aging.

10. No apparent benefit was observed in the use of foaming agent in Mix 5 (Section 9).

11. Structural evaluation by computer modeling showed that foamed mixes may be susceptible to fatigue failure. For structural design purposes, the thickness equivalency factors for foamed mixes of 1.5 to 2.0 is tentatively recommended.

12. Limited performance data on a single test section for 15 months does not provide sufficient information to establish mix design criteria. However, for mix design and evaluation purposes, curing conditions I (1 day at 104° F) and M (3 days at 120° F) can be used to reasonably estimate foamed mix properties one to four weeks after construction and fully cured, respectively.

In summary, the test road has performed satisfactorily for almost two years. The few early construction problems encountered were to be expected for experimental projects dealing with new materials and technologies. Overall results to date are encouraging and foamed asphalt mixes have proved to have the potential as a viable base material in areas where marginal aggregates are available. It is hoped and expected that performance evaluation of the test sections will be continued and that more foamed asphalt trial projects will be constructed and monitored so that experiences and findings from this project can be verified and mix design criteria can be gradually established.

For future foamed asphalt projects, in addition to the excellent recommendations made by Simmering and Jones [14], with respect to moisture control, minimum mixing time, and the use of test strip to specify compaction, it is recommended that anti-stripping additives, such as hydrated lime, be added in view of the potential moisture susceptibility of foamed mixes observed in the laboratory evaluation.

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APPENDIX A: DATA ON LABORATORY PREPARED SPECIMENS

Table A1

MARSHALL 77

M	C	S	TAC	CWC	MWC	BSG	MS77	MF77	MRB
1	E	1	4.7	5.51	6.67	2.010	480	9.0	
1	E	2	4.7	5.51	6.67	2.106			2400
1	E	3	4.7	5.51	6.67	2.087	502	9.7	
1	F	1	4.7	5.46	7.01	2.241	759	8.5	
1	F	2	4.7	5.86	7.01	2.253	666	10.1	8000
1	F	3	4.7	5.05	7.01	2.226	686	11.6	
1	G	1	4.7	1.69	6.63	2.017	1316	9.4	
1	G	2	4.7	2.50	6.63	2.030	990	8.4	
1	G	3	4.7	0.67	6.63	2.013	2400	12.1	
1	H	1	4.7	0.00	6.36	2.150	6063	6.0	
1	H	2	4.7	0.00	6.36	2.144	6500	8.2	
1	H	3	4.7	0.00	6.36	2.147	6386	8.2	
1	I	1	4.7	2.43	6.24	2.066	1114	8.4	
1	I	2	4.7	3.19	6.24	2.090	912	8.1	
1	I	3	4.7	2.56	6.24	2.072	1056	8.2	
1	J	1	4.7	0.63	7.01	2.135	4909	12.0	
1	J	2	4.7	0.58	7.01	2.131	4690	12.6	
1	J	3	4.7	0.41	7.01	2.139	4680	11.5	
1	K	1	4.7	0.00	6.63	1.885	4032	10.2	
1	K	2	4.7	0.00	6.63	2.007	4013	10.1	
1	K	3	4.7	0.00	6.63	2.011	4128	10.7	
1	L	1	4.7	4.93	7.95	2.199	806	8.7	
1	L	2	4.7	4.61	7.95	2.187	892	9.4	
1	L	3	4.7	2.15	6.14	2.075	1114	7.5	
1	M	1	4.7	0.33	6.55	2.095	5500	7.2	
1	M	2	4.7	0.35	6.55	2.103	5740	9.5	
1	M	3	4.7	0.20	6.55	2.093	5990	10.0	
1	N	1	4.7	0.58	6.24	2.030	3024	11.2	
1	N	2	4.7	0.51	6.24	2.036	3192	10.7	
1	N	3	4.7	0.35	6.24	2.036	3888	12.4	
1	O	1	4.7	0.00	6.55	2.102	6105	8.8	
1	O	2	4.7	0.00	6.55	2.102	6219	8.8	
1	O	3	4.7	0.00	6.55	2.106	6240	8.2	
2	C	1	5.7	5.00	6.07	2.207	650	10.4	
2	D	2	5.7	5.66	6.07	2.217	715	10.5	
2	D	3	5.7	5.69	6.07	2.215	650	10.2	
2	E	1	5.7	2.08	5.13	2.054	907	9.2	
2	E	2	5.7	2.49	5.34	2.137	625	9.3	
2	E	3	5.7	3.14	5.34	2.129	635	11.3	
2	F	1	5.7	4.04	5.18	2.140	701	8.7	
2	F	2	5.7	3.98	5.18	2.123	274	14.5	5700
2	F	3	5.7	2.86	5.18	2.096	922	10.1	
2	G	1	5.7	0.14	4.96	2.053	2698	12.1	

2	G	2	5.7	0.14	4.96	2.052	2530	11.7	
2	G	3	5.7	0.03	4.96	2.054	2851	10.0	
2	H	1	5.7	0.16	4.37	2.011	2474	10.0	
2	H	2	5.7	0.12	4.37	2.020	2604	9.2	
2	H	3	5.7	0.17	4.37	2.016	2418	9.1	
2	I	1	5.7	2.13	5.35	2.062	970	9.5	
2	I	2	5.7	2.78	5.35	2.079	883	8.8	
2	I	3	5.7	2.19	5.35	2.066	1075	8.5	
2	J	1	5.7	0.36	5.18	2.046	3144	10.8	
2	J	2	5.7	0.40	5.18	2.042	2736	13.0	
2	J	3	5.7	0.38	5.18	2.052	3072	11.3	
2	K	1	5.7	0.00	4.96	2.056	3888	8.8	
2	K	2	5.7	0.00	4.96	2.040	3648	9.3	
2	K	3	5.7	0.00	4.96	2.056	3754	9.3	
2	L	1	5.7	0.39	5.13	2.013	2350	9.1	370500
2	L	2	5.7	0.66	5.34	2.090	2100	12.5	
2	L	3	5.7	0.54	5.34	2.080	2400	12.6	
2	M	1	5.7	0.13	4.94	2.028	2947	11.6	
2	M	2	5.7	0.13	4.94	2.040	3110	13.0	
2	M	3	5.7	0.15	4.94	2.051	3360	11.5	
2	N	1	5.7	0.22	5.34	2.076	4260	8.3	280200
2	N	2	5.7	0.25	5.34	2.085	3340	11.6	
2	N	3	5.7	0.00	5.34	2.082	3930	11.7	
2	O	1	5.7	0.00	4.85	2.014	3515	8.7	
2	O	2	5.7	0.00	4.85	2.025	3658	9.0	
2	O	3	5.7	0.00	4.85	2.025	3763	8.5	
3	B	1	4.6	5.78	6.54	2.144	350	8.7	
3	B	2	4.6	5.81	6.54	2.177	370	8.8	
3	B	3	4.6	5.91	6.54	2.140	220	9.5	
3	C	1	4.6	6.28	6.54	2.142	364	8.5	
3	C	2	4.6	6.14	6.54	2.144	365	8.5	
3	C	3	4.6	6.26	6.54	2.146	400	9.7	
3	D	1	4.6	6.08	6.38	2.151	542	9.8	
3	D	2	4.6	5.83	6.38	2.148	494	10.7	
3	D	3	4.6	5.95	6.38	2.152	466	9.7	
3	E	1	4.6	3.85	6.22	2.071	634	9.2	418700
3	E	2	4.6	4.36	5.46	2.181	730	8.0	
3	E	3	4.6	3.40	5.46	2.158	760	9.0	
3	F	1	4.6	0.00	6.92	2.043	1860	12.0	606900
3	F	2	4.6	1.96	8.00	2.121	2059	11.6	
3	F	3	4.6	1.40	8.00	2.103	2132	16.5	
3	G	1	4.6	2.60	7.34	2.137	1440	11.3	
3	G	2	4.6	1.62	7.34	2.097	1883	6.0	
3	G	3	4.6	3.09	7.34	2.126	1362	10.5	
3	H	1	4.6	0.51	7.34	2.081	4951	12.4	
3	H	2	4.6	0.77	7.34	2.102	5096	12.0	
3	H	3	4.6	0.86	7.34	2.091	4831	11.7	
3	I	1	4.6	0.48	6.22	1.998	2148	13.2	209500
3	I	2	4.6	1.76	7.34	2.101	1768	11.0	

3	I	3	4.6	1.90	7.34	2.117	1924	10.2	
3	J	1	4.6	0.81	8.00	2.105	4545	16.2	
3	J	2	4.6	0.78	8.00	2.105	4524	14.8	
3	J	3	4.6	0.14	6.66	2.060	4185	11.5	
3	K	1	4.6	0.40	7.34	2.076	5086	11.5	
3	K	2	4.6	0.41	7.34	2.078	4919	11.3	
3	K	3	4.6	0.24	7.34	2.074	4888	11.3	
3	L	1	4.6	0.22	6.22	2.002	2717	10.9	722000
3	L	2	4.6	2.54	5.46	2.130	730	8.0	
3	L	3	4.6	1.89	5.46	2.100	760	9.0	
3	M	1	4.6	0.45	8.00	2.087	3680	15.4	484200
3	M	2	4.6	1.02	8.00	2.101	3900	18.8	
3	M	3	4.6	1.08	8.00	2.101	4394	14.0	
3	N	1	4.6	0.24	5.43	2.076	3740	10.6	130700
3	N	2	4.6	0.00	5.43	2.093	3370	6.4	
3	N	3	4.6	0.00	5.43	2.102	3744	12.2	
3	O	1	4.6	0.14	7.26	2.060	4950	9.5	
3	O	2	4.6	0.32	7.26	2.068	5002	10.7	
3	O	3	4.6	0.44	7.26	2.069	4900	10.2	
4	C	1	5.6	6.29	7.25	2.186	525	11.4	
4	E	1	5.6	3.40	5.71	2.052	493	11.2	
4	E	2	5.6	4.09	5.71	2.068	488	15.5	4100
4	E	3	5.6	4.36	5.71	2.063	442	14.4	
4	F	1	5.6	4.24	6.12	2.101	548	10.0	
4	F	2	5.6	4.56	6.12	2.118			
4	F	3	5.6	3.04	6.12	2.102	845	11.8	
4	G	1	5.6	2.06	7.02	2.052	190	11.2	
4	G	2	5.6	4.28	7.02	2.098	778	9.7	
4	G	3	5.6	1.98	7.02	2.044	1258	10.1	
4	H	1	5.6	0.48	7.02	2.031	4186	9.5	
4	H	2	5.6	0.32	7.02	2.017	4186	9.5	
4	H	3	5.6	0.54	7.02	2.036	4147	9.2	
4	I	1	5.6	3.02	5.33	2.061	944	9.2	
4	I	2	5.6	2.87	5.33	2.052	758	9.2	
4	I	3	5.6	2.27	5.33	2.033	977	11.5	
4	J	1	5.6	0.19	5.33	1.976	2976	8.2	
4	J	2	5.6	0.17	5.33	1.989	2957	9.7	
4	J	3	5.6	0.13	5.33	1.972	2661	10.3	
4	K	1	5.6	0.50	7.02	2.014	3811	9.7	
4	K	2	5.6	0.64	7.02	2.008	3888	9.5	
4	K	3	5.6	0.64	7.02	2.002	3802	9.7	
4	L	1	5.6	3.78	6.85	2.103	624	8.5	
4	L	2	5.6	3.25	6.85	2.098	624	8.5	
4	L	3	5.6	2.44	6.85	2.071	797	7.9	
4	M	1	5.6	0.08	5.98	2.019	4080	8.0	
4	M	2	5.6	0.20	5.98	2.029	4339	8.0	
4	M	3	5.6	0.19	5.98	2.027	4128	8.0	
4	N	1	5.6	1.31	6.33	2.038	1483	10.2	
4	N	2	5.6	1.35	6.33	2.057	1464	10.6	

4	N	3	5.6	0.78	6.33	2.041	1982	12.8	
4	O	1	5.6	0.21	5.98	2.023	4061	8.0	
4	O	2	5.6	0.20	5.98	2.028	4080	8.0	
4	O	3	5.6	0.14	5.98	2.024	4176	7.5	
5	E	1	4.7	4.48	5.58	2.142	499	10.0	
5	E	2	4.7	4.78	5.58	2.155	240	11.3	7600
5	E	3	4.7	4.57	5.58	2.150	480	9.5	
5	F	1	4.7	5.97	7.10	2.234	832	9.9	
5	F	2	4.7	6.05	7.10	2.229	780	9.4	6900
5	F	3	4.7	5.03	7.10	2.210	863	13.0	
5	G	1	4.7	1.75	6.05	2.089	1625	9.0	
5	G	2	4.7	2.28	6.05	2.113	1270	8.8	
5	G	3	4.7	1.47	6.05	2.088	1985	9.5	
5	H	1	4.7	0.00	7.95	2.068	4620	12.2	
5	H	2	4.7	0.00	7.95	2.071	4997	12.0	
5	H	3	4.7	0.00	7.95	2.065	4888	12.2	
5	I	1	4.7	2.87	6.00	2.133	1055	8.2	
5	I	2	4.7	3.61	6.00	2.152	900	8.0	
5	I	3	4.7	2.66	6.00	2.143	1065	8.0	
5	J	1	4.7	0.53	7.10	2.102	3921	12.8	
5	J	2	4.7	0.55	7.10	2.108	3713	13.5	
5	K	1	4.7	0.10	5.81	2.073	3100	8.3	
5	K	2	4.7	0.17	5.81	2.079	3180	8.0	
5	K	3	4.7	0.48	6.24	2.071	4080	8.5	
5	L	1	4.7	5.47	8.66	2.207	660	10.7	
5	L	2	4.7	5.29	8.66	2.192	775	10.6	
5	L	3	4.7	4.58	8.66	2.170	894	11.7	
5	M	1	4.7	0.42	6.28	2.080	4270	10.4	
5	M	2	4.7	0.37	6.28	2.100	4500	10.2	
5	M	3	4.7	0.10	6.28	2.087	5130	9.5	
5	N	1	4.7	0.81	6.00	2.087	2815	10.2	
5	N	2	4.7	1.00	6.00	2.125	3275	10.2	
5	N	3	4.7	0.89	6.00	2.102	3275	10.2	
5	O	1	4.7	0.16	6.28	2.086	4760	8.3	
5	O	2	4.7	0.16	6.28	2.091	4910	7.2	
5	O	3	4.7	0.10	6.28	2.081	4930	7.4	

Table A2

MARSHALL 140

M	C	S	TAC	CWC	MWC	BSG	MS140	MF140	MRB
1	H	4	4.7	0.00	6.36	2.145	894	6.0	
1	H	5	4.7	0.00	6.36	2.149	1024	5.5	
1	H	6	4.7	0.00	6.36	2.155	948	6.2	
1	J	4	4.7	0.11	6.24	2.011	106	5.4	
1	J	5	4.7	0.25	6.24	1.984	154	5.4	
1	J	6	4.7	0.22	6.24	2.015	163	5.7	
1	K	4	4.7	0.23	6.18	2.073	525	5.7	
1	K	5	4.7	0.25	6.18	2.084	565	6.0	
1	K	6	4.7	0.40	6.18	2.080	590	6.0	
1	M	4	4.7	0.44	6.55	2.116	1110	6.1	
1	M	5	4.7	0.25	6.55	2.097	1100	6.2	
1	M	6	4.7	0.21	6.55	2.102	1180	6.2	
1	N	4	4.7	0.60	6.24	2.045	154	6.2	
1	N	5	4.7	0.61	6.24	2.034	178	6.0	
1	N	6	4.7	0.33	6.24	2.021	336	5.3	
1	O	4	4.7	0.00	6.55	2.113	1664	7.2	
1	O	5	4.7	0.00	6.55	2.120	1612	5.9	
1	O	6	4.7	0.00	6.55	2.102	1763	6.8	
2	H	4	5.7	0.25	6.07	2.092	250	7.5	
2	J	4	5.7	0.03	5.40	2.064	394	5.0	
2	K	4	5.7	0.22	6.07	2.089	675	7.8	
2	K	5	5.7	0.00	4.96	2.058			
2	K	6	5.7	0.00	4.96	2.058			
2	L	4	5.7	0.64	6.07	2.091	230	5.8	
2	L	5	5.7	0.66	5.45	2.049			
2	L	6	5.7	0.66	5.45	2.046			
2	M	4	5.7	0.03	5.40	2.070	495	6.4	
2	M	5	5.7	0.26	4.94	2.038	230	7.5	
2	M	6	5.7	0.28	4.94	2.039	850	9.0	
2	N	4	5.7	0.36	5.40	2.095	380	4.8	
2	N	5	5.7	0.38	5.40	2.089	355	6.5	
2	N	6	5.7	0.38	5.40	2.098	330	5.9	
2	O	4	5.7	0.14	4.99	2.031	336	12.2	
2	O	5	5.7	0.06	4.99	2.032	322	5.0	
2	O	6	5.7	0.06	4.99	1.999	367	4.5	
3	E	4	4.6	4.13	6.22	2.178	225	5.6	520300
3	H	4	5.7	0.00	4.74	2.087	295	5.4	
3	H	5	5.7	0.38	7.23	2.013	0	0.0	
3	H	6	5.7	0.40	7.23	2.025	85	5.5	
3	J	4	4.6	0.14	6.66	2.068	285	7.0	
3	J	5	4.6	0.26	6.42	2.026	230	5.0	
3	J	6	4.6	0.29	6.42	2.019	202	4.5	
3	K	4	4.6	0.00	6.84	2.057	520	6.5	
3	K	5	4.6	0.29	7.23	2.020	1115	9.0	

3	K	6	4.6	0.47	7.23	2.014	1250	8.2	
3	L	4	4.6	1.68	5.50	2.131			852700
3	M	4	4.6	0.00	6.84	2.054	560	5.2	
3	M	5	4.6	0.00	6.84	2.054	600	5.3	
3	M	6	4.6	0.00	6.84	2.052	593	5.4	
3	N	4	4.6	0.93	7.26	2.083	200	7.0	
3	N	5	4.6	0.00	6.22	1.996	422	5.6	373300
3	N	6	4.6	0.43	6.95	2.066	370	13.6	
3	O	4	4.6	0.27	7.30	2.060	855	6.3	
3	O	5	4.6	0.24	7.30	2.047	765	6.8	
3	O	6	4.6	0.28	7.30	2.069	935	7.8	
4	H	4	5.6	0.00	7.25	2.040	371	7.0	
4	H	5	5.6	0.00	5.17	1.987	67	5.5	
4	H	6	5.6	0.02	5.17	1.990	65	5.5	
4	J	4	5.6	0.24	6.80	2.036	466	6.0	
4	J	5	5.6	0.00	5.18	2.013	130	5.0	
4	J	6	5.6	0.00	5.18	2.011	144	5.0	
4	K	4	5.6	0.58	7.25	2.047	635	6.2	
4	K	5	5.6	0.75	7.02	1.998	242	5.5	
4	K	6	5.6	0.83	7.02	2.008	259	6.1	
4	M	4	5.6	0.22	6.80	2.043	670	6.1	
4	M	5	5.6	0.06	6.57	2.044	660	7.4	
4	M	6	5.6	0.00	6.57	2.049	710	8.1	
4	N	4	5.6	0.99	6.26	2.145	146	7.0	
4	N	5	5.6	0.96	6.26	2.143	260	6.0	
4	N	6	5.6	0.88	6.26	2.140	360	5.8	
4	O	4	5.6	0.00	6.57	2.058	910	6.4	
4	O	5	5.6	0.00	6.57	2.063	1045	6.2	
4	O	6	5.6	0.00	6.57	2.058	1000	7.1	
5	H	5	4.7	0.20	5.96	2.069	82	5.7	
5	J	4	4.7	0.07	5.81	2.074	250	5.5	
5	J	5	4.7	0.05	5.81	2.068	225	5.3	
5	K	4	4.7	0.39	6.24	2.063	525	6.0	
5	K	5	4.7	0.31	6.24	2.072	430	5.9	
5	K	6	4.7	0.24	6.24	2.071	375	6.0	
5	M	4	4.7	0.31	6.28	2.089	685	6.6	
5	M	5	4.7	0.10	6.28	2.075	730	6.0	
5	M	6	4.7	0.03	6.28	2.079	760	6.2	
5	N	4	4.7	1.12	6.00	2.112	210	5.6	
5	N	5	4.7	1.03	6.00	2.090	140	6.0	
5	N	6	4.7	1.01	6.00	2.092	175	5.0	
5	O	4	4.7	0.16	6.28	2.082	1025	5.8	
5	O	5	4.7	0.12	6.28	2.086	1080	6.4	
5	O	6	4.7	0.12	6.28	2.084	915	5.8	

Table A3

FREEZE AND THAW

M	C	S	TAC	CWC	MWC	BSG	MI	MS77	MF77	MRB	MRA	MRA/MRB
1	G	7	4.7	1.13	6.98	2.177	3.24	1951	14.0			
1	G	8	4.7	1.69	6.98	2.179	3.28	935	10.0	108900	10200	0.09
1	G	9	4.7	1.31	6.98	2.175	2.90	1581	15.0			
1	H	7	4.7	0.51	6.98	2.149	2.82	2340	12.2			
1	H	8	4.7	0.27	6.98	2.152	3.16	1755	15.0	974800	28800	0.03
1	H	9	4.7	0.42	6.98	2.158	3.27	2600	11.4			
1	I	7	4.7	2.15	6.98	2.204	2.88	992	15.7			
1	I	8	4.7	2.98	6.98	2.146	3.25	875	13.7	54100	6600	0.12
1	I	9	4.7	2.06	6.98	2.207	2.96	545	17.5			
1	J	7	4.7	0.29	6.46	2.125	3.56	2465	11.1			
1	J	8	4.7	0.29	6.46	2.131	3.89	1955	9.5	242400	15100	0.06
1	J	9	4.7	0.22	6.46	2.137	3.38	2808	6.1			
1	K	7	4.7	0.00	6.98	2.154	2.53	5341	7.0			
1	K	8	4.7	0.30	6.98	2.162	2.53	2135	10.4	685500	30300	0.04
1	K	9	4.7	0.27	6.98	2.160	2.31	5995	12.3			
1	L	7	4.7	0.81	6.98	2.181	3.18	2006	12.7			
1	L	8	4.7	0.84	6.98	2.171	3.03	1590	14.2	195600	73600	0.38
1	L	9	4.7	0.92	6.98	2.178	2.82	2180	11.7			
1	M	7	4.7	0.51	7.07	2.141	2.76	3422	11.6			
1	M	8	4.7	0.00	7.07	2.126	2.88	2278	11.8	234900	35500	0.15
1	M	9	4.7	0.00	7.07	2.139	3.16	3379	12.2			
1	N	7	4.7	0.91	6.98	2.185	1.65	4153	11.5			
1	N	8	4.7	0.95	6.98	2.187	1.93	2163	12.3	284900	16900	0.06
1	N	9	4.7	0.86	6.98	2.183	1.78	3902	11.0			
1	O	7	4.7	0.00	7.07	2.131	2.69	4659	6.5			
1	O	8	4.7	0.00	7.07	2.135	2.66	3951	11.0	1072700	123700	0.12
1	O	9	4.7	0.00	7.07	2.134	2.63	5962	12.7			
2	G	7	5.7	0.86	4.86	2.096	4.60	1110	13.7			
2	G	8	5.7	1.77	4.86	2.136	3.42	65	10.0	3100	0	0.00
2	G	9	5.7	1.32	4.86	2.102	1.69	797	19.0			
2	H	7	5.7	0.23	4.86	2.058	5.56	1046	13.0			
2	H	8	5.7	0.17	4.86	2.067	5.98	849	13.0	33600	9500	0.28
2	H	9	5.7	0.23	4.86	2.054	5.12	912	12.2			
2	I	7	5.7	0.64	4.44	2.079	5.54	1152	12.8			
2	I	8	5.7	0.61	4.44	2.069	6.07	775	14.5	103400	4300	0.04
2	I	9	5.7	0.61	4.44	2.069	5.38	984	13.4			
2	J	7	5.7	0.00	4.63	2.049	5.49	2093	10.6			
2	J	8	5.7	0.21	4.63	2.056	5.82	1670	9.9	58400	0	0.00
2	J	9	5.7	0.12	4.63	2.043	5.74	1814	11.8			
2	K	7	5.7	0.14	4.86	2.073	3.14	2986	9.9			
2	K	8	5.7	0.07	4.86	2.076	3.11	1457	11.5	20200	13800	0.68
2	K	9	5.7	0.11	4.86	2.116	3.18	2340	10.5			
2	L	7	5.7	0.60	4.44	2.066	5.37	845	12.0			

2	L	9	5.7	0.62	4.44	2.070	4.32	1018	10.0			
2	M	7	5.7	0.00	4.86	2.022	4.92	1841	10.7			
2	M	8	5.7	0.02	4.86	2.040	4.66	1595	12.0	39200	27800	0.71
2	M	9	5.7	0.00	4.86	2.039	4.33	2208	10.7			
2	N	7	5.7	0.04	4.38	2.122	2.05	2320	9.9			
2	N	8	5.7	0.00	4.38	2.125	2.64	1335	11.7	33500	21600	0.65
2	N	9	5.7	0.01	4.38	2.122	3.33	2535	9.9			
2	O	7	5.7	0.03	4.86	2.025	3.63	1958	9.5			
2	O	8	5.7	0.11	4.86	2.031	5.21	1210	15.0	34100	0	0.00
2	O	9	5.7	0.07	4.86	2.032	5.32	1805	8.4			
3	G	7	4.6	2.33	6.71	2.107	3.42	350	14.2			
3	G	8	4.6	3.34	6.71	2.144	3.01	129	14.0	5600	0	0.00
3	G	9	4.6	2.03	6.71	2.130	3.93	395	14.0			
3	H	7	4.6	0.00	6.71	2.052	5.50	2370	10.0			
3	H	8	4.6	0.02	6.71	2.053	5.69	1230	11.0	173100	19400	0.11
3	H	9	4.6	0.00	6.71	2.059	5.59	1500	12.5			
3	I	7	4.6	1.39	6.53	2.155	4.35	900	9.3			
3	I	8	4.6	2.15	6.53	2.125	4.77	728	13.2	21400	8800	0.41
3	I	9	4.6	1.79	6.53	2.129	3.48	735	10.5			
3	J	7	4.6	0.18	6.54	2.029	5.18	2180	9.3			
3	J	8	4.6	0.14	6.54	2.055	4.93	1830	7.8	73000	26900	0.37
3	J	9	4.6	0.00	6.54	2.031	4.47	2640	10.0			
3	K	7	4.6	0.00	6.54	2.044	3.78	3250	6.8			
3	K	8	4.6	0.00	6.54	2.037	3.68	2480	10.5	130600	58900	0.45
3	K	9	4.6	0.00	6.54	2.034	3.53	2980	10.5			
3	L	7	4.6	1.11	6.77	2.110	3.96	1390	10.1			
3	L	8	4.6	1.21	6.77	2.114	4.52	1186	11.4	56700	0	0.00
3	L	9	4.6	1.22	6.77	2.119	4.32	1206	10.0			
3	M	7	4.6	0.00	6.54	2.013	3.35	3680	10.6			
3	M	8	4.6	0.00	6.54	2.058	2.43	3110	14.7	232900	86200	0.37
3	M	9	4.6	0.00	6.54	2.059	3.07	4670	13.1			
3	N	7	4.6	0.40	6.77	2.093	3.39	2970	10.0			
3	N	8	4.6	0.54	6.77	2.098	3.64	3234	9.2	109700	54300	0.50
3	N	9	4.6	0.34	6.77	2.085	3.40	2395	11.2			
3	O	7	4.6	0.00	6.54	2.030	2.04	4397	11.6			
3	O	8	4.6	0.00	8.34	2.131	2.87	4098	12.0	308300	93300	0.30
3	O	9	4.6	0.00	8.34	2.000	2.71	4320	13.0			
4	G	7	5.6	2.60	6.67	2.161	2.55	931	16.2			
4	G	8	5.6	4.06	6.67	2.164	3.40	185	17.5	4800	0	0.00
4	G	9	5.6	3.89	6.67	2.150	1.31	660	18.7			
4	H	7	5.6	0.35	6.67	2.063	3.07	1500	12.5			
4	H	8	5.6	0.43	6.67	2.063	4.10	1662	8.1	181300	22300	0.12
4	H	9	5.6	0.58	6.67	2.055	4.67	2256	6.3			
4	I	7	5.6	3.02	7.77	2.133	1.69	1336	13.5			
4	I	8	5.6	2.83	7.77	2.158	2.40	535	13.7	10900	10400	0.95
4	I	9	5.6	2.28	7.77	2.188	1.51	1085	18.2			
4	J	7	5.6	0.28	6.57	2.036	4.67	1920	10.0			
4	J	8	5.6	0.43	6.57	2.046	4.63	1827	9.3	87400	21700	0.25
4	J	9	5.6	0.16	6.57	2.057	3.73	2240	10.2			

4	K	7	5.6	0.08	6.67	2.168	1.85	5690	6.8			
4	K	8	5.6	0.02	6.67	2.165	2.28	2300	9.2	367700	69700	0.19
4	K	9	5.6	0.12	6.67	2.140	2.35	4638	9.5			
4	L	7	5.6	1.51	7.77	2.162	3.00	1177	13.0			
4	L	8	5.6	0.85	6.38	2.131	2.61	1004	11.7	32900	17700	0.54
4	L	9	5.6	0.76	6.38	2.151	3.00	1446	11.7			
4	M	7	5.6	0.48	6.67	2.037	2.20	3264	10.1			
4	M	8	5.6	0.43	6.67	2.024	2.84	2510	9.5	132700	56600	0.43
4	M	9	5.6	0.56	6.67	2.022	2.33	2899	10.0			
4	N	7	5.6	1.01	6.26	1.771	2.97	2142	10.0			
4	N	8	5.6	1.01	6.26	1.770	3.11	1387	10.2	28300	16200	0.57
4	N	9	5.6	0.91	6.26	1.758	2.41	1950	10.0			
4	O	7	5.6	0.55	6.67	2.026	3.48	3091	9.7			
4	O	8	5.6	0.10	6.66	2.027	2.56	3024	10.5	182600	80900	0.44
4	O	9	5.6	0.33	6.66	2.024	2.23	3907	10.5			
5	G	7	4.7	2.21	7.41	2.102	3.63	920	13.3			
5	G	8	4.7	2.86	7.41	2.132	3.62	325	14.2	15600	5700	0.37
5	G	9	4.7	1.81	7.41	2.095	3.99	590	14.3			
5	H	7	4.7	0.75	7.41	2.070	4.78	1600	11.0			
5	H	8	4.7	0.14	7.41	2.063	4.48	1180	11.5	246800	12200	0.05
5	H	9	4.7	0.39	7.41	2.067	4.42	1800	11.9			
5	I	7	4.7	3.46	7.41	2.151	2.67	720	16.7			
5	I	8	4.7	4.05	7.41	2.166	3.21	290	14.3	9800	7300	0.74
5	I	9	4.7	3.58	7.41	2.149	2.88	715	16.0			
5	J	7	4.7	0.82	8.06	2.089	4.63	2028	11.5			
5	J	8	4.7	1.10	8.06	2.090	4.02	1355	11.4	82400	19100	0.23
5	J	9	4.7	0.79	8.06	2.081	3.88	1976	13.1			
5	K	7	4.7	0.82	7.41	2.069	2.58	3040	6.2			
5	K	8	4.7	1.01	7.41	2.061	3.07	2510	9.8	256700	46100	0.18
5	K	9	4.7	1.11	7.41	2.071	3.48	3170	10.3			
5	L	7	4.7	1.72	7.41	2.103	1.59	1750	11.2			
5	L	8	4.7	1.93	7.41	2.095	1.87	1080	9.0	36600	7900	0.22
5	L	9	4.7	1.94	7.41	2.092	2.06	2060	11.5			
5	M	7	4.7	0.51	8.05	2.116	3.04	3078	14.7			
5	M	8	4.7	0.62	8.05	2.113	2.74	2314	13.7	192300	26200	0.14
5	M	9	4.7	1.03	8.05	2.119	3.16	3016	13.8			
5	N	7	4.7	1.68	7.41	2.087	2.13	2980	10.3			
5	N	8	4.7	1.73	7.41	2.081	1.66	1685	9.8	66700	15100	0.23
5	N	9	4.7	1.78	7.41	2.069	1.77	2725	10.7			
5	O	7	4.7	0.81	8.05	2.121	2.66	4940	13.5			
5	O	8	4.7	0.78	8.05	2.107	2.29	3260	12.0	606200	71800	0.12
5	O	9	4.7	0.71	8.05	2.107	2.13	5169	13.4			

Table A4

Water Absorption

M	C	S	TAC	CWC	MWC	BSG	MI1	MI2	MI3	MI4	MS77	MF77	MRB	MRA	MRA/MRB
1	G	10	4.7	0.54	6.29	2.010	4.67	6.94	7.69						
1	G	11	4.7	0.69	6.29	2.011	2.68	3.46	3.77	3.96	754	6.6	13200	4000	0.30
1	G	12	4.7	0.37	6.29	2.008	4.51	6.32	6.91	7.34	691	10.0			
1	H	10	4.7	0.04	5.60	2.043	4.24	5.80	6.21	6.48	1142	10.4			
1	H	11	4.7	0.19	5.60	2.044	3.84	5.11	5.39	5.60	1032	6.9	91400	10400	0.11
1	H	12	4.7	0.11	5.60	2.008	5.01	6.66	7.13	7.41	865	10.7			
1	I	10	4.7	4.35	6.67	2.096									
1	I	11	4.7	4.45	6.67	2.117	4.05						6900	0	0.00
1	I	12	4.7	3.85	6.67	2.103									
1	J	10	4.7	1.24	5.83	2.014	3.98	6.32	7.44						
1	J	11	4.7	2.02	5.83	2.025	4.75						12400	0	0.00
1	J	12	4.7	1.37	5.83	2.011	5.36	6.47	7.36						
1	K	10	4.7	0.00	5.60	2.062	2.41	4.36	4.77	5.19	2235	9.5			
1	K	11	4.7	0.00	5.60	2.058	1.65	3.57	4.84	5.23	2000	7.5	144200	32400	0.23
1	K	12	4.7	0.00	5.60	2.092	1.39	3.11	4.31	4.60	2575	8.8			
1	L	10	4.7	2.49	6.57	2.070	4.26	5.72	8.41						
1	L	11	4.7	3.24	6.57	2.087	3.66	4.94					12300	0	0.00
1	L	12	4.7	2.35	6.57	2.072	4.14	5.68	6.61						
1	M	10	4.7	0.07	5.91	2.011	2.33	4.33	4.70	5.04	2410	10.3			
1	M	11	4.7	0.02	5.91	2.010	1.22	2.93	3.85	4.26	2323	8.4	184100	38800	0.21
1	M	12	4.7	0.01	5.91	2.007	2.12	3.90	4.63	4.96	2515	10.0			
1	N	10	4.7	0.42	6.57	2.026	2.53	3.66	4.30	4.45	2139	9.8			
1	N	11	4.7	0.49	6.57	2.024	1.88	3.13	3.70	3.81	1882	7.2	61900	17200	0.28
1	N	12	4.7	0.55	6.57	2.029	2.33	4.36	4.87	4.99	1877	9.5			
1	O	10	4.7	0.05	5.91	2.009	1.40	3.01	3.93	4.29	2909	11.6			
1	O	11	4.7	0.11	5.91	2.008	1.06	2.25	2.88	3.15	3149	8.9	271200	56600	0.21
1	O	12	4.7	0.06	5.91	2.012	1.32	3.20	3.63	3.97	3043	11.2			
2	H	10	5.7	0.09	4.42	2.009	6.48	6.99	7.10	7.10	1004	8.8			
2	H	11	5.7	0.09	4.42	2.007	5.18	5.79	5.81	5.94	767	8.4	21300	6600	0.31
2	H	12	5.7	0.09	4.42	2.000	6.52	7.00	7.38	7.41	884	9.2			
2	I	10	5.7	1.73	4.13	2.051									
2	I	11	5.7	1.93	4.13	2.067							12500	0	0.00
2	I	12	5.7	1.72	4.13	2.056									
2	J	10	5.7	0.66	4.25	1.977	5.85	6.96	7.51	7.39	654	12.5			
2	J	11	5.7	0.86	4.25	1.983	5.44	6.21					17000	0	0.00
2	J	12	5.7	0.77	4.25	1.998	5.46	7.20	7.46	7.51	700	12.0			
2	K	10	5.7	0.16	4.29	2.014	5.51	6.61	6.97	7.06	1395	10.0			
2	K	11	5.7	0.12	4.29	2.019	4.25	5.12	5.58	5.76	1000	11.2	41800	11200	0.27
2	K	12	5.7	0.14	4.29	2.018	5.70	6.33	6.44	6.79	1562	10.3			
2	L	10	5.7	1.13	5.04	2.067					874	8.75			
2	L	11	5.7	1.13	5.04	2.059	3.13	5.09	5.29	5.69	721	8.5	39300	10400	0.26
2	L	12	5.7	0.80	5.04	2.055					1022	8.9			
2	M	10	5.7	0.25	4.94	2.040	3.10	5.33	5.91	6.15	2122	8.7			

2	M	11	5.7	0.55	4.94	2.028	3.61	5.48	6.10	6.14	1824	9.6	27600	11400	0.41
2	M	12	5.7	0.05	4.42	2.003	3.50	4.59	4.95	5.17	1265	7.4			
2	N	10	5.7	0.25	5.04	2.042	2.59	4.16	4.76	4.95	2112	9.7			
2	N	11	5.7	0.38	5.04	2.048	2.11	3.62	3.97	4.03	1776	6.8	67600	14500	0.21
2	N	12	5.7	0.48	5.04	2.056	2.36	4.64	5.26	5.33	1718	9.1			
2	O	10	5.7	0.01	4.42	2.021	3.27	4.84	5.54	5.47	2093	10.2			
2	O	11	5.7	0.06	4.42	2.024	2.59	3.82	4.40	4.61	1716	7.5	32200	20600	0.64
2	O	12	5.7	0.06	4.42	2.057	3.67	4.05	4.78	4.77	2822	11.7			
3	F	10	4.6	2.27	8.00	2.095	2.31	3.69	3.96	4.05	442	13.2			
3	H	10	4.6	0.71	7.34	2.091	2.40	4.44	4.90	4.86	2252	10.1			
3	H	11	4.6	0.00	6.84	2.045	3.63				3120	10.0			
3	H	12	4.6	0.26	8.51	2.039	2.97	4.87	5.11	5.36	1480	9.7	61900	17400	0.28
3	I	10	4.6	1.54	6.66	2.105	3.37	5.08	5.45	5.77	614	9.8			
3	I	11	4.6	1.11	6.66	2.084	4.52				890	8.1			
3	J	10	4.6	0.55	8.00	2.094	1.84	3.75	4.36	4.57	2220	14.4			
3	J	11	4.6	0.00	6.84	2.070	1.98	4.01		4.60	2465	9.5			
3	J	12	4.6	0.00	6.84	2.063	2.03	4.03	4.65	4.75	1924	9.5			
3	K	10	4.6	0.37	7.34	2.065	2.03	3.25	3.76	3.90	2756	10.0			
3	K	11	4.6	0.13	6.54	2.023	1.70	2.95	3.64	3.70	2645	10.0			
3	K	12	4.6	0.21	6.54	2.026	2.32	3.96	4.81	4.87	2440	9.5			
3	L	11	4.6	3.42	6.33	2.090							9100	0	0.00
3	M	10	4.6	1.19	8.00	2.110	0.98	1.91	2.55	2.79	2889	11.0			
3	M	11	4.6	0.00	6.84	2.045	2.33	4.310		4.58	2735	10.6			
3	M	12	4.6	0.00	6.84	2.068	1.63	3.11	4.04	4.20	2730	10.9			
3	N	10	4.6	0.92	7.26	2.082	2.13	4.28	4.97	5.20	1225	7.5			
3	N	11	4.6	0.73	7.26	2.079	1.96				1875	9.2			
3	N	12	4.6	0.44	6.33	2.033	1.75	4.06	4.45	4.74	1968	6.9	74700	19000	0.25
3	O	10	4.6	0.19	7.26	2.065					2808	9.3	510600	0	0.00
3	O	11	4.6	0.21	7.26	2.060	0.73	1.52	2.33	2.52	3830	10.6			
3	O	12	4.6	0.36	7.26	2.064	0.73	1.76	2.32	2.44	3775	10.5			
4	G	10	5.6	3.49	7.25	2.121	4.87				200	9.0			
4	G	11	5.6	0.20	5.47	2.003	4.88	6.46	6.97	7.04	625	6.7	20500	4900	0.24
4	G	12	5.6	0.24	5.47	2.002	4.96	6.82	7.39	7.33	642	11.2			
4	H	10	5.6	0.22	6.31	1.919	4.09	5.83	6.43	6.49	917	9.9			
4	H	11	5.6	0.18	6.31	2.029	2.90	4.54	4.82	5.05	1008	7.3	50900	16200	0.32
4	H	12	5.6	0.23	6.31	2.024	3.70	5.80	6.24	6.42	1032	9.5			
4	I	10	5.6	1.66	7.25	2.082	3.51				380	11.5			
4	I	11	5.6	3.53	5.91	2.056					474	9.7	6600	0	0.00
4	I	12	5.6	3.33	5.91	2.059									
4	J	10	5.6	1.19	6.82	2.001	4.22	5.78	6.15	6.15	1400	9.3			
4	J	11	5.6	1.18	6.82	2.001	2.62	4.64	5.00	5.19	1218	7.5	31400	11600	0.37
4	J	12	5.6	1.04	6.82	2.000	3.63	5.22	5.97	6.36	1535	9.7			
4	K	10	5.6	0.15	6.44	1.980	2.07	5.38	5.67	5.89	2120	9.9			
4	K	11	5.6	0.13	6.44	1.980	2.27	4.20	5.08	5.48	1762	7.5	98800	29100	0.29
4	K	12	5.6	0.02	6.44	1.980	2.27	4.68	5.40	5.74	2130	11.6			
4	L	10	5.6	0.00	7.25	2.043	1.72				2000	18.5			
4	L	11	5.6	1.60	5.92	2.051	3.62	5.04	5.32	5.44	720	7.0	27000	4200	0.16
4	L	12	5.6	1.68	5.92	2.057	5.21	7.57	8.49	8.88	562	13.2			
4	M	10	5.6	0.00	5.18	2.012	1.59	3.54	3.93	4.17	2198	12.1			

4	M	11	5.6	0.00	5.18	2.008							155100	0	0.00
4	M	12	5.6	0.00	5.18	2.020	1.71	2.90	3.83	4.09	2400	11.5			
4	N	10	5.6	0.54	5.92	2.019	2.32	4.51	5.18	5.35	1704	9.7			
4	N	11	5.6	0.51	5.92	2.024	2.06	4.53	4.89	5.24	1747	6.8	68000	12800	0.19
4	N	12	5.6	0.33	5.92	2.016	1.75	3.48	4.24	4.64	2026	10.1			
4	O	10	5.6	0.00	6.22	2.025	1.47	2.97	3.51	3.86	3264	10.5			
4	O	11	5.6	0.00	6.22	2.028	1.17	2.48	3.43	3.85	3302	8.7	348300	60700	0.17
4	O	12	5.6	0.00	6.22	2.022	1.11	2.19	3.20	3.57	3494	10.6			
5	H	10	4.7	0.07	6.39	2.064	2.90	4.76	5.33	5.54	1335	10.5			
5	H	11	4.7	0.00	6.39	2.065	2.49	4.22	4.44	4.54	1520	7.9	90100	19600	0.22
5	M	10	4.7	0.22	6.03	2.070	2.04	3.48	4.27	4.19	2600	6.5			
5	M	11	4.7	0.19	6.03	2.064	1.03	2.87	4.28		2585	8.8	146500	47100	0.32
5	M	12	4.7	0.58	6.03	2.083	1.31	3.23	3.89	3.89	2940	10.2			
5	O	10	4.7	0.23	6.03	2.061	1.98	3.33	4.21	4.03	3175	10.2			
5	O	11	4.7	0.23	6.03	2.076	0.91	2.19	3.00	3.23	3275	8.6	191500	76200	0.40
5	O	12	4.7	0.19	6.03	2.067	1.51	2.52	3.31	3.22	3485	10.7			

Table A5

VACUUM SATURATION

M	C	S	TAC	CWC	MWC	BSG	MI	MS77	MF77	MRB	MRA	MRA/MRB
1	G	13	4.7	0.33	6.30	2.020	9.24	1126	8.0			
1	G	14	4.7	0.45	6.30	2.034	9.94	581	6.0	47600	5900	0.12
1	G	15	4.7	0.34	6.30	2.029	9.10	1022	8.0			
1	H	13	4.7	0.00	5.60	2.046	9.19	1459	8.7			
1	H	14	4.7	0.00	5.60	2.049	9.22	1118	6.6	111500	20700	0.19
1	H	15	4.7	0.00	5.60	2.049	9.21	1416	8.8			
1	J	13	4.7	1.65	5.83	2.018	5.28	572	7.2	18400	4100	0.22
1	J	14	4.7	2.61	5.83	2.032						
1	J	15	4.7	1.62	5.83	2.025	5.17	526	9.5	13900	3600	0.26
1	K	13	4.7	0.15	7.07	2.133	7.66	3973	11.0			
1	K	14	4.7	0.26	7.07	2.132	7.42	2236	7.3	591600	53200	0.09
1	K	15	4.7	0.43	7.07	2.141	7.56	4113	11.2			
1	L	13	4.7	2.01	5.60	2.113						
1	L	14	4.7	1.94	5.60	2.115		1987	15.0	23400	13400	0.57
1	L	15	4.7	1.87	5.60	2.110						
1	M	13	4.7	0.41	5.96	2.056	8.30	3139	9.8			
1	M	14	4.7	0.54	5.96	2.063	8.52	1968	12.8	292500		
1	M	15	4.7	0.53	5.96	2.057	8.28	3091	9.5			
1	N	13	4.7	1.36	5.60	2.099	7.78	763	7.9			
1	N	14	4.7	1.11	5.60	2.089	7.76	610	12.2			
1	N	15	4.7	0.76	5.60	2.080	8.12	1160	8.5			
1	O	13	4.7	0.18	5.96	2.061	8.45	3975	9.8			
1	O	14	4.7	0.24	5.96	2.069	8.40	2015	4.7			
1	O	15	4.7	0.17	5.96	2.066	8.32	3730	9.7			
2	G	13	5.7	0.04	4.90	2.061	9.18	912	8.1			
2	G	14	5.7	0.25	5.13	2.013	9.55	865	7.7			
2	G	15	5.7	0.27	5.13	2.010	9.55	945	8.6			
2	H	13	5.7	0.33	6.07	2.083	8.42	2045	7.7			
2	H	14	5.7	0.00	4.42	2.006	6.25	632	5.7	23500	9300	0.40
2	H	15	5.7	0.11	4.42	2.001	9.76	1167	8.7			
2	J	13	5.7	0.66	4.25	1.997	6.11	587	11.0	19200	3900	0.20
2	J	14	5.7	0.83	4.25	2.006	9.36	481	13.0			
2	J	15	5.7	0.54	4.25	2.013	9.09	512	7.3	19700	4100	0.21
2	K	13	5.7	0.09	4.42	2.059	9.04	2323	9.7			
2	K	14	5.7	0.09	4.42	2.057	8.95	1296	6.7	49100	12900	0.26
2	K	15	5.7	0.05	4.42	2.053	9.32	2246	9.2			
2	L	13	5.7	1.05	4.38	2.044						
2	L	14	5.7	0.97	4.38	2.046	7.06	939	11.6			
2	L	15	5.7	0.82	4.38	2.017	8.95	433	22.2			
2	M	13	5.7	0.07	4.42	2.048	9.48	2112	9.3			
2	M	14	5.7	0.17	4.42	2.052	8.34	1320	9.2	44100	20100	0.46
2	M	15	5.7	0.20	4.42	2.058	8.62	2323	9.3			
2	N	13	5.7	1.88	4.31	2.069	7.58	823	9.7			

2	N	14	5.7	0.50	4.31	2.044	8.73	684	9.0	22300	7900	0.35
2	N	15	5.7	0.35	4.31	2.038	9.10	1204	9.2			
2	O	13	5.7	0.35	5.42	2.058	9.11	2587	9.4			
2	O	14	5.7	0.33	5.42	2.059	9.05	1430	13.7	166600	21700	0.13
2	O	15	5.7	0.26	5.42	2.067	8.99	3160	9.5			
3	G	13	4.6	0.18	5.91	2.083	9.25	1085	8.3			
3	G	14	4.6	0.00	6.22	2.086	7.84	1118	8.7			
3	G	15	4.6	0.49	6.22	2.097						
3	H	13	4.6	0.24	8.51	2.033	9.98	1935	12.5			
3	H	14	4.6	0.00	6.22	2.067	8.51	1245	7.2	73600	16100	0.22
3	H	15	4.6	0.00	6.22	2.082	3.98	1550	7.6			
3	I	13	4.6	0.41	6.22	2.003	10.1	931	8.8			
3	I	14	4.6	2.05	6.22	2.085	7.86	230	16.0	16500	7300	0.44
3	I	15	4.6	1.91	6.22	2.096						
3	J	13	4.6	0.00	6.92	2.039	3.38	2682	7.5	520100	9500	0.02
3	J	14	4.6	0.00	6.92	2.028	1.69	3000	7.0	61900		
3	K	13	4.6	0.28	5.91	2.082	3.23	3280	10.4			
3	K	14	4.6	0.05	5.91	2.090	8.62	1620	6.8	95900	27700	0.29
3	K	15	4.6	0.00	6.22	2.057	8.71	3620	11.7			
3	L	13	4.6	0.56	6.22	2.048	10.2	1762	8.4			
3	L	14	4.6	0.45	6.22	2.051	8.28	1426	8.0	34200	9600	0.28
3	L	15	4.6	0.33	6.22	2.055	10.25	2170	9.8			
3	M	13	4.6	0.00	6.92	2.023	2.59	3975	12.5	524800		
3	M	14	4.6	0.00	6.92	2.020	9.98	1435	6.8	53100	21900	0.41
3	M	15	4.6	0.00	6.92	2.023	10.2	3015	12.5			
3	N	13	4.6	0.00	7.02	2.043	2.09	1830	9.0	59000	18300	0.31
3	N	14	4.6	0.13	6.22	2.040	8.82	2122	11.8	26500	22900	0.87
3	N	15	4.6	0.12	6.22	2.036	8.65	3379	10.5			
3	O	13	4.6	0.41	6.92	2.036	10.7	3035	10.2	68300	46900	0.69
3	O	14	4.6	0.37	6.92	2.022	10.1	1517	9.0	136100	35000	0.26
3	O	15	4.6	0.22	6.92	2.019	2.41	4445	11.8			
4	G	13	5.6	0.32	6.60	2.048	9.51	1105	7.5			
4	G	14	5.6	0.06	6.39	1.996	10.05	1286	7.7			
4	G	15	5.6	0.09	6.39	2.003	9.71	1186	7.7			
4	H	13	5.6	0.14	7.25	2.042	8.73	2285	10.5			
4	H	14	5.6	0.31	6.31	2.040	8.69	859	5.7	64900	18500	0.29
4	H	15	5.6	0.46	6.31	2.038	4.46	1824	11.4			
4	I	13	5.6	0.56	6.23	1.996	10.2	791	10.5			
4	J	13	5.6	0.45	5.47	2.018	9.77	970	7.9			
4	J	14	5.6	0.57	5.47	2.026	3.35	826	7.2	37700	13200	0.35
4	J	15	5.6	0.61	5.47	2.017	9.83	744	7.8			
4	K	13	5.6	0.49	6.36	2.069	8.94	3390	9.5			
4	K	14	5.6	0.59	6.36	2.059	9.21	1770	6.1	277600	44700	0.16
4	K	15	5.6	0.56	6.36	2.061	9.13	3100	9.7			
4	L	13	5.6	2.14	6.33	2.070	8.44	336	12.7			
4	L	14	5.6	2.39	6.33	2.072	7.45	197	16.7			
4	L	15	5.6	1.71	6.33	2.058	8.42	518	10.7			
4	M	13	5.6	0.40	6.36	2.065	9.01	3090	10.3			
4	M	14	5.6	1.79	6.36	2.072	9.15	2010	6.7	420700	72800	0.17

4	M	15	5.6	1.28	6.36	2.076	9.01	3370	9.4			
4	N	13	5.6	1.32	6.33	2.046	8.44	734	8.8			
4	N	14	5.6	1.21	6.33	2.026	8.85	662	12.2			
4	N	15	5.6	0.89	6.33	2.042	8.97	1152	8.4			
4	O	13	5.6	0.44	6.36	2.070	8.98	3780	9.4			
4	O	14	5.6	0.41	6.36	2.062	9.14	2180	5.8	365600	60300	0.16
4	O	15	5.6	0.33	6.36	2.065	9.11	3850	9.3			
5	K	13	4.7	0.27	6.24	2.060	9.1	2450	9.2			
5	K	14	4.7	0.28	6.24	2.084	8.34	1510	12.7	196700	47800	0.24
5	M	13	4.7	0.00	5.07	2.048	8.86	2698	9.5			
5	M	14	4.7	0.00	5.07	2.052	8.60	1995	13.3	290300	59400	0.20
5	M	15	4.7	0.00	5.07	2.056	8.59	2970	10.5			
5	O	13	4.7	0.00	5.07	2.059	8.75	3270	8.9			
5	O	14	4.7	0.00	5.07	2.072	8.36	2170	13.9	395900	96800	0.24
5	O	15	4.7	0.00	5.07	2.048	8.90	2995	9.0			

M - Foamed asphalt mix type
C - Curing condition
S - Specimen number
TAC - True asphalt cement content (% by mix)
CWC - Cured water content (% by mix)
MWC - Molded water content (% by mix)
BSG - Bulk specific gravity
MS77 - Marshall stability at 77 deg. F (lbs.)
MF77 - Marshall flow at 77 deg. F (0.01 inches)
MRB - Resilient modulus at 77 deg. F before treatment (psi)
MRA - Resilient modulus at 77 deg. F after treatment (psi)
MS140 - Marshall stability at 140 deg. F (lbs)
MF140 - Marshall flow at 140 deg. F (0.01 inches)
MI - Moisture increase (% by cured wt.)
MI1 - Moisture increase after 1 hour (% by cured wt.)
MI2 - Moisture increase after 1 day (% by cured wt.)
MI3 - Moisture increase after 3 days (% by cured wt.)
MI4 - Moisture increase after 4 days (% by cured wt.)

APPENDIX B: PROPERTIES OF CORE SAMPLES

Appendix B

Properties of Core Samples

Month	Section	Core	Lift	BSG	MS77	MF77	Mr	WC
1	1	1	T	2.147	1768	10.1	30000	
1	1	1	B	2.179	2182	10.8	39000	
1	1	2	T	2.198	2850	9.5	96000	
1	1	2	B	2.224	2043	12.9	27000	
1	1	3	T	2.163	1939	15.0		0.91
1	1	3	B	2.271	2447	14.2		0.91
1	1	4	T	2.202	2995	10.3		3.05
1	1	4	B	2.203	2254	11.5		3.05
1	4	1	T	2.139	1877	9.7	38000	
1	4	1	B	2.203	1891	7.2	35000	
1	4	2	T	2.107	2894	11.4		
1	4	2	B	2.180	2866	11.0		
1	4	3	T	2.013	1104	11.5	35000	
1	4	3	B	2.225	2016	7.6	57000	
1.5	1	1	T	2.191	897	11.9	12000	
1.5	1	1	B	2.241	895	9.0	11000	
1.5	1	2	T	2.206	2121	13.2	41000	
1.5	1	2	B	2.204	845	11.9	9000	
1.5	1	3	T	2.147	1380	12.8		0.91
1.5	1	3	B	2.207	2484	10.0		0.91
1.5	1	4	T	2.206	2371	12.2		
1.5	1	4	B	2.196	1872	11.3		
1.5	3	1	T	2.208	326	13.3	76000	5.54
1.5	3	1	B	2.198	1186	14.0		5.54
1.5	4	1	T	2.122	333	7.5	32000	4.88
1.5	4	1	B	2.208	912	10.1	15000	4.88
1.5	4	2	T	2.121	2182	8.8		1.91
1.5	4	2	B	2.206	1947	12.1		1.91
1.5	4	3	T	2.062	985	9.0	28000	
1.5	4	3	B	2.165	1249	8.8	34000	
1.5	5	1	T	2.165	1227	17.4		6.63
1.5	5	2	T	2.196	1379	13.6	43000	
1.5	5	2	B	2.297	626	7.5		
1.5	6	1	T	2.150	1253	15.0		3.89
1.5	6	2	T	2.141	1320	13.0		
1.5	6	2	B	2.049	178	6.0		
1.5	6	3	T	2.278	7809	10.2		
1.5	6	3	B	2.190	1121	7.9		
1.5	6	4	T	2.151	1795	10.7	43000	5.44
1.5	6	4	B	2.162				5.44
1.5	6	5	T	2.182	960	8.7	9700	5.30
1.5	6	5	B	2.251	650	14.1	8400	5.30
1.5	7	1	T	2.137	188	5.2		3.64
1.5	7	1	B	2.141	650	8.7	8100	3.64

1.5	7	2	T	2.160				2.50
1.5	7	2	B	2.252	405	11.5	4700	2.50
1.5	7	3	T	2.077	725	18.4		1.10
1.5	7	3	B	2.079	143	5.1		1.10
1.5	7	4	T	2.208	1650	11.9		
1.5	7	4	B	2.187	1367	10.5		
1.5	8	1	T	2.181	515	7.5	16000	3.84
1.5	8	1	B	2.131	439	12.0		3.84
1.5	8	2	T	2.120	814	11.5		3.36
1.5	8	3	T	2.182	544	17.5		4.75
1.5	8	4	T	2.191	608	10.5	9800	4.41
1.5	8	4	B	2.182	350	8.7	4800	4.41
1.5	8	5	T	2.198	1848	11.2		
1.5	8	5	B	2.207	808	9.8		
1.5	8	6	T	2.163	305	7.8		6.87
1.5	8	6	B	2.152	375	10.6		6.87
1.5	9	1	T	2.192	278	7.5	16000	7.88
1.5	9	1	B	2.265	1286	13.8	17000	7.88
1.5	9	2	T	2.174	333	8.0	15000	7.16
1.5	9	2	B	2.313	1540	10.1	16000	7.16
8	1	1	T	2.168	4242	10.3	63100	
8	1	1	B	2.167	3331	13.5	76200	
8	1	2	T	2.179	1150	13.0		
8	1	2	B	2.154	1125	8.5		
8	1	3	T	2.214	2541	7.5		
8	1	3	B	2.199	1667	8.2		
8	1	4	T	2.181	2051	9.7		
8	1	4	B	2.169	1647	8.7		
8	1	5	T	2.195	2038	12.0		
8	1	5	B	2.235	1824	12.5		
8	1	6	T	2.185	2554	14.3		
8	1	6	B	2.190	2054	10.5		
8	2	1	T	2.182	1251	21.0		
8	2	1	B	2.197	306	17.0		
8	4	1	T	2.119	835	12.5		
8	4	1	B	2.196	875	14.0		
8	4	2	T	2.144	653	12.8	13300	
8	4	2	B	2.084	348	7.0	18800	
8	4	3	T	2.140	788	5.5		
8	4	3	B	2.235	901	11.0		
8	4	4	T	2.129	824	9.0		
8	4	4	B	2.208	850	7.5		
8	4	5	T	2.049	1152	11.7	32600	
8	4	5	B	2.150	1135	12.0	25300	
8	4	6	T	2.172	511	14.0		
8	4	6	B	2.216	1169	11.0		
8	5	2	T	2.150	451	9.0		
8	5	3	T	2.212	967	10.5		
8	5	4	T	2.142	937	14.0		
8	5	4	B	2.242	636	9.0		
8	5	5	T	2.163	700	20.0		
8	5	6	T	2.128	882	10.5	21400	

8	6	1	T	2.059	875	11.5		5.4
8	6	1	B	2.067	1946	11.5		5.4
8	6	2	B	2.196	985	9.0		
8	6	3	T	2.146	1549	14.0		
8	6	4	B	2.160	1820	9.7		
14.5	1	1	T	2.155	6136	8.0		.2
14.5	1	1	B	2.197	6612	11.5		.2
14.5	1	2	T	2.195	2444	30.0		.8
14.5	1	2	B	2.167	4646	16.0		.5
14.5	1	3	T	2.176	6847	15.0	159850	.2
14.5	1	3	B	2.166	4938	11.0	88300	.4
14.5	1	4	T	2.190	7144	16.0		.2
14.5	1	5	T	2.199	3256	13.5		1.0
14.5	1	5	B	2.171	4472	17.0		.6
14.5	4	1	T	2.150	1000	25.0		2.0
14.5	4	1	B	2.228				
14.5	4	2	T	2.208	2772	14.0	34850	.8
14.5	4	2	B	2.138	3127	8.0		1.1
14.5	4	3	T	2.298	2184	15.0	14950	.9
14.5	4	3	B	2.163	2975	12.5	22500	1.1
14.5	4	4	T	2.137	7104	15.5		.3
14.5	4	4	B	2.240	5450	14.0		.4
14.5	4	5	T	2.085	3822	10.0	53300	.1
14.5	4	6	T	2.206	5320	13.0		.3
14.5	5	1	T	2.207				
14.5	5	2	T	2.200	1872	13.5		1.2
14.5	5	2	B	2.263	1548	13.5		2.3
14.5	5	3	B	2.242				
14.5	5	4	B	2.229	1520	12.5		2.9
14.5	5	6	T	2.135	3496	17.0		1.1
14.5	5	6	B	2.194	1104	11.5	17650	1.8
14.5	7	1	T	2.179				
14.5	7	1	B	2.127				
14.5	7	2	T	2.143	916	14.0		.9
14.5	7	3	T	2.138				
14.5	7	3	B	2.235	1213	7.5		3.0
14.5	7	4	T	2.221	2252	11.0		2.3
14.5	7	4	B	2.222	1677	6.0		1.7
14.5	7	5	T	2.179	1545	4.5		1.5
14.5	7	5	B	2.165	1874	7.0		1.9
14.5	7	6	T	2.228	5875	12.5		.6
14.5	7	6	B	2.179	3121	6.5		1.2

APPENDIX C: SAMPLE COMPUTER INPUT AND OUTPUT FOR RUN NO. 3

```
TYPE B:FOAM3.INP
    1    1    0
 MUSCATINE FOAM, TRIAL 3
    2    7    0          300
    4500.0    70.0000      13.50
 24.0 25.0 14.0 27.0 42.0 48.0 61.0 69.0 65.0 55.0 48.0 41.0
 17.0 28.0 30.0 32.0 48.0 49.0 56.0 56.0 65.0 72.0 76.0 81.0
20      .35     4.00     0.00    15.70     9.70      .00       .00       .00
  2460000.   2050000.   1968000.   1845000.   1271000.   1230000.   1025000.   1025000.
   615000.    410000.    369000.    307500.
40      .45      .00
     4500.      4500.     27300.     50000.      1400.      2100.      2900.      3700.
     4500.      4500.      4500.      4500.
    18.400   .004325    3.2910    .854000    4.8400    .690000
.13650E-08.44770E+01
0
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DDDDDDDD          AAAAA        MMM     MMM         AAAAA
 DDDDDDDDD        AAAAAAA       MMMM   MMMM        AAAAAAA
 DD      DDD     AAA   AAA      MMMMM MMMMM       AAA   AAA
 DD        DDD  AAA       AAA   MM MMMMM MM      AAA       AAA
 DD         DD  AAA       AAA   MM   MMM   MM    AA         AA
 DD         DD  AA         AA   MM         MM    AA         AA
 DD         DD  AAAAAAAAAAA     MM         MM    AAAAAAAAAAA
 DD         DD  AAAAAAAAAAA     MM         MM    AAAAAAAAAAA
 DD        DDD  AA         AA   MM         MM    AA         AA
 DDDDDDDDD      AA         AA   MM         MM    AA         AA
 DDDDDDDD       AA         AA   MM         MM    AA         AA
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THIS PROGRAM WAS DEVELOPED FOR THE ASPHALT INSTITUTE

BY PROF. M. W. WITCZAK AND DAEKYOO HWANG.
(REVISED APRIL 1983 BY ROSEMARY ALLENDER)

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THE ASPHALT INSTITUTE BLDG.
COLLEGE PARK, MARYLAND 20740

TELEPHONE (301) 277-4258

DAMA USES THE CHEVRON N-LAYER PROGRAM AS THE ANALYTICAL STRESS-STRAIN-DISPLACEMENT MODEL.

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**************************************************
*                                                *
* ALL REASONABLE CARE HAS BEEN TAKEN IN THE      *
* PREPARATION OF THIS COMPUTER PROGRAM, DAMA,    *
* AND THE USER'S MANUAL; HOWEVER, THE ASPHALT    *
* INSTITUTE CAN ACCEPT NO RESPONSIBILITY FOR     *
* THE CONSEQUENCES OF ANY INACCURACIES WHICH THEY*
* MAY CONTAIN, NOR THEIR SUITIBILITY OR UTILITY  *
* FOR USE IN ANY SPECIFIC SET OF CIRCUMSTANCES.  *
*                                                *
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***** NOTE *****

THE COMPUTER PROGRAM, DAMA, WAS WRITTEN FOR USE WITH U.S. CUSTOMARY UNITS OF MEASUREMENTS, UNLESS OTHERWISE STATED FOR A SPECIFIC INPUT VARIABLE.

MUSCATINE FOAM, TRIAL 3

LAYER AND MATERIAL PROPERTIES

LAYER NUMBER	MATERIAL TYPE	POISSON'S RATIO	THICKNESS (IN)
1	ASPH. CONC.	.35	4.00
2	SUBGR. SOIL	.45	

CURING CONDITIONS

LAYER NUMBER	MATERIAL TYPE	CURE TIME (MONTHS)	MONTH OPENED TO TRAFFIC	MONTHS CURED BEFORE OPENING
1	ASPH. CONC.	.0	JULY	0

TRAFFIC CONDITION

NUMBER OF REPETITIONS PER MONTH 300

ENVIRONMENTAL CONDITIONS
(MEAN MONTHLY AIR TEMPERATURES, DEG. F)

JAN.	FEB.	MAR.	APR	MAY	JUNE	JULY	AUG.	SEPT	OCT.	NOV.	DEC.
24.0	25.0	14.0	27.0	42.0	48.0	61.0	69.0	65.0	55.0	48.0	41.0

LOAD CONFIGURATION AND COMPUTATIONAL POINTS

LOAD PER TIRE = 4500. LBS
CONTACT PRESSURE = 70.00 PSI
RADIUS OF LOAD = 4.52 IN
LOAD SPACING = 13.50 IN

COMPUTATIONAL POINT 1 X = 0.0 IN (CENTER OF ONE TIRE)
COMPUTATIONAL POINT 2 X = 4.52 IN (EDGE OF ONE TIRE)
COMPUTATIONAL POINT 3 X = 6.75 IN (MIDPOINT OF TWO TIRES)

MODULI CONDITIONS

ASPHALT STABILIZED LAYER

LAYER NUMBER	MATERIAL TYPE	POINT NUMBER	TEMP. (DEG. F)	MODULUS EI (PSI)	MODULUS EF (PSI)
1	ASPH. CONC.				
		1	17.0	2460000.	
		2	28.0	2050000.	
		3	30.0	1968000.	
		4	32.0	1845000.	
		5	48.0	1271000.	
		6	49.0	1230000.	
		7	56.0	1025000.	
		8	56.0	1025000.	
		9	65.0	615000.	
		10	72.0	410000.	
		11	76.0	369000.	
		12	81.0	307500.	

SUBGRADE LAYER

LAYER NUMBER	MATERIAL TYPE	MONTH	MODULUS (PSI)
2	SUBGR. SOIL		
		JAN.	4500.
		FEB.	4500.
		MAR.	27300.
		APR	50000.
		MAY	1400.
		JUNE	2100.
		JULY	2900.
		AUG.	3700.
		SEPT	4500.
		OCT.	4500.
		NOV.	4500.
		DEC.	4500.

DAMAGE MODELS

FATIGUE DAMAGE   NF = (F0   ) * (F1) * (10**M) * (ET)**(-F2) * (MOD)**(-F3)

WHERE

NF IS LOAD REPETITIONS TO FAILURE
F0 IS DISTRESS TO PERFORMANCE FACTOR
10**M IS MIX FACTOR (M= F4*(VB/(VB+VV)-F5)

VV IS VOLUME OF VOIDS IN ASPHALT MIX (PERCENT)
VB IS VOLUME OF BITUMEN IN ASPHALT MIX (PERCENT)

ET IS TENSILE STRAIN IN ASPHALT LAYER
MOD IS MODULUS OF ASPHALT
F1, F2 AND F3 ARE COEFFICIENTS OF LAB FATIGUE EQUATION
GIVEN BY   NF = F1 * ET**(-F2) * MOD**(-F3)

PARAMETERS OF LAYER 1

F0 =.18400E+02 F1 =.43250E-02 F2 =.32910E+01 F3 =.85400E+00

F4 =.48400E+01 F5 =.69000E+00 VB = 9.70 VV = 15.70

FINAL FATIGUE EQUATION: NF=.25677E-02*(ET)**(-.32910E+01)*MOD**(-.85400E+00)

DEFORMATION DAMAGE   NF = D0 * EC**(-D1)

WHERE

NF IS LOAD REPETITIONS TO FAILURE
D0 AND D1 ARE COEFFICIENTS FOR SUBGRADE DEFORMATION MODEL
EC IS VERTICAL COMPRESSIVE STRAIN AT TOP OF SUBGRADE LAYER(S)

D0 =.13650E-08   D1 =.44770E+01

***** MONTHLY STRUCTURAL RESPONSE *****

TYPES OF STRUCTURAL RESPONSES

DZ VERTICAL DEFORMATION AT THE TOP OF LAYER (IN)
ET TENSILE STRAIN AT THE BOTTOM OF LAYER (IN/IN)
EC COMPRESSIVE STRAIN AT THE TOP OF LAYER(IN/IN)

STRUCTURAL RESPONSES

MON	L	PVT. TEMP	MODULUS (PSI)	RESP TYPE	COMPUTATIONAL POINTS CENTER	EDGE	MID. PT.
1	1	72	409326.	DZ	.7038E-01	.7289E-01	.7303E-01
1	1	72	409326.	ET	.5954E-03	.6089E-03	.5986E-03
1	2		2900.	EC	.1573E-02	.1474E-02	.1394E-02
2	1	81	307500.	DZ	.6284E-01	.6519E-01	.6510E-01
2	1	81	307500.	ET	.6736E-03	.6854E-03	.6725E-03
2	2		3700.	EC	.1685E-02	.1525E-02	.1419E-02
3	1	76	358228.	DZ	.5220E-01	.5415E-01	.5406E-01
3	1	76	358228.	ET	.5702E-03	.5798E-03	.5688E-03
3	2		4500.	EC	.1420E-02	.1281E-02	.1190E-02
4	1	64	617186.	DZ	.4569E-01	.4732E-01	.4741E-01
4	1	64	617186.	ET	.3916E-03	.4004E-03	.3936E-03
4	2		4500.	EC	.1032E-02	.9649E-03	.9117E-03
5	1	56	989277.	DZ	.4036E-01	.4168E-01	.4192E-01
5	1	56	989277.	ET	.2785E-03	.2855E-03	.2811E-03
5	2		4500.	EC	.7734E-03	.7392E-03	.7073E-03
6	1	48	1258042.	DZ	.3778E-01	.3895E-01	.3926E-01
6	1	48	1258042.	ET	.2329E-03	.2389E-03	.2356E-03
6	2		4500.	EC	.6649E-03	.6410E-03	.6176E-03
7	1	28	2044775.	DZ	.3293E-01	.3383E-01	.3414E-01
7	1	28	2044775.	ET	.1605E-03	.1647E-03	.1635E-03
7	2		4500.	EC	.4858E-03	.4744E-03	.4643E-03

8	1	29	1995811.	DZ	.3316E-01	.3407E-01	.3439E-01
8	1	29	1995811.	ET	.1635E-03	.1679E-03	.1665E-03
8	2		4500.	EC	.4936E-03	.4817E-03	.4711E-03
9	1	16	2460000.	DZ	.8355E-02	.8666E-02	.8658E-02
9	1	16	2460000.	ET	.8642E-04	.8802E-04	.8640E-04
9	2		27300.	EC	.2179E-03	.1984E-03	.1852E-03
10	1	31	1863699.	DZ	.5571E-02	.5751E-02	.5712E-02
10	1	31	1863699.	ET	.8369E-04	.8389E-04	.8173E-04
10	2		50000.	EC	.1956E-03	.1632E-03	.1459E-03
11	1	49	1214086.	DZ	.8805E-01	.8994E-01	.8991E-01
11	1	49	1214086.	ET	.3077E-03	.3161E-03	.3174E-03
11	2		1400.	EC	.1013E-02	.1002E-02	.9963E-03
12	1	56	989277.	DZ	.6984E-01	.7173E-01	.7238E-01
12	1	56	989277.	ET	.3343E-03	.3432E-03	.3408E-03
12	2		2100.	EC	.1017E-02	.9935E-03	.9734E-03

***** MONTHLY DAMAGES *****

TYPES OF STRUCTURAL RESPONSES

DZ VERTICAL DEFORMATION AT THE TOP OF LAYER (IN)
ET TENSILE STRAIN AT THE BOTTOM OF LAYER (IN/IN)
EC COMPRESSIVE STRAIN AT THE TOP OF LAYER(IN/IN)

		PVT.	MODULUS	RESP	COMPUTATIONAL POINTS		
MON	L	TEMP	(PSI)	TYPE	CENTER	EDGE	MID. PT.
1	1	72	409326.	DZ			
1	1	72	409326.	ET	.1763E+00	.1897E+00	.1794E+00
1	2		2900.	EC	.6198E-01	.4626E-01	.3601E-01
2	1	81	307500.	DZ			
2	1	81	307500.	ET	.2073E+00	.2195E+00	.2062E+00
2	2		3700.	EC	.8428E-01	.5389E-01	.3906E-01
3	1	76	358228.	DZ			
3	1	76	358228.	ET	.1364E+00	.1442E+00	.1353E+00
3	2		4500.	EC	.3922E-01	.2470E-01	.1777E-01

4	1	64	617186.	DZ			
4	1	64	617186.	ET	.6304E-01	.6781E-01	.6410E-01
4	2		4500.	EC	.9364E-02	.6942E-02	.5384E-02
5	1	56	989277.	DZ			
5	1	56	989277.	ET	.3072E-01	.3333E-01	.3168E-01
5	2		4500.	EC	.2579E-02	.2106E-02	.1729E-02
6	1	48	1258042.	DZ			
6	1	48	1258042.	ET	.2094E-01	.2277E-01	.2176E-01
6	2		4500.	EC	.1310E-02	.1113E-02	.9422E-03
7	1	28	2044775.	DZ			
7	1	28	2044775.	ET	.9311E-02	.1015E-01	.9894E-02
7	2		4500.	EC	.3215E-03	.2891E-03	.2624E-03
8	1	29	1995811.	DZ			
8	1	29	1995811.	ET	.9705E-02	.1057E-01	.1030E-01
8	2		4500.	EC	.3452E-03	.3097E-03	.2802E-03
9	1	16	2460000.	DZ			
9	1	16	2460000.	ET	.1422E-02	.1510E-02	.1421E-02
9	2		27300.	EC	.8883E-05	.5838E-05	.4285E-05
10	1	31	1863699.	DZ			
10	1	31	1863699.	ET	.1009E-02	.1017E-02	.9335E-03
10	2		50000.	EC	.5480E-05	.2434E-05	.1472E-05
11	1	49	1214086.	DZ			
11	1	49	1214086.	ET	.5080E-01	.5554E-01	.5627E-01
11	2		1400.	EC	.8643E-02	.8220E-02	.8013E-02
12	1	56	989277.	DZ			
12	1	56	989277.	ET	.5606E-01	.6109E-01	.5970E-01
12	2		2100.	EC	.8766E-02	.7913E-02	.7220E-02

DAMAGE SUM FOR 12 MONTHS

LAYER 1	.7630E+00	.8172E+00	.7769E+00
LAYER 2	.2168E+00	.1517E+00	.1167E+00

********** DESIGN LIFE OF PAVEMENT **********

LAYER	DAMAGE TYPE	CUMULATIVE DAMAGE	CRITICAL POSITION	DESIGN LIFE(YEARS)	DESIGN REPETITIONS
1	FATIGUE	1.000	2	1.2	.4406E+04
2	DEFORMATION	1.000	1	4.6	.1660E+05

LAYER 1 CONTROLS DESIGN LIFE