D.Y. Lee T. Demirel
August 1987

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Beneficial Effects of Selected Additives on Asphalt Cement Mixes

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

Iowa DOT Project HR-278
ERI Project 1802
ISU-ERI-Ames-88070

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TABLE OF CONTENTS

	Page
ABSTRACT	xiii
1. INTRODUCTION	1
2. PROGRAM OF STUDY	2
3. EFFECTS OF ADDITIVES ON THE PROPERTIES OF ASPHALT CEMENTS--PHASE I	5
3.1. Materials	5
3.2. Procedures	8
3.3. Results and Discussions	14
3.3.1. Rheological Properties	14
3.3.2. Tensile, Ductility and Elastic Properties	29
3.3.3. Chemical Properties	34
3.3.4. Temperature Susceptibility	50
3.3.5. Potential for Cracking and Rutting	56
4. EFFECTS OF ADDITIVES ON THE PROPERTIES OF ASPHALT CONCRETE MIXTURES--PHASE II	61
4.1. Materials	61
4.2. Procedures	63
4.3. Results and Discussion	67
4.3.1. Marshall Properties	67
4.3.2. Resilient Moduli	74
4.3.3. Tensile Strength	74
4.3.4. Moisture Damage	74
4.3.4.1. Marshall Immersion	80
4.3.4.2. Tensile-Strength	80
4.3.4.3. Resilient Modulus	86
4.3.4.4. Life Benefit-to-Cost Ratio	87
4.3.5. Fatigue Resistance	88
4.3.6. Rutting Resistance	96
5. STRUCTURAL AND PERFORMANCE EVALUATION--PHASE III	105
5.1. The Asphalt Institute Method	105
5.2. The University of Nottingham (Brown) Method	112
6. SUMMARY AND CONCLUSIONS	123
7. RECOMMENDATIONS	133
8. ACKNOWLEDGMENTS	135
9. REFERENCES	137

TABLE OF CONTENTS (Cont'd.)

		Page
APPENDIX A:	TENSILE STRENGTH TEST	143
APPENDIX B:	ELASTIC RECOVERY TEST	145
APPENDIX C:	DROPPING BALL TEST	147
APPENDIX D:	NOMOGRAPH FOR PREDICTING ASPHALT STIFFNESS	149
APPENDIX E:	NOMOGRAPH FOR PREDICTING CRACKING TEMPERATURE	151
APPENDIX F:	SAMPLE COMPUTER PRINTOUT FROM DAMA	153

LIST OF TABLES

		Page
Table 1.	Sample identification—Phase I.	6
Table 2.	Rheological properties.	15
Table 3.	Tensile properties of binders.	30
Table 4.	Ductility and elastic properties.	33
Table 5.	Temperature susceptibility.	51
Table 6.	Low-temperature cracking properties.	59
Table 7.	Mix identification—Phase II.	64
Table 8a.	Mix properties, LS/AC-5.	68
b.	Mix properties, G/AC-5.	69
c.	Mix properties, LS/AC-20.	70
d.	Mix properties, G/AC-20.	71
Table 9a.	Indirect tensile strength and resilient modulus, LS/AC-5.	75
b.	Indirect tensile strength and resilient modulus, G/AC-5.	76
c.	Indirect tensile strength and resilient modulus, LS/AC-20.	77
d.	Indirect tensile strength and resilient modulus, G/AC-20.	78
Table 10.	Results of fatigue analyses (microstrain).	94
Table 11.	Results of DAMA structural analyses.	107
Table 12a.	Summary of structural analyses by Brown method, LS/AC-5.	114
b.	Summary of structural analyses by Brown method, G/AC-5 (Mixes 2, 4, and 6).	115
c.	Summary of structural analyses by Brown method, LS/AC-20 (Mixes 7, 9, and 11).	116
d.	Summary of structural analyses by Brown method, G/AC-20 (Mixes 8, 10, and 12).	117
Table 13.	Summary of effects of additives on binder properties.	124
Table 14.	Summary of effects of additives on mixture properties.	125

LIST OF FIGURES

		Page
Fig. 1.	Binder study flow chart.	9
Fig. 2.	Dropping ball test, definitions of times.	12
Fig. 3.	Definitions of toughness and tenacity.	12
Fig. 4.	Penetration at 77° F (25° C).	17
Fig. 5.	Penetration at 41° F (5° C).	18
Fig. 6.	Ring-and-ball softening point.	19
Fig. 7.	Viscosity at 140° F (60° C) and 275° F (135° C).	20
Fig. 8.	Viscosity at 77° F (25° C).	22
Fig. 9.	Viscosity ratio at 77° F (25° C).	23
Fig. 10.	Percent of retained penetration.	24
Fig. 11.	Typical Class S, B, and W behavior of asphalt.	26
Fig. 12a.	BTDC of Asphadur-modified AC-5.	27
b.	BTDC of lime-modified AC-5.	27
c.	BTDC of Styrelf-modified AC-5.	27
Fig. 13a.	BTDC of Asphadur-modified AC-20.	28
b.	BTDC of lime-modified AC-20.	28
c.	BTDC of Styrelf-modified AC-20.	28
Fig. 14.	Toughness.	31
Fig. 15.	Tenacity.	32
Fig. 16.	Results of dropping ball test.	35
Fig. 17a.	HPLC chromatogram of AC-5 without additives.	36
b.	HPLC chromatogram of SBS in AC-20.	37
Fig. 18.	Percent of LMS determined by HPLC.	38
Fig. 19.	Fluorescence micrographs of Asphadur in AC-5.	41
Fig. 20.	Fluorescence micrographs of Asphadur in AC-20.	42
Fig. 21.	Theta/two-theta scan, AC-5 versus AC-20.	44

LIST OF FIGURES (Cont'd.)

		Page
Fig. 22.	Theta/two-theta scan, AC-5 with additives.	45
Fig. 23.	Theta/two-theta scan, AC-5 with additives (vertical scale offsets).	46
Fig. 24.	Two-theta scan, lime (5%) in AC-5.	48
Fig. 25.	Two-theta scan, Asphadur (4%) in AC-5.	49
Fig. 26.	Penetration index.	53
Fig. 27.	Viscosity temperature susceptibility.	54
Fig. 28.	Penetration-viscosity number (PVN).	55
	a. AC-5.	
	b. AC-20.	
Fig. 29.	Low-temperature cracking properties.	58
Fig. 30.	Aggregate gradations.	62
Fig. 31.	Mixture evaluation flow chart.	66
Fig. 32a.	Marshall stability.	72
	b. Marshall stiffness.	73
Fig. 33.	Indirect tensile strength (ITS).	79
Fig. 34.	Moisture damage, Marshall immersion stability.	81
Fig. 35a.	Moisture damage, ITS, and resilient modulus, AC-5/LS.	82
	b. Moisture damage, ITS, and resilient modulus, AC-5/G.	83
	c. Moisture damage, ITS, and resilient modulus, AC-20/LS.	84
	d. Moisture damage, ITS, and resilient modulus, AC-20/G.	85
Fig. 36a.	Percent change of design life and benefit-to-cost ratio, AC-5/LS.	89
	b. Percent change of design life and benefit-to-cost ratio, AC-5/G.	90
	c. Percent change of design life and benefit-to-cost ratio, AC-20/LS.	91
	d. Percent change of design life and benefit-to-cost ratio, AC-20/G.	92

LIST OF FIGURES (Cont'd.)

		Page
Fig. 37.	Fatigue strain.	95
	a. AC-5.	
	b. AC-20.	
Fig. 38.	Typical strain versus time curves, Mixes C9 and AH9.	97
Fig. 39.	Effect of aggregate type on Smix versus Sbit curves, Mixes C1 and C2.	98
Fig. 40.	Effect of AC grade on Smix versus Sbit curves, Mixes C3 and C9.	99
Fig. 41.	Effect of AC content on Smix versus Sbit curves, Mixes K8, K10, and K12.	100
Fig. 42.	Effect of additives on Smix versus Sbit curves.	101
Fig. 43.	Rut depth estimation by Shell procedure.	103
Fig. 44a.	Structural analyses by DAMA procedure, H1 = 4 in., SGE = 4,500 psi.	108
b.	Structural analyses by DAMA procedure, H1 = 4 in., SGE = 12,000 psi.	108
c.	Structural analyses by DAMA procedure, H1 = 8 in., SGE = 4,500 psi.	110
d.	Structural analyses by DAMA procedure, H1 = 8 in., SGE = 12,000 psi.	111
Fig. 45a.	Structural analyses by Brown procedure, LS/AC-5.	118
b.	Structural analyses by Brown procedure, LS/AC-20.	119
c.	Structural analyses by Brown procedure, G/AC-5.	120
d.	Structural analyses by Brown procedure, G/AC-20.	121

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

MULTIPLY	BY	TO OBTAIN
inches	2.54	centimeters
feet	0.3048	meters
square inches	6.4516	square centimeters
square yards	0.83612736	square meters
knots	0.5144444	meters per second
pounds	0.45359237	kilograms
kips	0.45359237	metric tons
pounds per cubic foot	16.018489	kilograms per cubic meter
pounds	4.448222	newtons
kips	4.448222	kilonewtons (kN)
pounds per square inch	6.894757	kilopascals
pounds per cubic inch	2.7144712	kilopascals per centimeters
gallons (U. S. liquid)	3.785412	cubic decimeters
Fahrenheit degrees	5/9	Celsius degrees of Kelvins*

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F-32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F-32) + 273.15$.

ABSTRACT

Effects of polyolefins, neoprene, styrene-butadiene-styrene (SBS) block copolymers, styrene-butadiene rubber (SBR) latex, and hydrated lime on two asphalt cements were evaluated. Physical and chemical tests were performed on a total of 16 binder blends. Asphalt concrete mixes were prepared and tested with these modified binders and two aggregates (a crushed limestone and a gravel), each at three asphalt content levels.

Properties evaluated on the modified binders (both original and thin-film oven aged) included: viscosity at 25° C, 60° C and 135° C with capillary tube and cone-plate viscometer, penetration at 5° C and 25° C, softening point, force ductility, and elastic recovery at 10° C, dropping ball test, tensile strength, and toughness and tenacity tests at 25° C. From these the penetration index, the viscosity-temperature susceptibility, the penetration-viscosity number, the critical low-temperature, long loading-time stiffness, and the cracking temperature were calculated. In addition, the binders were studied with x-ray diffraction, reflected fluorescence microscopy, and high-performance liquid chromatography techniques.

Engineering properties evaluated on the 72 asphalt concrete mixes containing additives included: Marshall stability and flow, Marshall stiffness, voids properties, resilient modulus, indirect tensile strength, permanent deformation (creep), and effects of moisture by vacuum-saturation and Lottman treatments. Pavement sections of varied asphalt concrete thicknesses and containing different additives were compared to control mixes in terms of structural responses and pavement lives for different subgrades.

Although all of the additives tested improved at least one aspect of the binder/mixture properties, no additive was found to improve all the relevant binder/mixture properties at the same time. On the basis of overall considerations, the optimum beneficial effects can be expected when the additives are used in conjunction with softer grade asphalts.

1. INTRODUCTION

Because of the inherent properties of paving asphalts traditionally produced as waste products and because of the inadequacy of current specifications, asphalt paving mixtures—even those designed and constructed with the best of current technology and knowledge—frequently do not possess all of the desirable characteristics at the same time. With heavier truck loads and higher traffic volumes as well as decreased resources for timely maintenance, asphalt pavements have experienced accelerated deterioration.

In an attempt to improve the performance of asphalts and to increase the service life of asphalt pavements, additives have been incorporated to change the characteristics of the asphalt or the asphalt mixture. Some of these additives are hydrated lime, sulfur, antioxidants, antistripping agents, carbon black, asbestos fiber, and a variety of polymers (11,12,19,22,23,24,26,34,37,40,46,47, and 50). Highway Research Project HR-278 was initiated in 1985 to study three of the more promising additives (hydrated lime, Asphadur, and Styrelf) and to identify their beneficial effects. A project progress report summarizing the results of Phase I (Binder Evaluation) during the first year was submitted in August 1986 (25). Phase II (Mixture Evaluation) of the project was modified in October 1986 to include four more polymerized asphalt cements (PACs). This Final Report describes all work conducted and the findings resulting from HR-278.

2. PROGRAM OF STUDY

Since most of the asphalt pavement problems that can be attributed to binders are stripping, thermal cracking, rutting, and hardening of the binders, the study was mainly designed to evaluate the effects, benefits, and mechanisms of additives on these properties.

The research was conducted in three phases. Phase I was the evaluation of the effects of selected additives on the durability and rheological properties of asphalt cement binders and their effects on the rutting and low-temperature cracking susceptibility of the asphalt pavements. Phase II was an evaluation of the effects of these additives on asphalt concrete mixtures in terms of rutting, stripping, stability, and low-temperature cracking potential. Phase III was the prediction of performance with a pavement design and analysis system, such as DAMA.

3. EFFECTS OF ADDITIVES ON THE PROPERTIES OF ASPHALT CEMENTS--PHASE I

3.1. Materials

Two asphalt cements, one from Bituminous Materials of Terre Haute, Indiana, and the other from Exxon of Baytown, Texas, were evaluated in conjunction with three additives. Two of the additives (Asphadur and lime) were added to the two asphalt cements at two levels of concentration each; the third additive (SBS—styrene-butadiene-styrene) was incorporated in the these asphalts by the supplier at one single "optimum" concentration and were received and tested as modified asphalts (Styrelf). The factorial combination and sample identifications of the 16 binders are given in Table 1.

Styrelf was developed by the French Highway Department and was introduced in the United States by Group Elf Aquitaine. Styrelf is a unique combination of asphalt cement and the polymer SBS. It involves a chemical reaction between the polymer and the asphalt. The reaction starts from the small chain polymer and then increases in size while linking irreversibly to the bituminous matrix. The quantity of polymer and reactant have been selected to obtain optimum performance (10). Usually 3% of the polymer is added. Chemical analysis shows that with this concentration the reactional places of the bitumen have been blocked by a polymer-bitumen bond or a bitumen-bitumen bond. Therefore, no further reaction, such as oxidation, can take place. Different tests performed by the manufacturer have shown that the Styrelf will improve the performance of the pavement.

Table I. Sample identification - Phase I.

AC GRADE	AC-5			AC-20		
ADDITIVE CONTENT	0	L	H	0	L	H
ASPHADUR A: PARTIALLY DISSOLVED B: TOTALLY DISSOLVED	1	2A 2B (4%)	3A 3B (6%)	7	8A 8B (4%)	9A 9B (6%)
HYDRATED LIME MIXING 6 MIN @ 280 F		4 (5%)	5 (10%)		10 (5%)	11 (10%)
STYRELF		6			12	

0 : no additive (control).
L : low level.
H : high level.
A : mixing 3 min. @ 400 F.
B : mixing 3 min. @ 320 F followed by heating in oven @ 320 F for 12 hrs.

Hydrated lime has been used in pavements as an antistripping agent for a long time. Recently, a number of studies have been carried out to evaluate the performance of lime in asphalt pavements, not only as an antistripping agent but also an an agent to improve the other qualities of asphalt. The National Lime Association's bulletin (37) has presented the beneficial effects of lime in asphalt pavements. In addition to functioning as an antistripping agent, hydrated lime may also act as a modifier in asphalt cement by reducing the rate of hardening. Considering these properties, we selected lime for this study, and its performance was evaluated when it was added only in the binder. High-calcium hydrated lime of the Snow-flake brand was used. This lime met the ASTM specifications C207 (Type N) and C6 (Type N) and Federal specifications SS-L-351 (Class M).

Asphadur is a grained, mixed polymer, known as polyolefin, and is manufactured by Schiker and Company of Austria under the trade name of Asphadur. This material was distributed in the United States by the Minnesota Mining and Manufacturing Company of Minneapolis, Minn., under the trade name "Stabilizing Additive 5990" (48). The process of preparing asphalt mix with the additive polyolefin was patented in the United States by Paul Haberl of Austria in December 1974 (14). The Iowa Department of Transportation, after using this additive in different pavements across Iowa, stated that "this additive is capable of improving the viscosity, stability, flow and strength characteristics of asphalt cement concrete, making it less susceptible to rutting and shoving" (17). Although Asphadur is generally added to the asphalt mix, the research on Phase I was done by adding it in the binder.

3.2. Procedures (See flow chart in Fig. 1.)

The samples with Asphadur were prepared with two different mixing plans, as shown in Table 1. The samples labelled "a" were mixed for 3 minutes at 400° F to get partially dissolved Asphadur. The samples labelled "b" were mixed for 3 minutes at 320° F and then followed by heating in oven at 320° F for 12 hours to get totally dissolved Asphadur. Hydrated lime was mixed for 6 minutes at 280° F and transferred into the cans. In each case, 800 grams of asphalt cement were taken and heated to mixing temperature. The additive was mixed in with a motorized stirrer while constant temperature was maintained.

In order to evaluate heat stability and the effects of hot plant mixing on these modified binders, the 16 binders were treated by following the thin film oven test (TFOT) procedure. The samples before and after TFOT treatments were identified as O and R samples, respectively.

In order to determine rheological properties, penetrations at 41° F (5° C) and 77° F (25° C), the softening point (R & B), and viscosities at 77° F (25° C), 140° F (60° C) and 275° F (135° C) were determined on both original and thin-film oven test residues of all binder blends. From these results, the penetration index, the viscosity-temperature susceptibility, the penetration viscosity number, the critical low-temperature, long loading-time stiffness, and the cracking temperature were calculated.

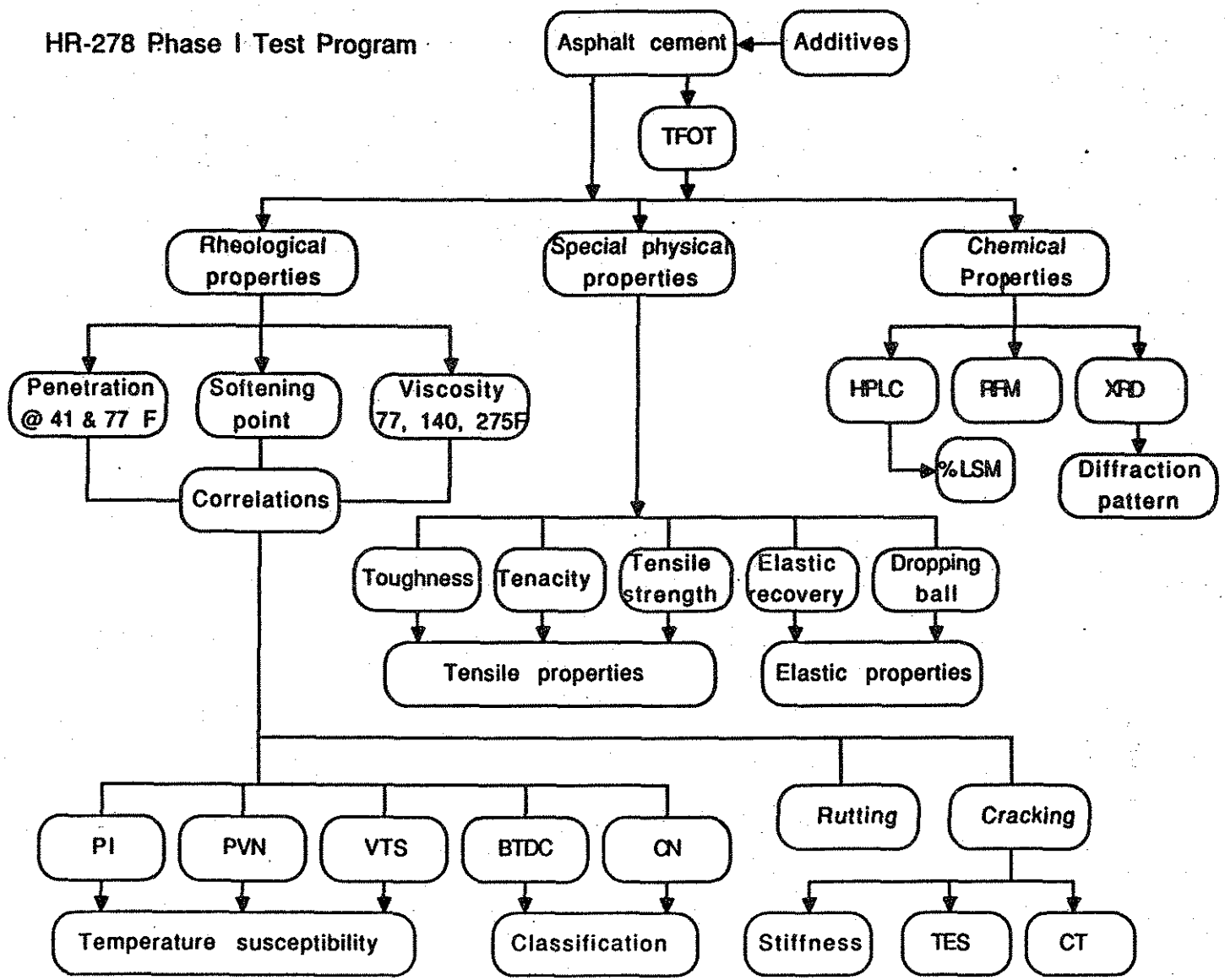


Fig. 1. Binder study flow chart.

Additional nonstandard physical tests that have been used to characterize polymer-modified asphalts were also explored.

- Tensile strength: At the Elf Aquitaine Asphalt Laboratory, Terre Haute, Indiana, tensile stress at 68° F (20° C) and 800% elongation (or at fracture) of all binders were determined, with an Instron tensile tester, at the rate of pull of 50 cm per min. This procedure is basically ASTM D412 (Standard Method for Rubber Properties in Tension), which is used routinely by the rubber industry to evaluate tensile strength. The modified procedure is given in Appendix A.
- Force ductility: The maximum force required to pull the standard ductility specimen with cross-sectional area of 1 sq cm, at rate of pull of 5 cm per min and at a temperature of 10° C (50° F), was determined by attaching a load cell to one end of the ductility mold (2).
- Elastic recovery: The procedure developed by the Elf Mineraloel Laboratories in Germany (23) was used to measure elastic recovery of all binders (Appendix B). A standard ductility specimen is stretched to 20 cm at 10° C (50° F) and held for five minutes. The specimen is then cut in the middle with a pair of scissors and allowed to stand undisturbed. After one hour, the combined length of the two sections is determined. The percent recovery is defined as follows:

$$\% \text{ recovery} = \frac{20 - L}{20} \times 100$$

where L = length after one hour.

- Dropping ball test: A very simple procedure for characterizing viscoelastic materials under constant stress conditions was developed in the Elf Aquitaine research labs in Solaize, France (23) (Appendix C). Exactly 8.0 grams of asphalt are poured into a machined metal cup and a ball of specified size and weight is embedded to a predetermined depth. The apparatus is inverted so that the ball is free to fall. The time required for the embedded portion of the ball to reach the point tangent to the surface of the cup is defined as t1. The time required for the ball to drop from that tangent plane to a point 30.0 cm below is defined as t2 (Fig. 2). Time t1 is closely related to the viscosity of the asphalt or its initial tensile strength. Time t2 depends somewhat on viscosity, but it is primarily affected by the tensile strength or elastic flow of the asphalt as it is stretched by the weight of the steel ball. The ratio t2/t1 provides a rough relationship of a material's elasticity or tensile stength after elongation to its original viscosity. The test was run at ambient temperatures.
- Toughness and tenacity: Another constant strain method for monitoring tensile strength of modified binders is the toughness and tenacity test (40). A metallic hemispherical head is embedded in hot molten asphalt to a depth of 7/16 in. The head and the asphalt are cooled to 25° C (77° F). The head is then pulled from the asphalt at the rate of 20 in. per min, and a load-deformation curve is plotted. Toughness and tenacity are

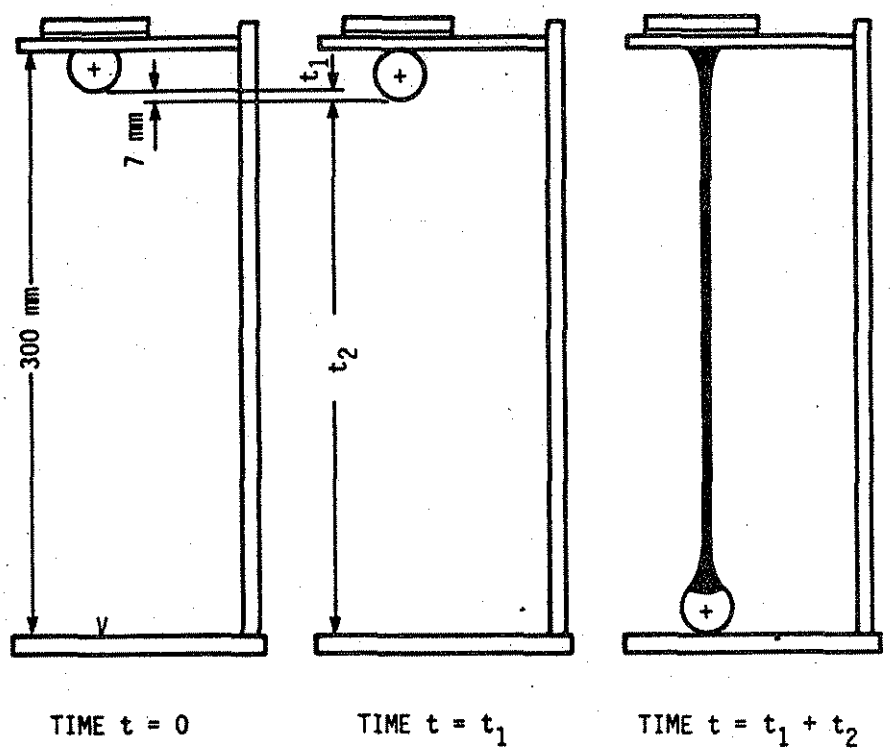


Fig. 2. Dropping ball test, definition of times.

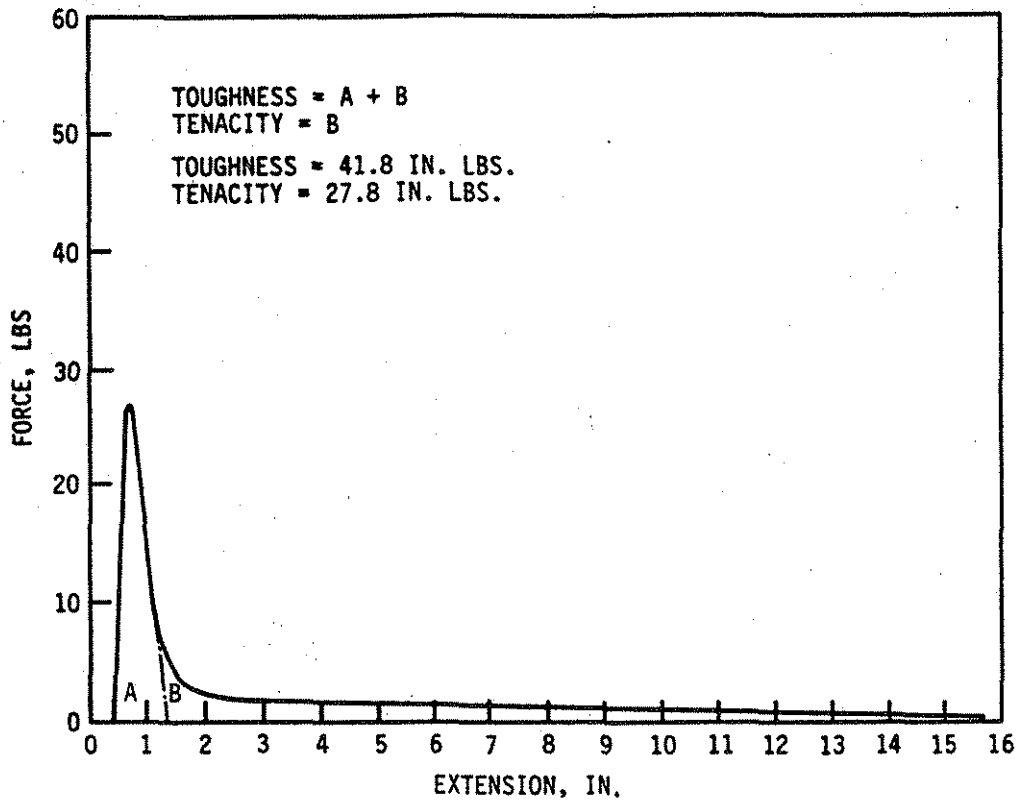


Fig. 3. Definitions of toughness and tenacity.

defined by the areas under the force-deformation curve (Fig. 3). The areas under the curve were measured by a planimeter. Tenacity is the work performed in pulling the binder material away from the tension head to its maximum extension. Toughness is the total work performed in pulling the tension head out of the sample as well as stretching the material while it is still attached to the head.

While chemical characterization of asphalt and polymer-modified asphalts is difficult, since no two asphalts are chemically identical and no conventional chemical methods are readily adaptable to the modified asphalts, three special techniques have been found to show potential in identifying effects of these additives: X-ray diffraction, reflected microscopy, and high-pressure liquid chromatography (HPLC).

- High-pressure liquid chromatography (HPLC): Samples of all binder blends were sent to Montana State University for determination of molecular size-distribution (MSD) by high-pressure liquid chromatography (HPLC) with a Waters Associates instrument and ultrastyragel columns (18).
- Reflected fluorescence microscopy: The homogeneity of dispersion (or microstructure) of the additives in asphalt was observed by using an Olympus light microscope (Model BHM) with reflected fluorescence attachment under blue excitation (8).

- X-ray Diffraction: This technique was used to determine any change in the structure and composition of asphalt, especially any chemical change, because of the additives (53). The technique uses an x-ray beam deflected from the surface of the material with a certain wavelength and at a certain angle. The wavelength of this deflected ray depends on the spacings between the planes (d) and angle of incidence (θ). The following relationship governs in this case.

$$n\lambda = 2d \sin \theta$$

where λ = wavelength

Samples 1, 2b, 4, 6, 7, 8b, 10 and 12 were selected as representative samples for the x-ray diffraction. Two different types of scans, i.e. $\theta/2\theta$ scan and 2θ scan with $\theta = 5°$ and $10°$, were used for the above samples (1).

3.3. Results and Discussion

3.3.1. Rheological Properties

For all the samples tested, the penetration values at 25° C and 5° C, are given in Table 2. Asphalt cement AC-5 and AC-20 were used in samples labelled 1-6 and 7-12 respectively. The results, listed in Table 2, are for both original and thin film oven test residue samples.

Table 2. Rheological properties.

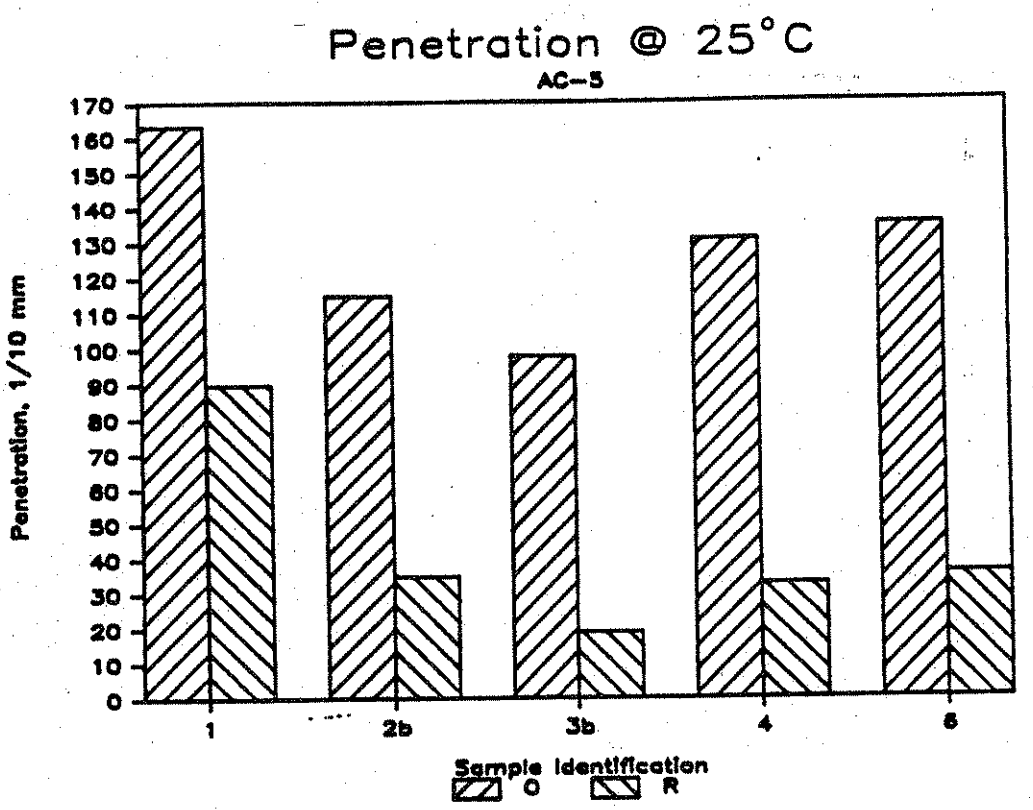
MATERIAL	SAMPLE No.	VIS, 60 poise	VIS, 135 stokes	Pm,25	Pm,5	S.P C	VIS,25 poise
AC-5	1-0	459	1.7	164	10	39	2.38E+05
AC-5+4% ASPHADUR	2b-0	1149	3.4	115	2	44	6.38E+05
AC-5+6% ASPHADUR	3b-0	11500	9.5	98	12	49	1.33E+06
AC-5+5% LIME	4-0	1700	1.5	131	8	42	2.40E+05
STYRELF IN AC-5	6-0	908	3.8	135	12	44	2.93E+05
AC-20	7-0	2215	3.4	55	2	50	2.38E+06
AC-20+4% ASPHADUR	8b-0	50000	12.0	35	5	56	5.96E+06
AC-20+6% ASPHADUR	9b-0	10000	16.0	20	4	58	8.48E+06
AC-20+5% LIME	10-0	4100	4.4	44	4	51	2.79E+06
STYRELF IN AC-20	12-0	2812	6.2	35	2	53	3.38E+06
AC-5	1-R	868	2.5	90	3	43	5.02E+05
AC-5+4% ASPHADUR	2b-R	c	8.8	35	1	61	8.53E+06
AC-5+6% ASPHADUR	3b-R	c	c	19	6	59	1.10E+07
AC-5+5% LIME	4-R	c	c	33	5	57	6.56E+06
STYRELF IN AC-5	6-R	8935	8.2	36	4	59	7.39E+06
AC-20	7-R	4264	9.0	35	0	63	1.53E+07
AC-20+4% ASPHADUR	8b-R	c	c	12	1	66	2.49E+07
AC-20+6% ASPHADUR	9b-R	c	c	11	1	71	2.50E+07
AC-20+5% LIME	10-R	c	c	13	2	67	2.88E+07
STYRELF IN AC-20	12-R	11914	18.1	14	1	66	3.97E+07

a : partially dissolved.
b : totally dissolved.
c : could not be determined due to high viscosity and/or nonhomogeneity.
VIS, 60 : viscosity @ 60 C.
VIS,135 : viscosity @ 135 C.
Pm, 25 : penetration @ 25 C, 100 g, 5 sec.
Pm, 5 : penetration @ 5 C, 100 g, 5 sec.
S.P : R & B softening point.
O : original.
R : thin film oven test residue.
VIS, 25 : viscosity @ 25 C and shear rate of 5 x E-2/sec.

Note that samples 2a, 3a, 5, 8a, 9a and 11, for both original and thin film oven test residues, may give erroneous results because of nonhomogeneity. For all other samples, a general decrease in penetration values is clear. The point to be considered is that samples 3b and 9b (with the higher percentage of Asphadur) and samples 6 and 12 (SBS) have lower penetration at 25° C but have higher penetration at 5° C than the nontreated asphalt. The penetration values are also represented as bar diagrams in Figs. 4 and 5.

Table 2 also lists the values of ring and ball softening points for all the samples. The samples with additives have higher softening points than the base binder in all the cases. Also the softening point increases with the increase in percentage of additives (Fig. 6).

Viscosities at 60° C and 135° C were determined by capillary tubes. Because of the nonhomogeneity of some samples, a Brookefield viscometer was used to estimate the viscosities at the above-mentioned temperatures. The viscosities are listed in Table 2 and plotted in Fig. 7. Because most of the entries for thin film oven test residue are missing, only the results of the original samples will be discussed here. The samples with additives show a substantial increase in viscosities at both temperatures with the exception of sample 2a-0 at 60° C and sample 4-0 at 135° C. This discrepancy may be due to the nonhomogeneity of the samples. Also the samples with Asphadur show a higher viscosity than the samples with lime and SBS.



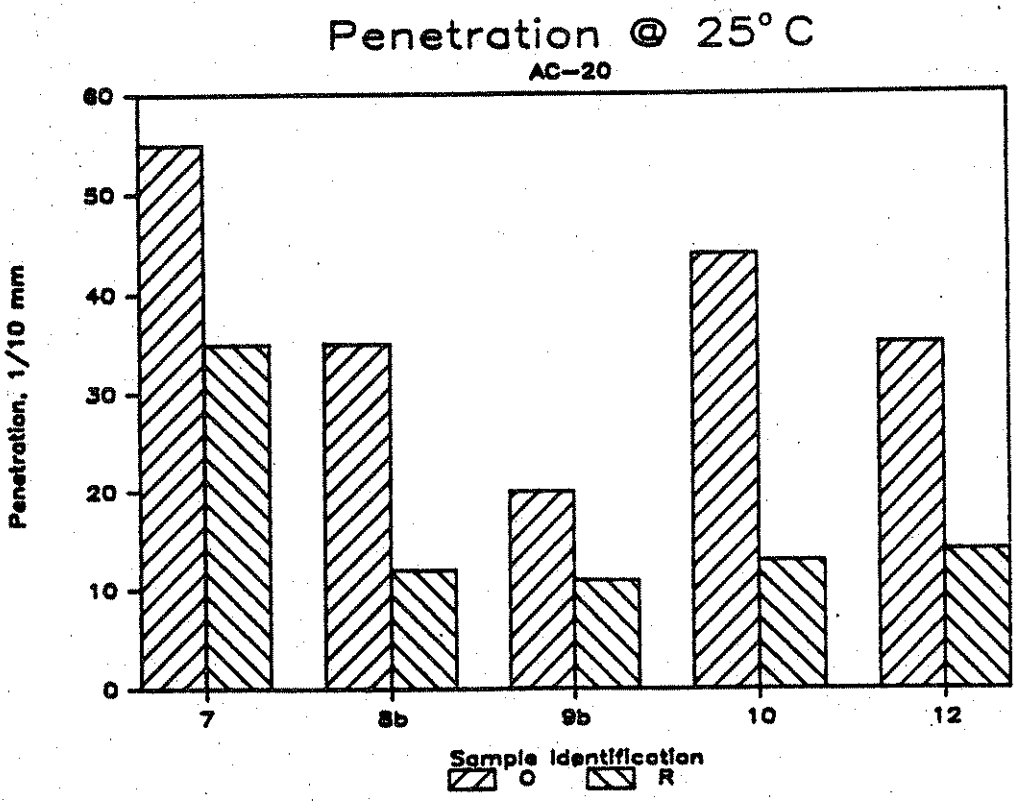
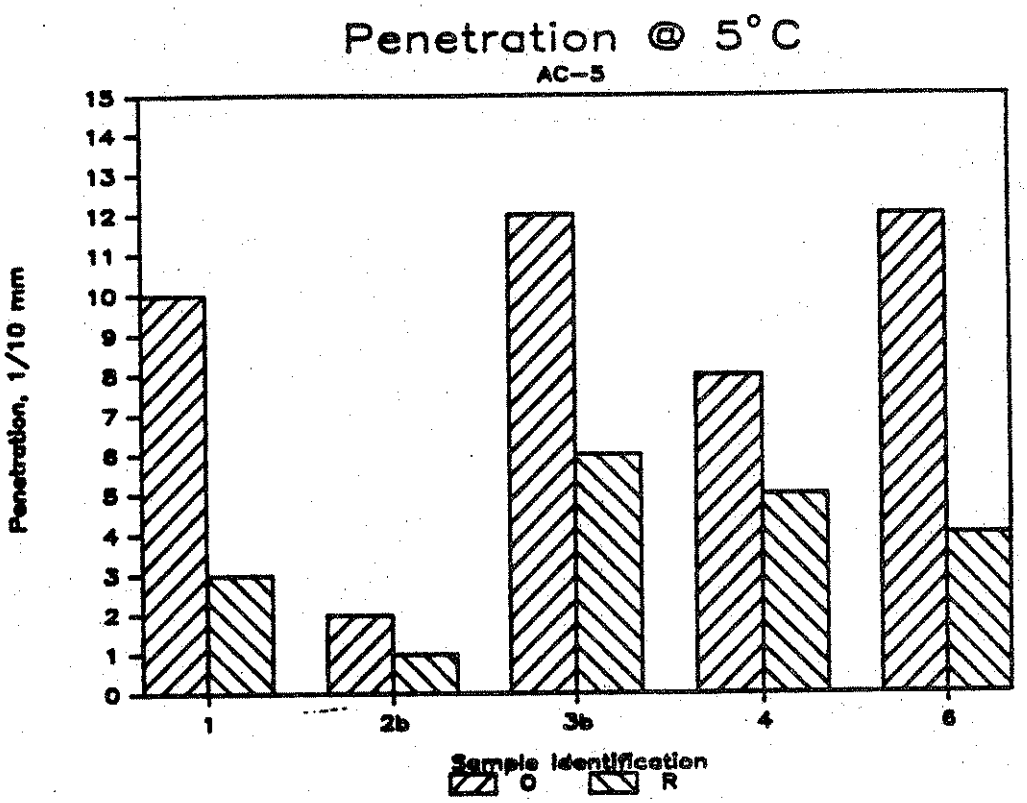


Fig. 4. Penetration at 77° F (25° C).



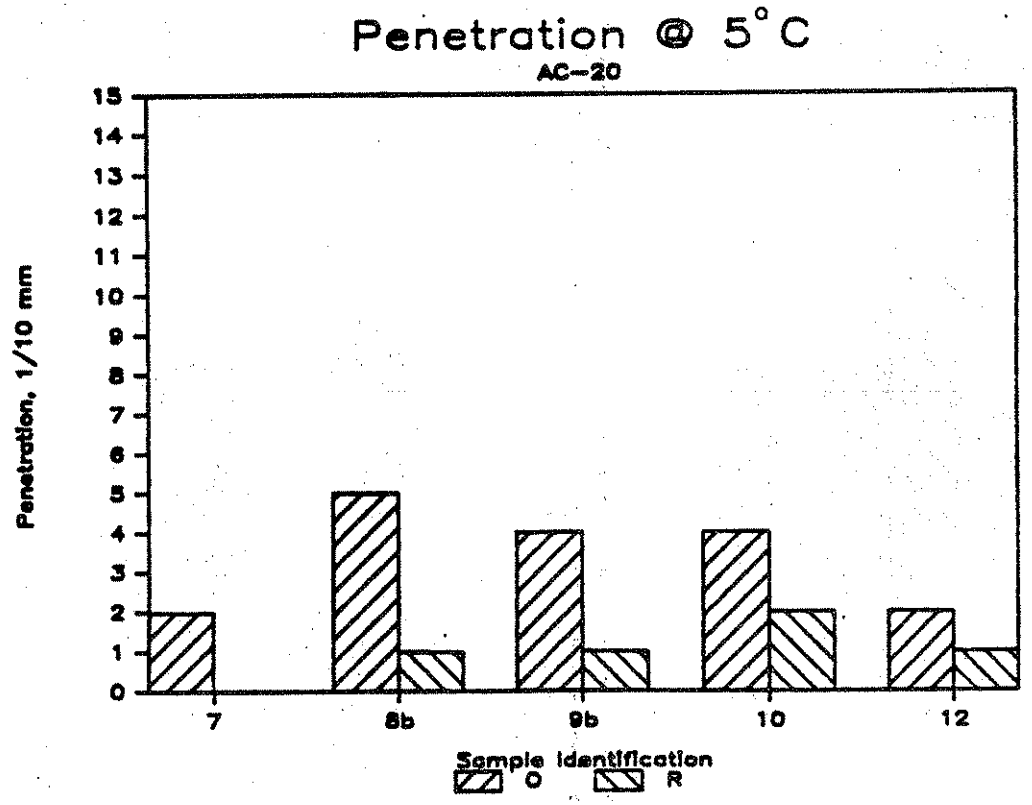


Fig. 5. Penetration at 41° F (5° C).

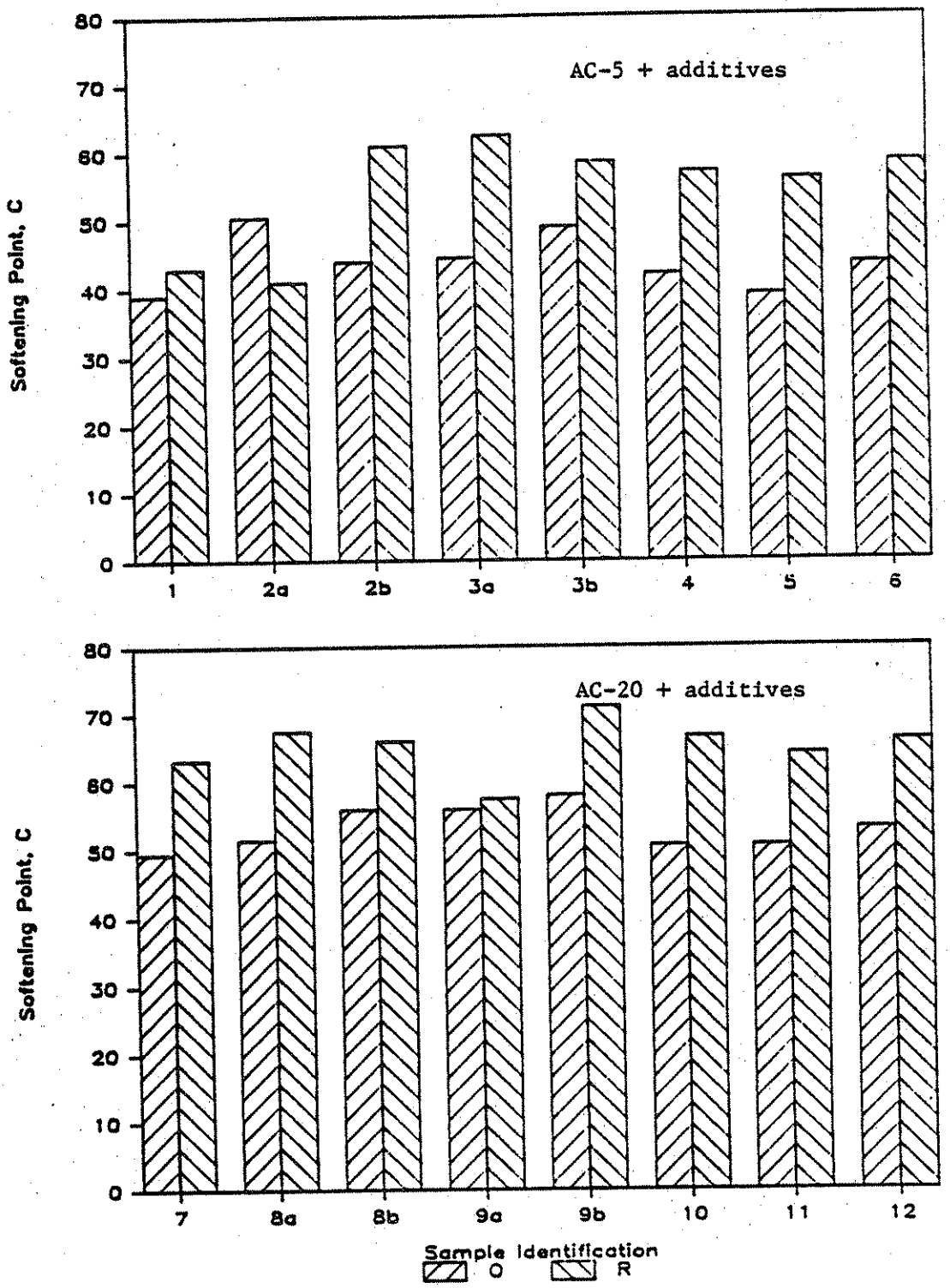


Fig. 6. Ring-and-ball softening point.

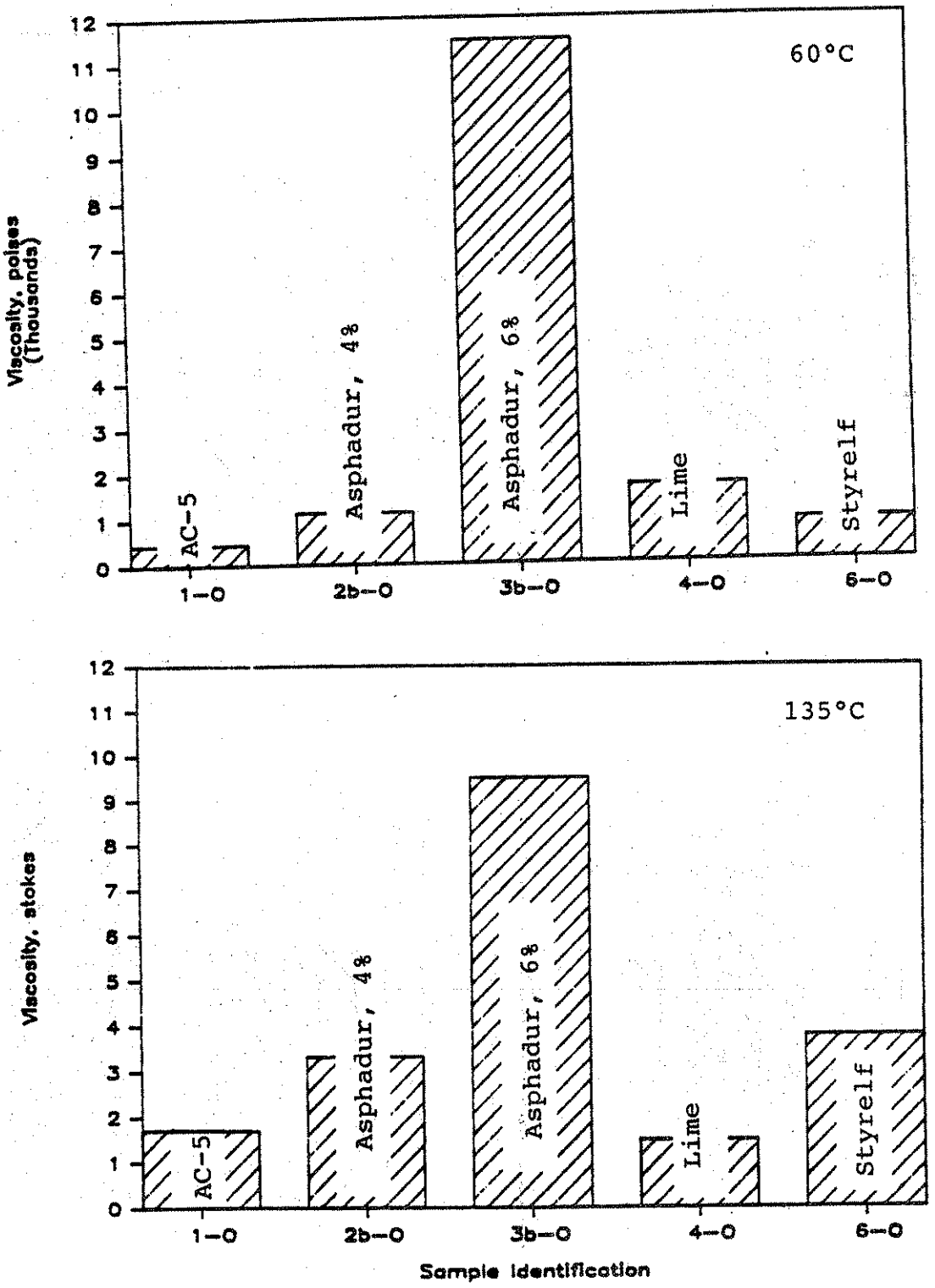
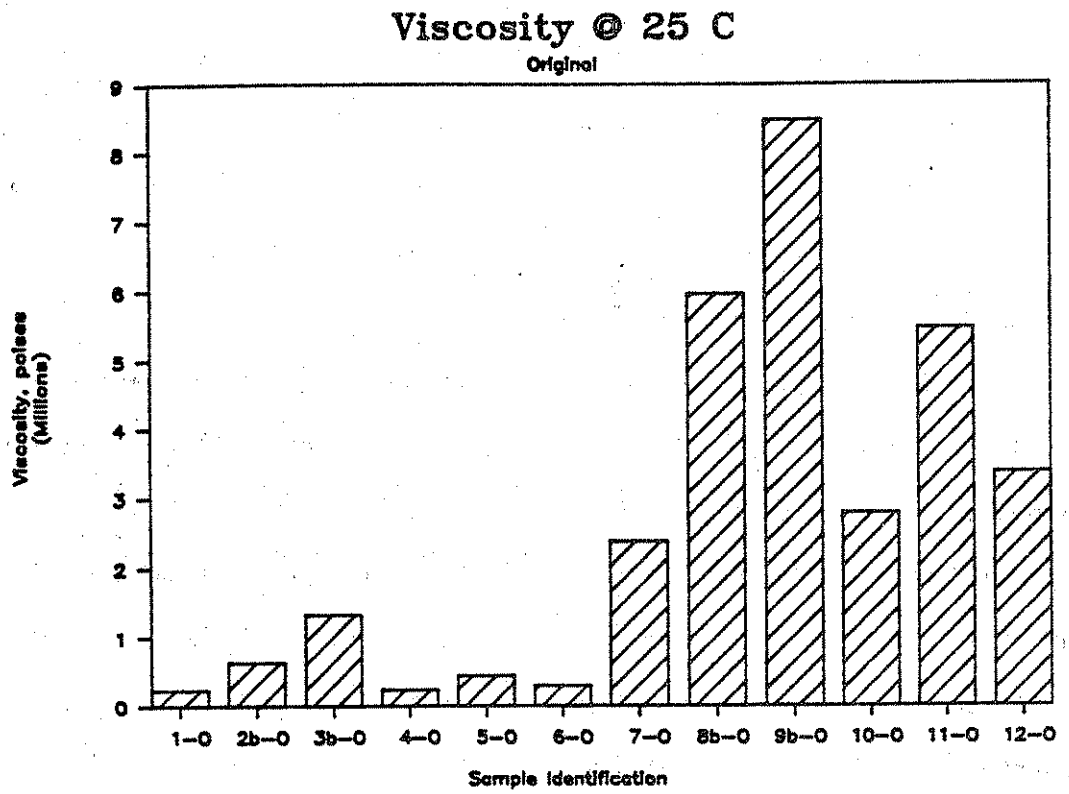


Fig. 7. Viscosity at 140° F (60° C) and 275° F (135° C) (AC-5).

Viscosities at 25° C, which were determined with a cone-plate viscometer, are listed in Table 2 and plotted in Fig. 8. The viscosities were determined for a shear rate of 5×10^{-2} sec^{-1}. The samples with additives showed higher viscosities than the base asphalt, especially for Asphadur-modified binders.

The effect of heat, as determined by viscosity and penetration at 25° C, on the thin film oven test residues, are shown in Figs. 9 and 10, respectively. The hardening of modified asphalts in terms of retained penetration varied from 19% to 30% for AC-5 and ranged from 30% to 55% for AC-20. These values were considerably lower than the reported 54% to 78% penetration retention for SBS-modified asphalts (24). The drastic hardening of modified asphalts is also reflected in increases in viscosity. Modified AC-5 asphalts were more sensitive to thin film oven heating than those of modified AC-20 asphalts. The only data on viscosity ratios at 60° C for modified binders were those of Styrelf; the viscosity ratio was 9.8 for SBS modified AC-5 and 4.2 for SBS modified AC-20. These were much higher than the reported values of 1.7 to 2.9 (24). The asphalt cements without additives had a viscosity ratio at 60° C of 1.9 for both AC-5 and AC-20. The normally specified maximum ratio (e.g. ASTM D3381) is 3 to 5.

Viscosities at 60° C and 135° C, penetrations at 25° C and 5° C, and softening points were used to determine the penetration index (PI), viscosity-temperature susceptibility (VTS), and penetration-viscosity number (PVN) at 60° C and 135° C. The effects of additives on temperature susceptibility will be discussed later.



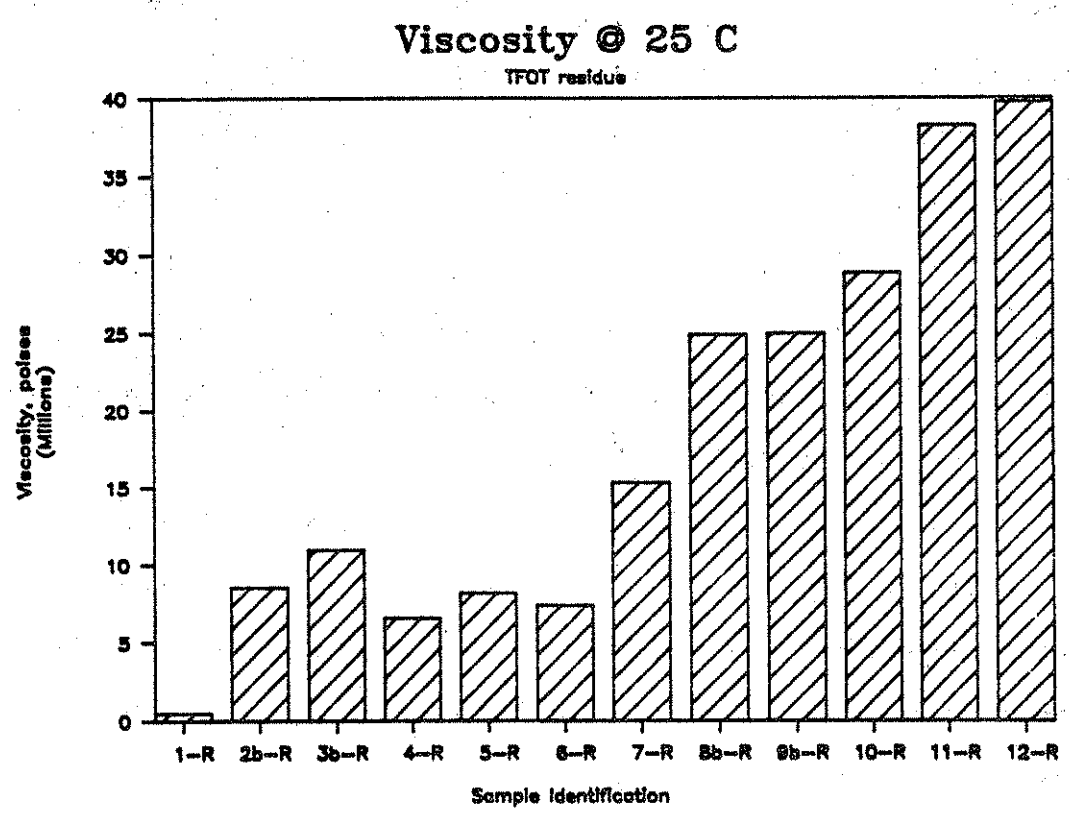
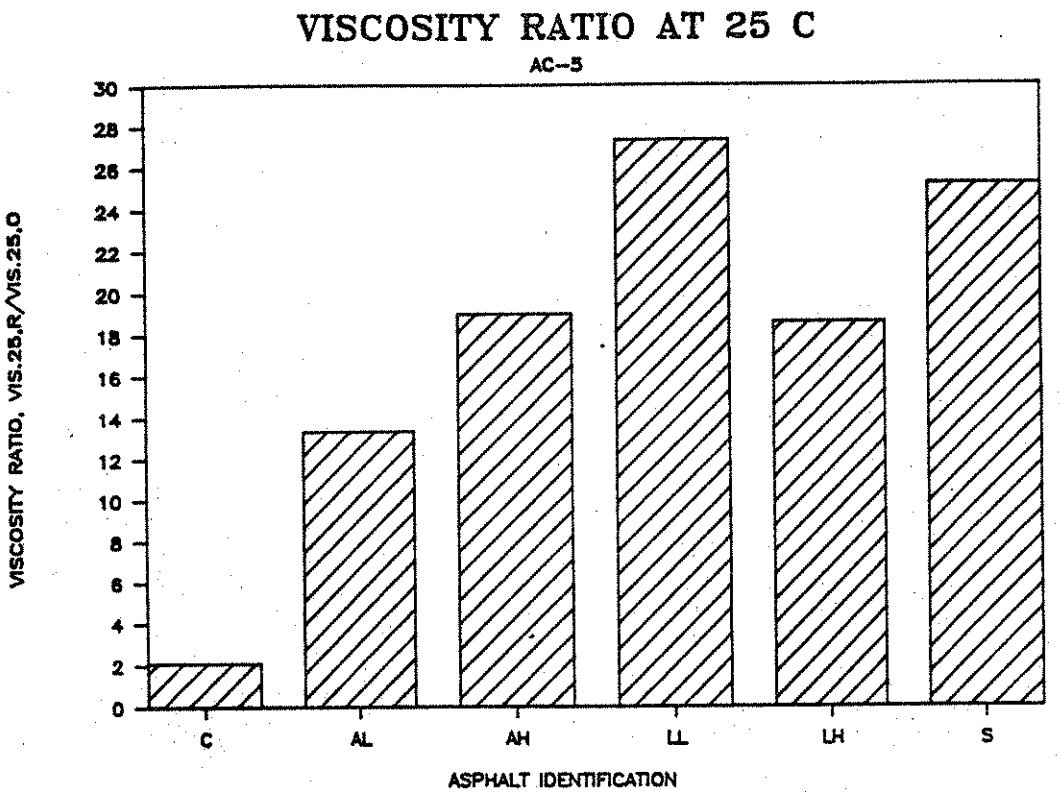


Fig. 8. Viscosity at 77° F (25° C).



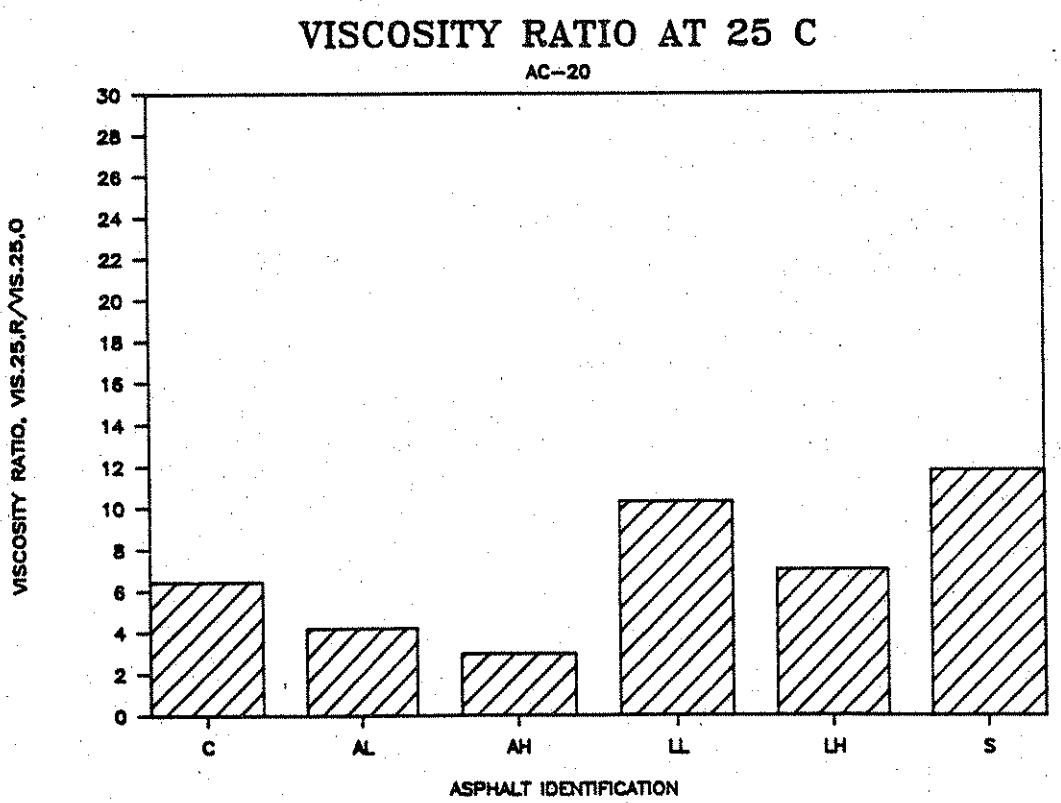


Fig. 9. Viscosity ratio at 77° F (25° C).

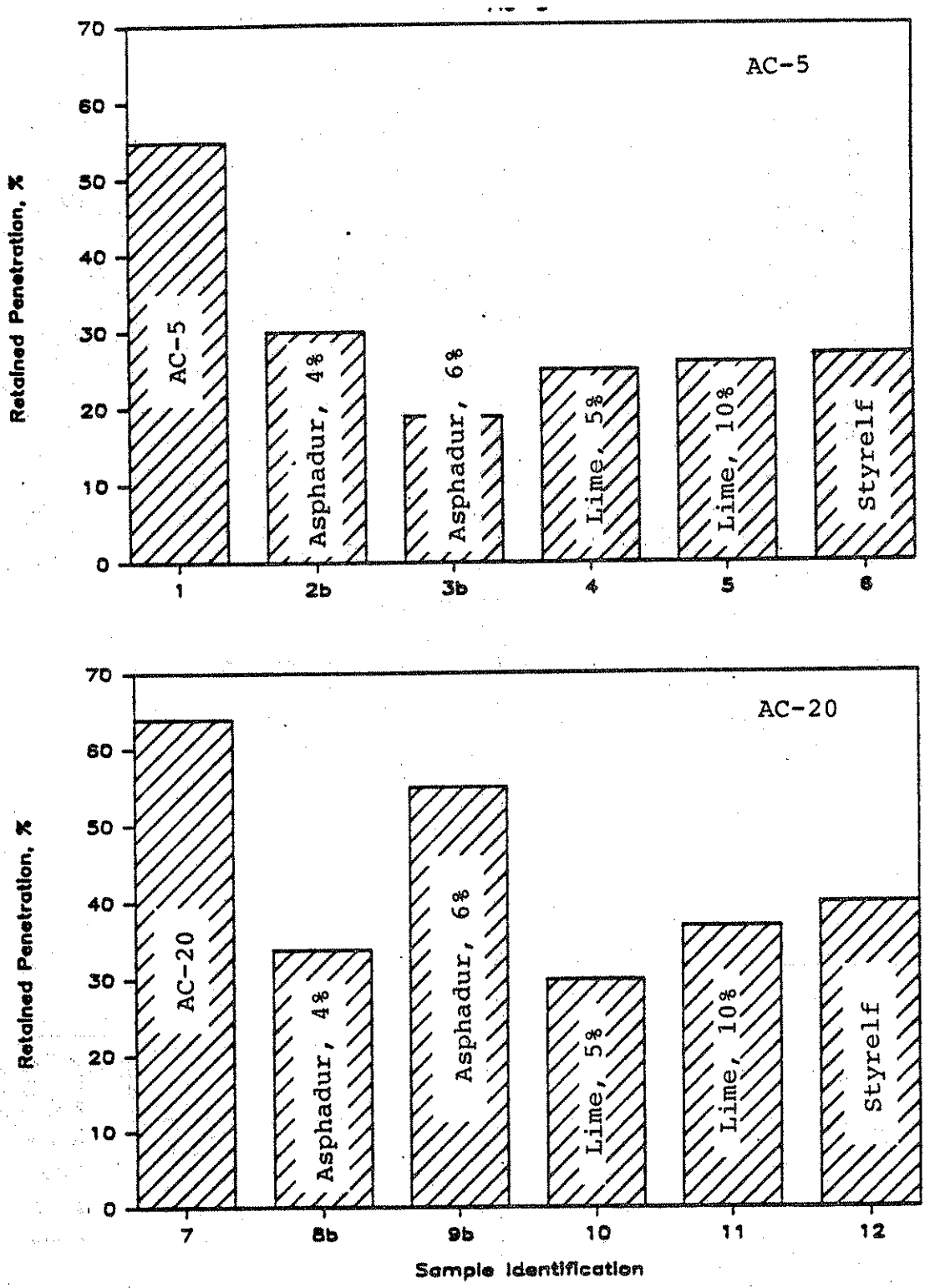


Fig. 10. Percent of retained penetration.

Data on original samples were plotted on the BITUMEN TEST DATA CHART (BTDC) for comparison and classifcation. Based on BTDC, Heukelom (8) defined three classes of asphalts: Class S (comprising straight-run residual and cracked asphalts), Class B (blown asphalts), and Class W (waxy asphalts). For Class S, both penetration and viscosities fell on the same straight line, but for Classes B and W, there was a departure from this simple relationship (Fig. 11). Also, Heukelom showed that the slope of the line in the chart indicates temperature susceptibility. The penetration index can also be obtained by this chart.

Samples 2b, 3b, 4, and 6 were plotted with Sample 1 (Figs. 12a, 12b, and 12c) and Samples 8b, 9b, 10, and 12 were plotted with Sample 7 (Figs. 13a, 13b, and 13c). Samples 1 (AC-5) and 7 (AC-20) are classified as Class W asphalts. Although it showed an increase in viscosity, Sample 2b with 4% Asphadur totally dissolved in AC-5 is also a Class W asphalt, but Sample 3b with 6% Asphadur totally dissolved in AC-5 indicates a Class B asphalt. Sample 4 (5% lime in AC-5) also falls in the category of Class B asphalts. Sample 6 (SBS in AC-5), however, indicates a Class W asphalt, because it exhibits a waxy nature.

For AC-20, the same additives were used in the same quantity but the results were not the same. At low Asphadur content (Sample 8b) the binder behaved as Class B; but at high Asphadur content (Sample 9b), the binder behaved as Class W. In Sample 10 (5% lime in AC-20) the binder changed from Class W to Class S. Sample 12 (SBS in AC-20) behaved in the same manner as Sample 6 and fell in the Class W asphalts.

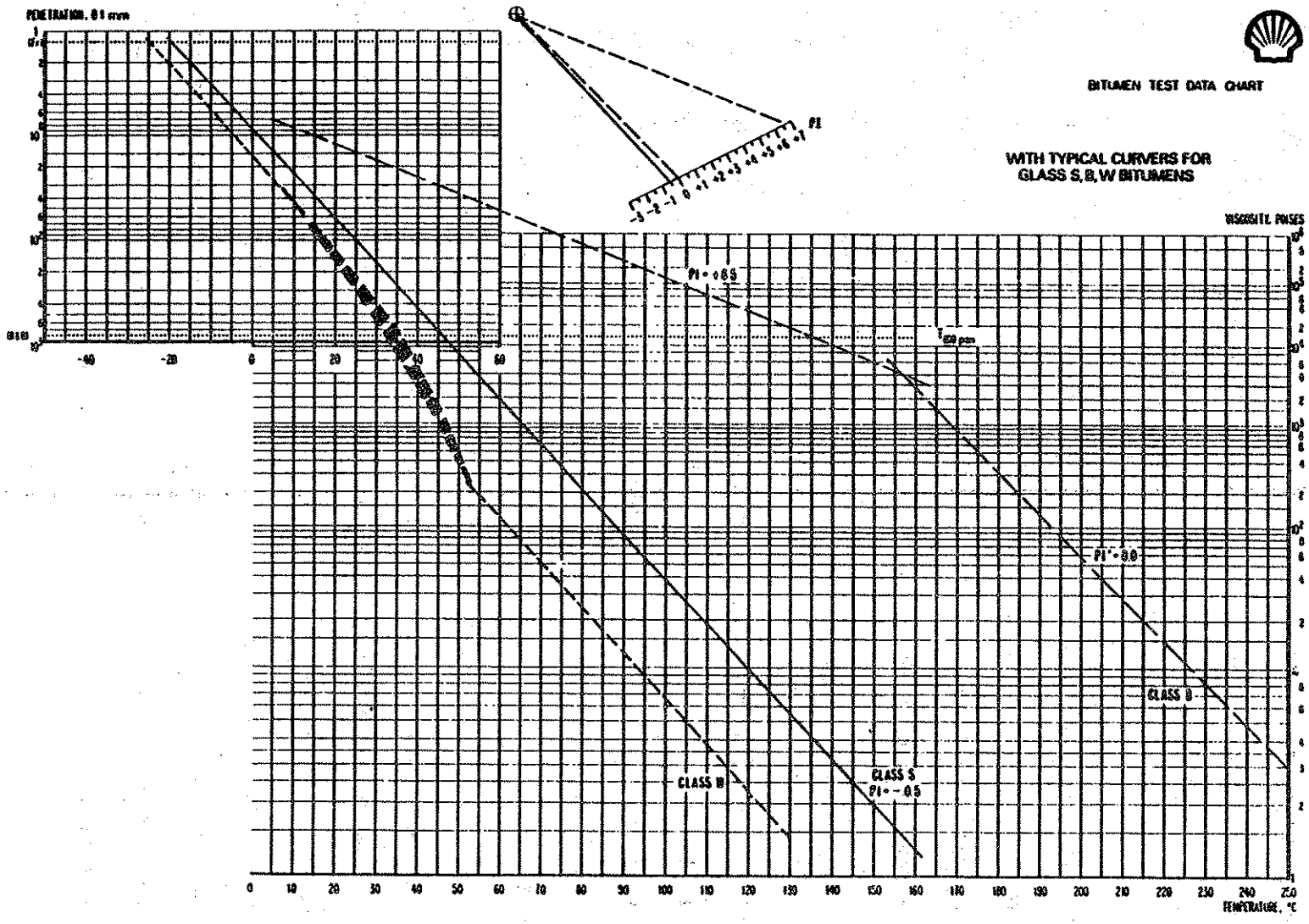


Fig. 11. Typical class S, B, and W behavior of asphalt.

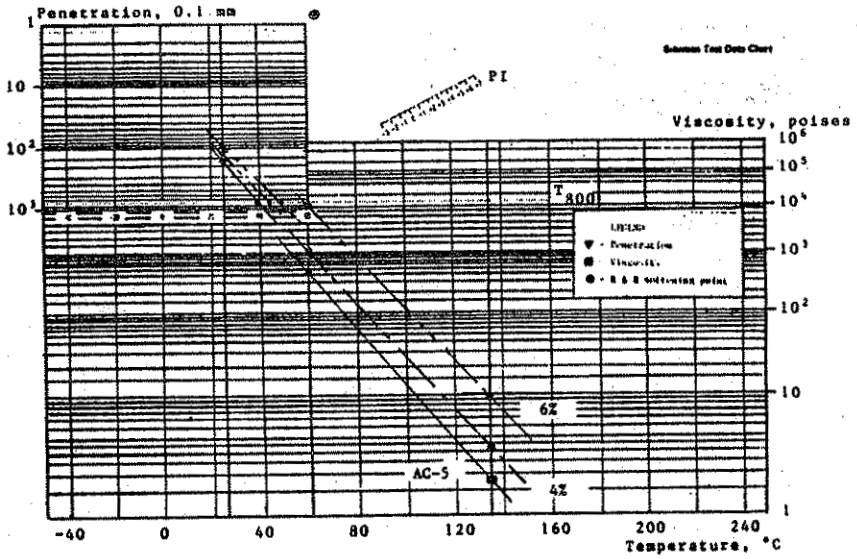


Fig. 12a. BTDC of Asphadur-modified AC-5.

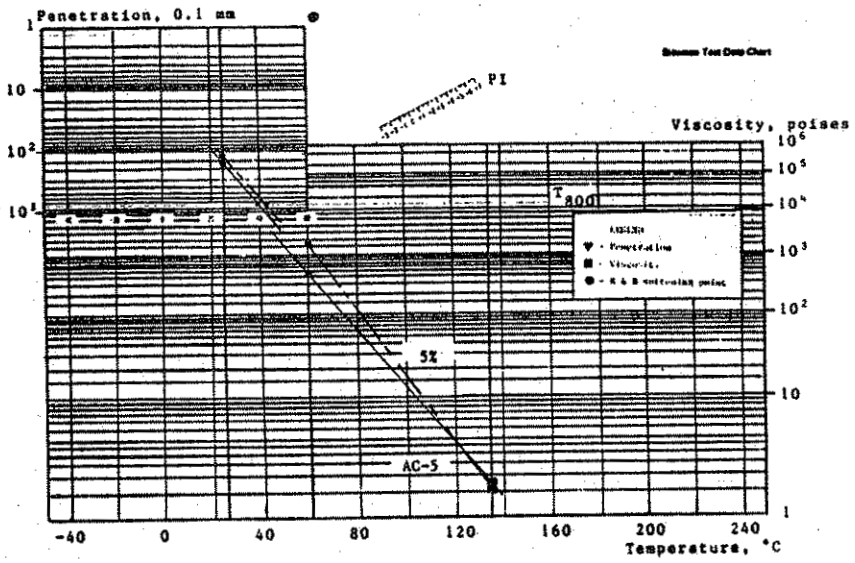


Fig. 12b. BTDC of lime-modified AC-5.

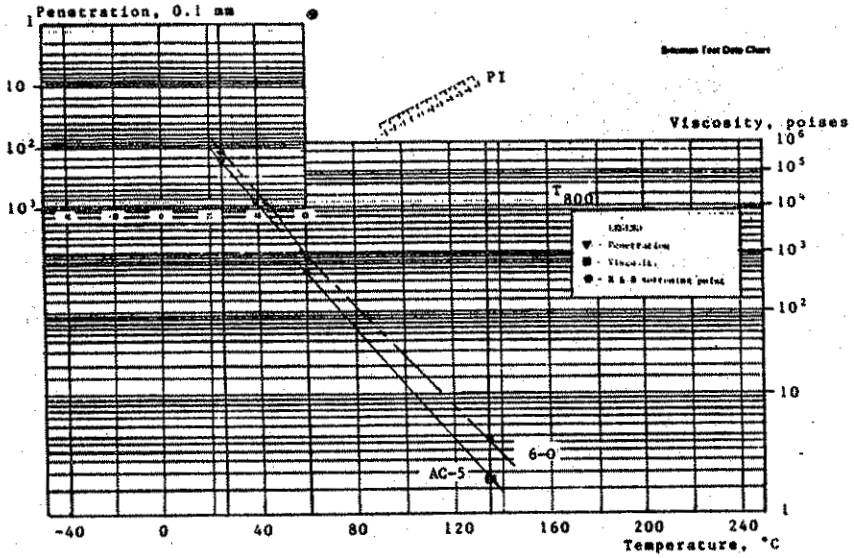


Fig. 12c. BTDC of Styrelf-modified AC-5.

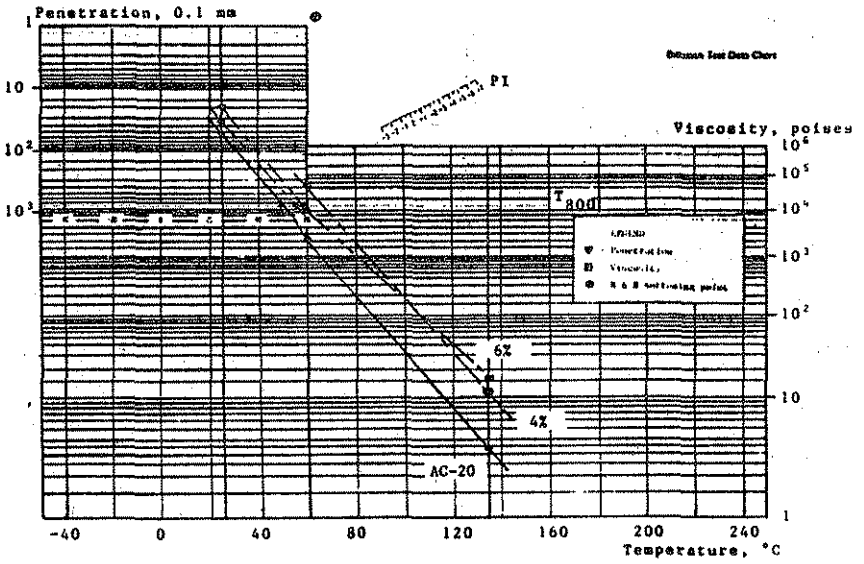


Fig. 13a. BTDC of Asphadur-modified AC-20.

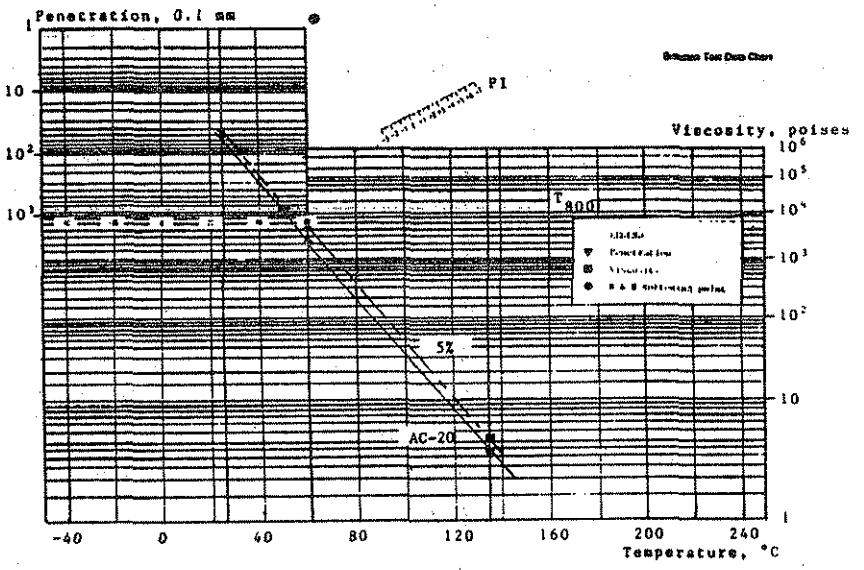


Fig. 13b. BTDC of lime-modified AC-20.

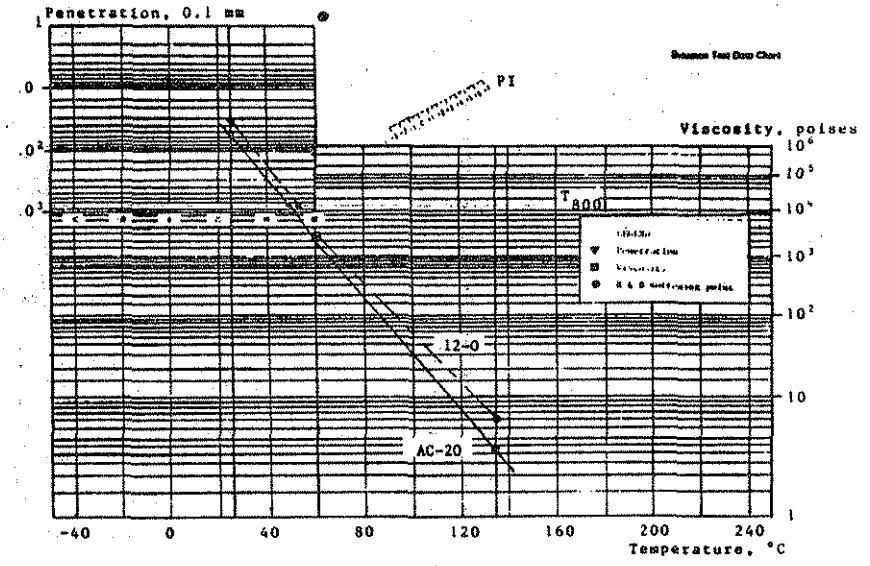


FIG. 13c. BTDC of Styrelf-modified AC-20.

These classifications indicate that the asphalt matrix changed notably with the additives, and in most of the cases the temperature susceptibility of the asphalt was improved. The data also indicated that the changes in temperature susceptibility depended not only on the type and amount of additives but also on the base asphalt.

3.3.2. Tensile, Ductility and Elastic Properties

Previous work on rubber- and neoprene-modified asphalts (22,23,24, and 40) indicated that tensile properties provide useful data on the degree to which polymers benefit asphalts. Toughness, tenacity, tensile stress, and elongation of modified asphalts were determined and the results are given in Table 3 and shown in Figs. 14 and 15.

Both Asphadur and SBS increased toughness and tenacity of the asphalts, while lime, as expected, had no effects. However, only SBS in AC-20 met the suggested specifications for polymer-modified asphalts of minimum values of 75 in.-lbs toughness and 50 in.-lbs tenacity. Except for the toughness of AC-5 binders, the thin film oven heating decreased the toughness and the tenacity of binders.

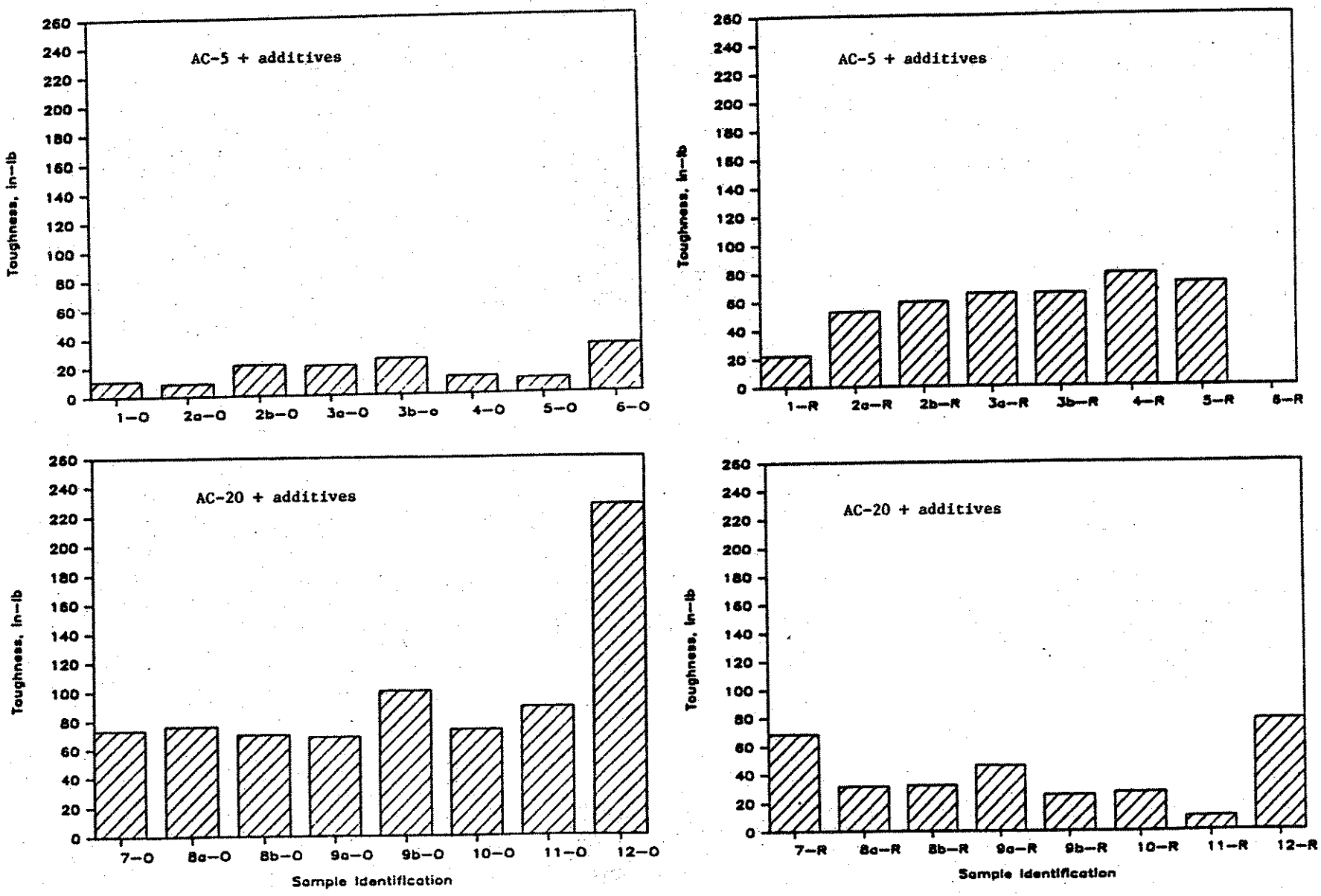
While both Asphadur and SBS increased tensile stresses of asphalts at 800% elongation, only SBS in AC-20 met the recommended stress of 4.3 psi. Furthermore, the improvements diminished upon thin film oven test heating.

Results of force ductility and elastic recovery of samples at 10° C are given in Table 4. Asphadur increased ductile force for both asphalts but did nothing to improve elastic recovery; SBS, however, reduced the ductile force but increased the percent elastic recovery significantly. Hydrated lime had no significant effects on either

Table 3. Tensile properties of binders.

MATERIAL	SAMPLE No.	TOUGHNESS in-lb	TENACITY in-lb	TENSILE stress, psi	STRESS % elong.
AC-5	1-0	11.3	4.0	0.000	800
AC-5+4% ASPHADUR	2b-0	21.4	6.1	0.000	800
AC-5+6% ASPHADUR	3b-0	24.8	6.3	0.142	800
AC-5+5% LIME	4-0	12.1	3.2	0.000	800
STYRELF IN AC-5	6-0	32.9	28.9	1.565	800
AC-20	7-0	73.6	11.9	0.853	800
AC-20+4% ASPHADUR	8b-0	70.6	15.1	2.418	6
AC-20+6% ASPHADUR	9b-0	100.4	4.9	0.000	207
AC-20+5% LIME	10-0	73.4	12.6	0.853	800
STYRELF IN AC-20	12-0	227.5	163.8	13.227	800
AC-5	1-R	22.5	5.9	0.000	800
AC-5+4% ASPHADUR	2b-R	59.9	0.9	0.000	189
AC-5+6% ASPHADUR	3b-R	65.6	3.4	8.676	4
AC-5+5% LIME	4-R	79.6	4.3	1.138	800
STYRELF IN AC-5	6-R	0.0	0.0	0.853	772
AC-20	7-R	68.9	0.0	0.000	267
AC-20+4% ASPHADUR	8b-R	32.6	0.0	0.000	10
AC-20+6% ASPHADUR	9b-R	25.9	0.0	0.000	14
AC-20+5% LIME	10-R	27.6	0.5	0.000	190
STYRELF IN AC-20	12-R	78.8	0.0	0.000	714

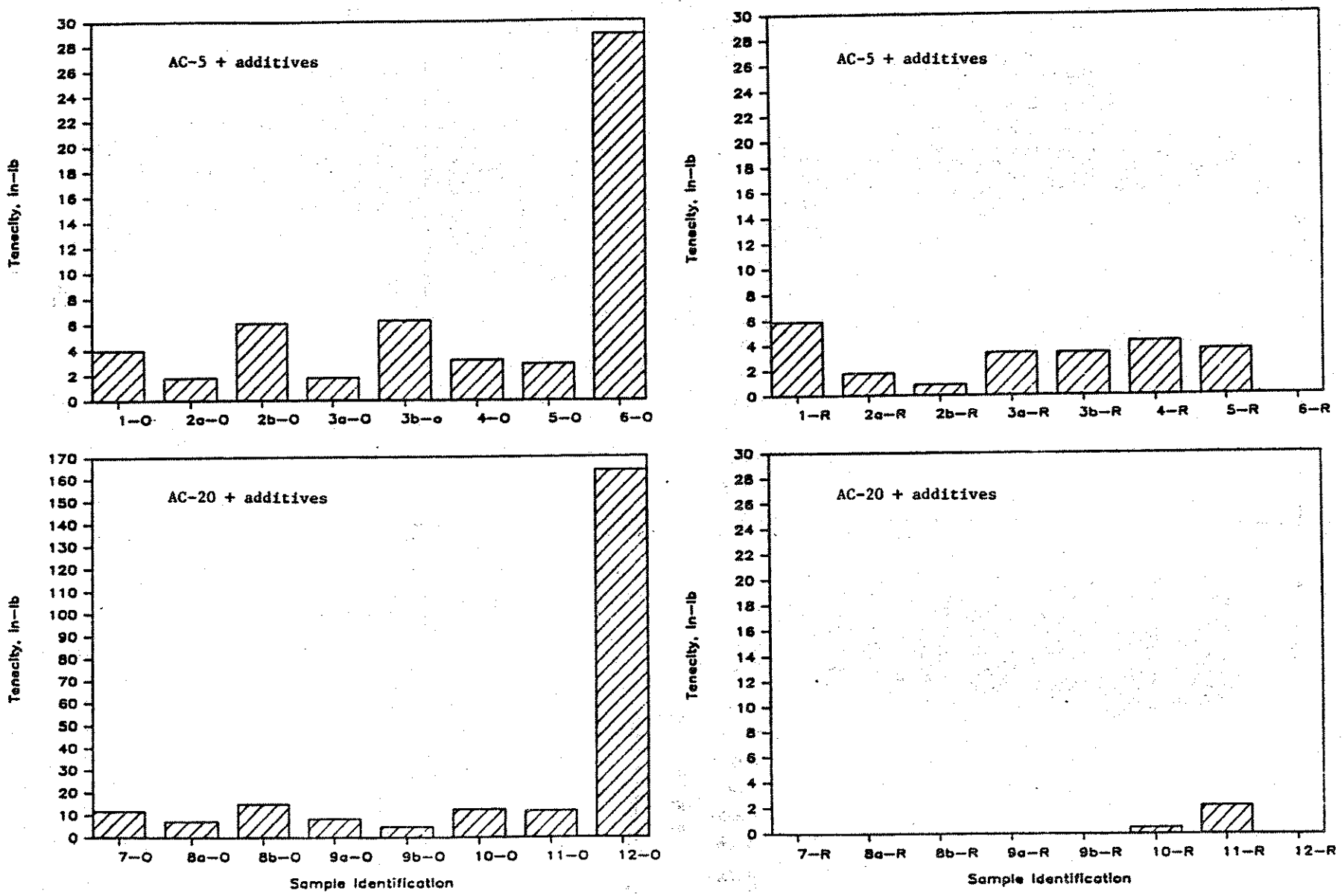
a : partially dissolved.
b : totally dissolved.
0 : original.
R : thin film oven test residue.



a. ORIGINAL BINDER BLENDS.

b. THIN FILM OVEN RESIDUES.

Fig. 14. Toughness.



a. ORIGINAL BLENDS.

b. THIN FILM OVEN RESIDUES.

Fig. 15. Tenacity.

Table 4. Ductility and elastic properties.

MATERIAL	SAMPLE No.	DROPPING BALL t2/t1	FORCE DUCT. lbs.	ELA. RECOV. %
AC-5	1-0	0.227	1.45	0.00
AC-5+4% ASPHADUR	2b-0	0.173	3.45	c
AC-5+6% ASPHADUR	3b-0	0.069	2.91	c
AC-5+5% LIME	4-0	0.034	1.50	2.50
STYRELF IN AC-5	6-0	0.923	1.27	61.25
AC-20	7-0	0.046	17.45	c
AC-20+4% ASPHADUR	8b-0	0.047	18.90	c
AC-20+6% ASPHADUR	9b-0	0.062	29.30	c
AC-20+5% LIME	10-0	0.047	15.64	c
STYRELF IN AC-20	12-0	0.615	10.00	65.00
AC-5	1-R	0.248	3.64	5.00
AC-5+4% ASPHADUR	2b-R	d	17.82	c
AC-5+6% ASPHADUR	3b-R	0.021	13.27	c
AC-5+5% LIME	4-R	0.048	8.10	c
STYRELF IN AC-5	6-R	0.334	13.64	c
AC-20	7-R	d	27.10	c
AC-20+4% ASPHADUR	8b-R	0.040	23.64	c
AC-20+6% ASPHADUR	9b-R	0.351	26.91	c
AC-20+5% LIME	10-R	d	32.73	c
STYRELF IN AC-20	12-R	d	38.00	c

a : partially dissolved.
b : totally dissolved.
c : the samples were broken before reaching 20 cm.
d : no flow.
0 : original.
R : thin film oven test residue.

property. Another measure of the elastic property of modified binders is the ratio t2/t1 obtained from the simple dropping ball test (Table 4, Fig. 16). The only significant improvement resulted from Styrelf. However, the benefits of Styrelf seemed to have diminished after thin film oven heating.

3.3.3. Chemical Properties

High pressure liquid chromatography (HPLC) is a technique whereby the molecules in an asphalt are separated according to relative size, as in sieve analysis. Although it permits the largest molecules to pass packed columns more quickly, it successively retards the passage of smaller ones. The area under the chromatogram is divided into three portions by selected elution times as the large molecular size (LMS), medium molecular size (MMS), and small molecular size (SMS). The dividing elution times were selected to maximize the differences among asphalts with respect to LMS which is found to correlate with cracking of asphalt pavements (18). Figure 17a shows the chromatogram for sample 1-0 (AC-5). Figure 17b shows the chromatograms of AC-20 (7-0) and AC-20 modified by SBS (12-0). Potentially this technique could be used to determine the percent of polymer in polymer-modified asphalts as shown by the shaded area at short retention time. Figure 18 presents the percent LMS for the 16 binder blends, original versus TFOT residues.

Data indicate that the two grades of asphalt were very similar in their molecular size distributions and that additives had little effects on percent LMS, with maximum increase of about 1% for Styrelf. However,

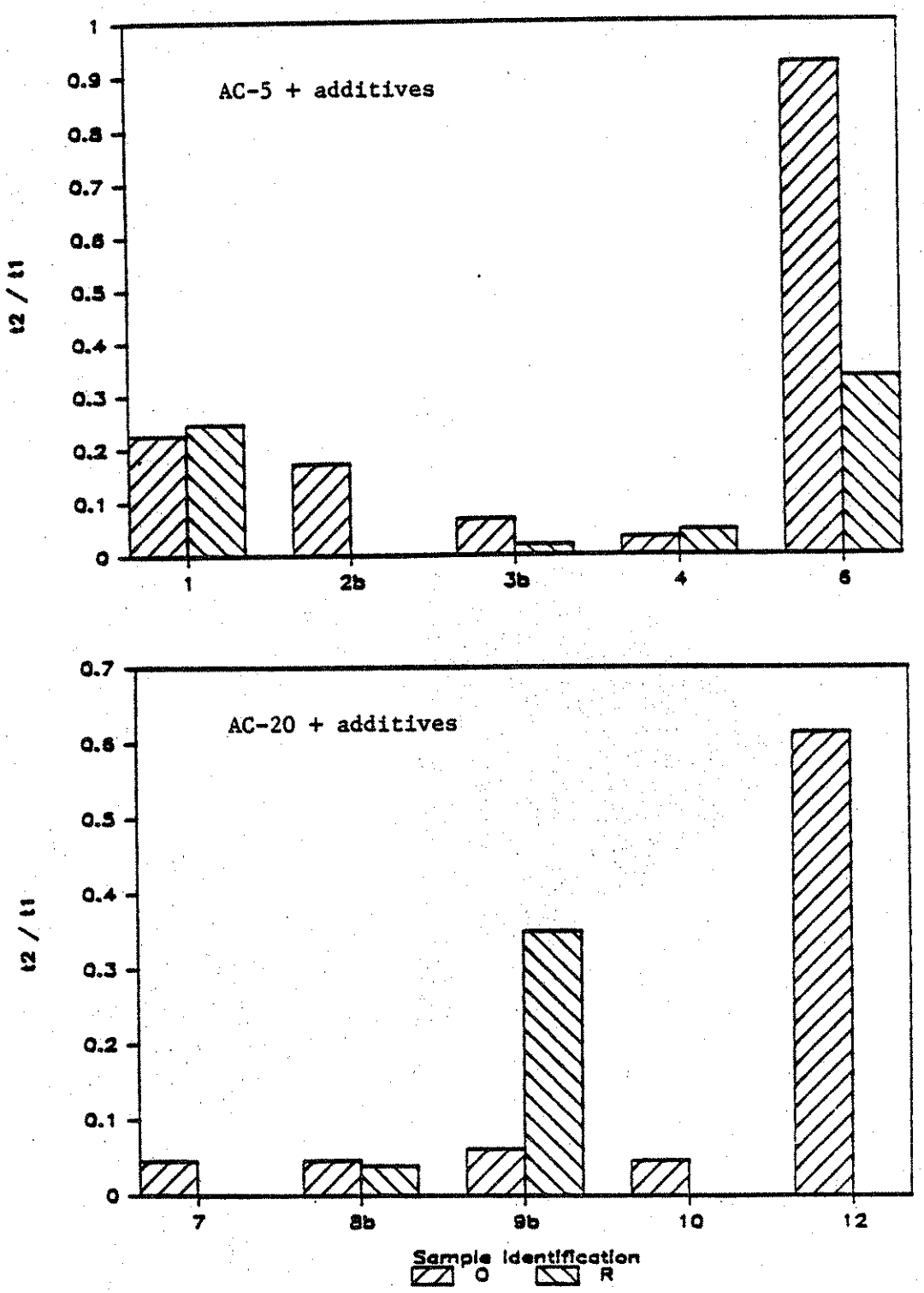


Fig. 16. Results of dropping ball tests.

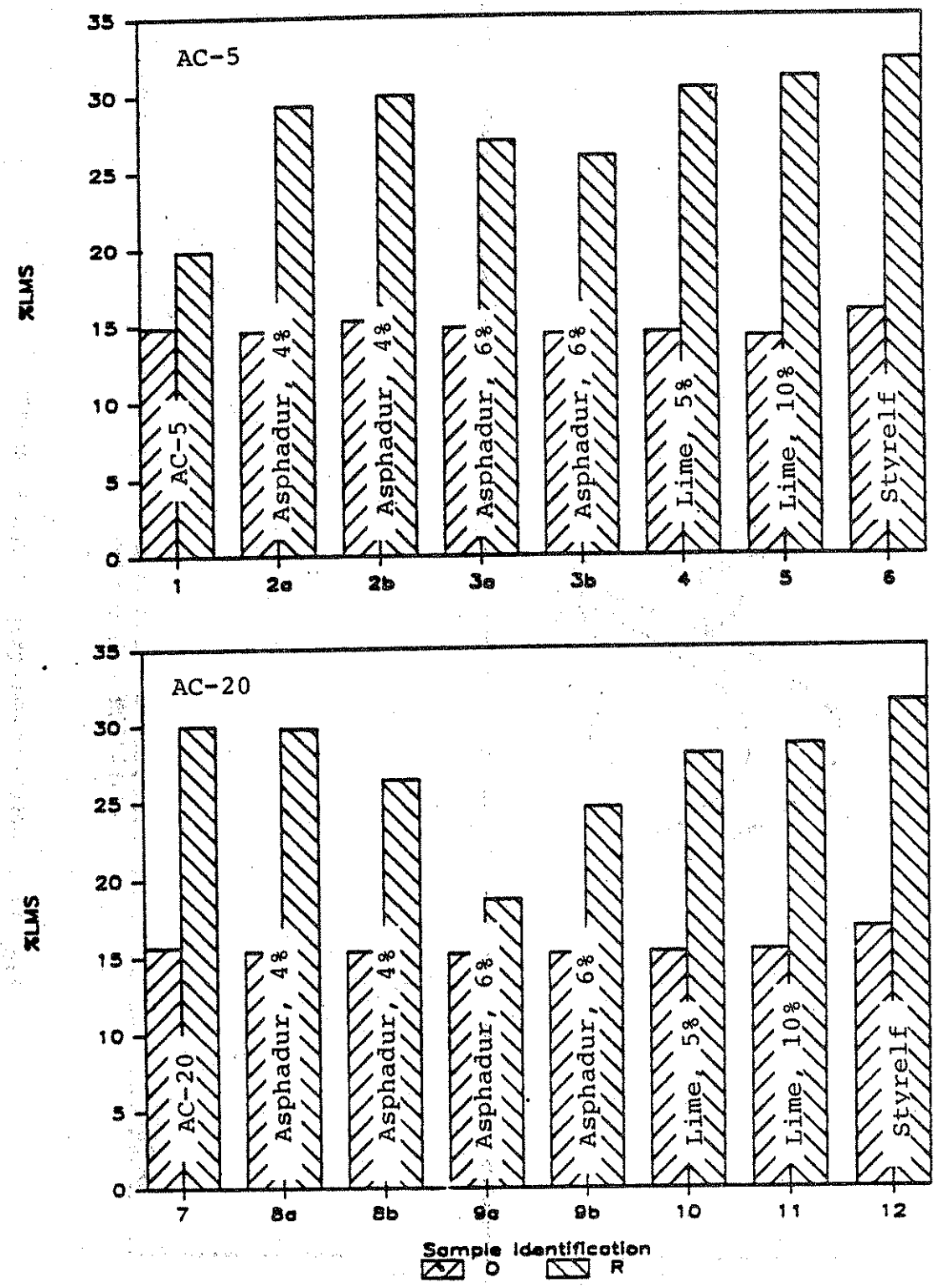


Fig. 18. Percent of LMS determined by HPLC.

the increases in percent LMS because of thin film oven treatment, which simulates hot plant mixing, were large. Excluding samples 2a, 3a, 8a and 9a because the dispersion was nonhomogeneous, the increases in percent LMS as percent of LMS in original asphalts varied from 62% for Asphadur (6%) in AC-20 to 119% for lime (10%) in AC-5. The increases in LMS for AC-5 and AC-20 without additives were 34% and 91%, respectively. The net increases in percent LMS because of thin film oven treatment ranged from 5.0% for Sample 1 (AC-5) to 16.9% for Sample 5 (10% lime in AC-5). These increases were unusually large compared to the normally expected increase of 2% to 5% based on data from asphalts extracted from pavements without additives.

On the basis of limited performance data, the maximum percent LMS recommended for climatic zone for Iowa was estimated to be about 26% (18). According to this criterion, the only satisfactory binder was AC-5 without additives. Binders with Asphadur and hydrated lime would be considered marginal and those with Styrelf would be critical with respect to cracking.

However, these remarks must be viewed with caution because of the problems of solubility of lime and Asphadur in THF (tetrahydrofuran) solvent used for the mobile phase in HPLC and because of the nonhomogeneous dispersion of some of the binder blends. Furthermore, the recommended criterion was based on asphalts in pavements without additives. It is likely that separate HPLC techniques and/or criterion must be developed for asphalt pavements with additives.

The reflected microscopy technique was explored as a possible means to better understand the polymer dispersion and the structure of the polymer-in-asphalt system and ultimately to provide information on the optimization of polymer modification.

Pure asphalt (AC-5) does not produce observable fluorescence under blue excitation. Likewise, asphalts with lime additions (Samples 4, 5, 10, and 11) showed no fluorescence. While samples 6 and 12 contained 3% to 5% SBS polymer, the reflected fluorescence micrographs indicated no fluorescence particles. This result indicates that SBS is not in a physical dispersion but rather forms a new cross-linked homogeneous reaction product because of the blending techniques and secondary additives used in the manufacturing process.

Of interest are the eight blends containing Asphadur (polyolefins). Figure 19 shows typical micrographs of 4% and 6% Asphadur in AC-5. Continued heating, either during blend preparation (2b and 3b) or thin film oven treatment (2a-R and 2b-R), appeared to have reduced the particle size and increased the uniformity of size distribution (2b-O, 2b-R and 3b-O). Higher polymer content is reflected in the higher particle density (3a-O and 3b-O). Figure 20 shows the micrographs of Asphadur in AC-20. The same observations made for samples 2a and 2b (Asphadur in AC-5) can be made here. However, undissolved large Asphadur particles are more evident for high viscosity AC-20 (Samples 8a and 9a). The significance of particle size and size distribution and the halos surrounding larger particles in partially dissolved samples (8a and 9a) need further study.

AC-5

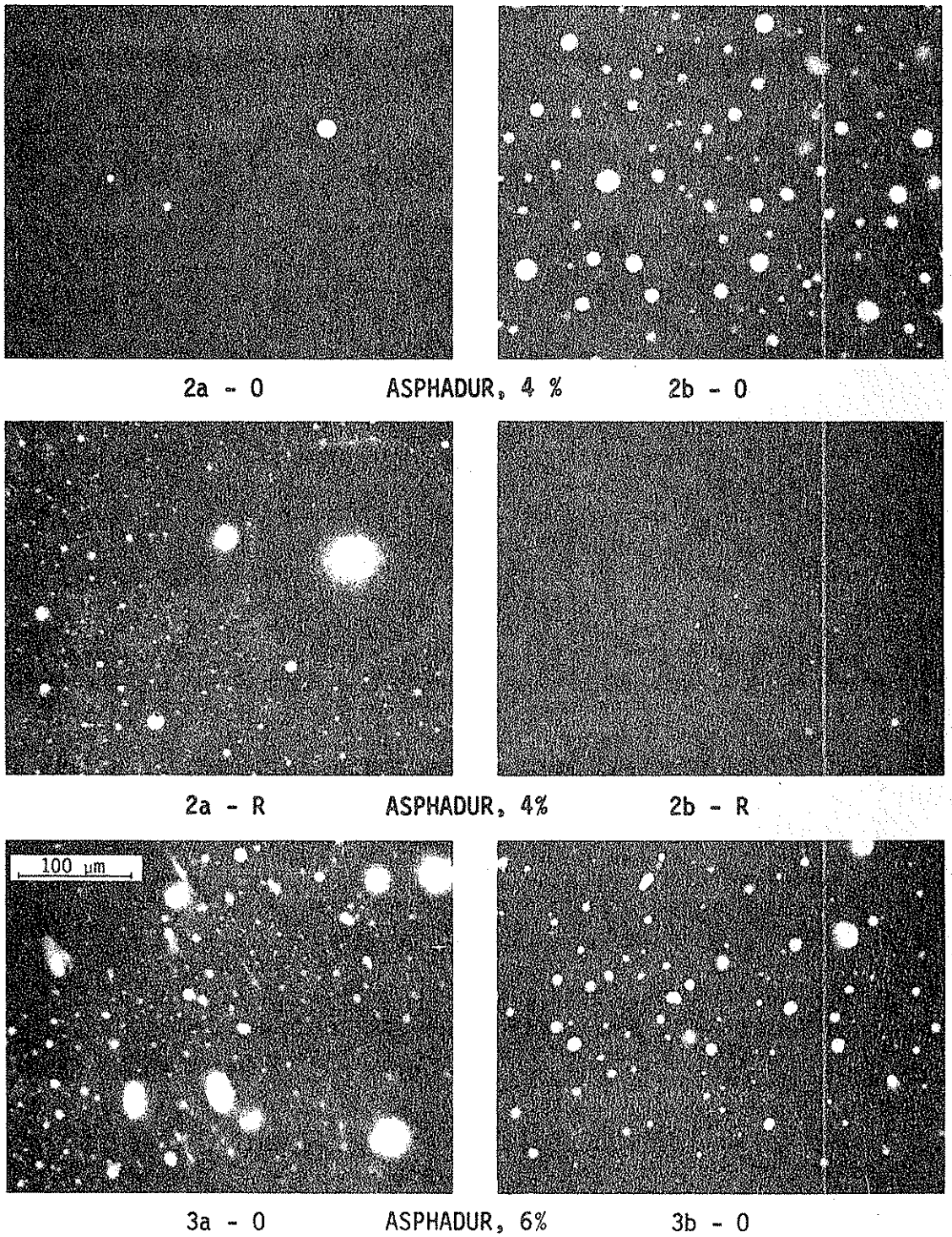
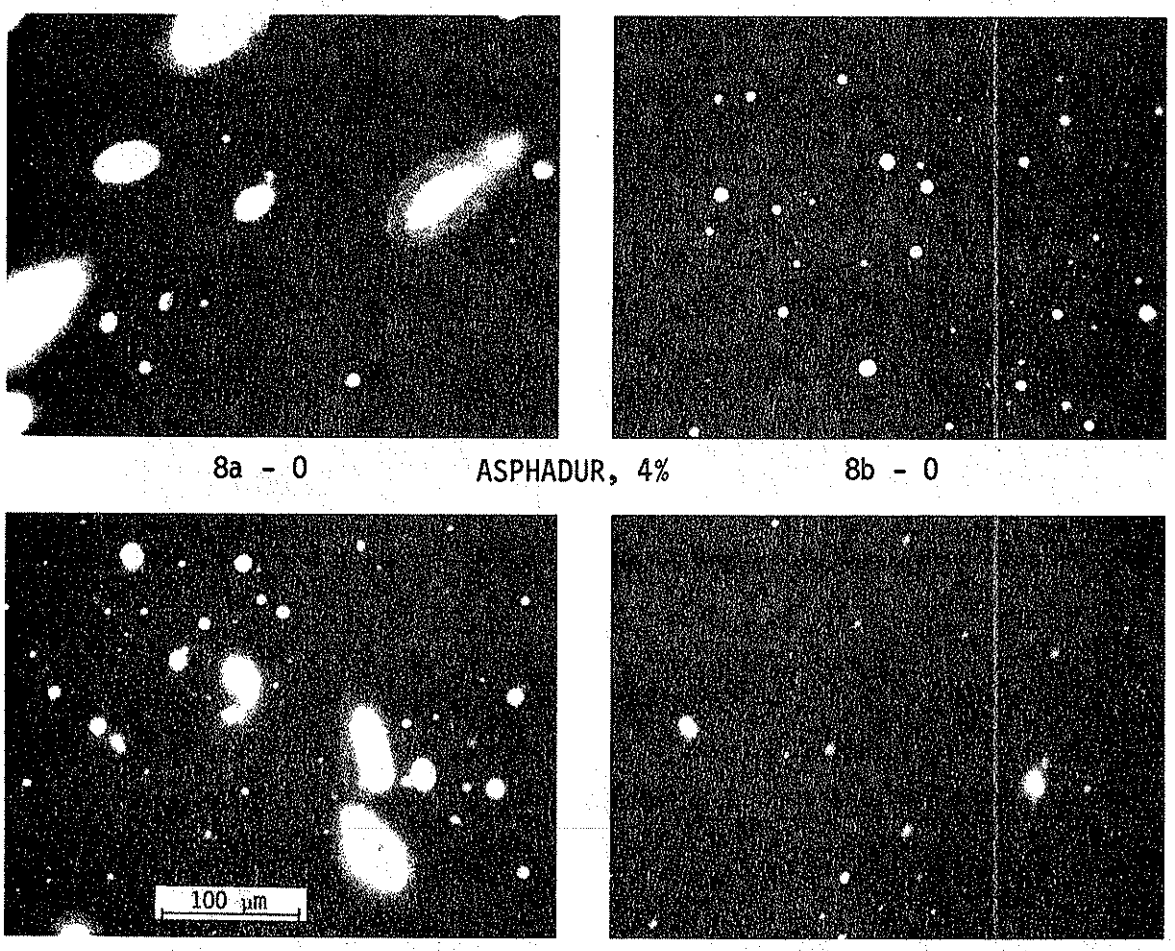


Fig. 19. Flourescent micrographs of Asphadur in AC-5.

AC-20



8a - 0 ASPHADUR, 4% 8b - 0

9a - 0 ASPHADUR, 6% 9b - 0

Fig. 20. Flourescent micrographs of Asphadur in AC-20.

Eight samples from the original (O series) were selected for x-ray diffraction study. The standard procedure is a $\theta/2\theta$ scan for the analysis of the materials. But because of some preferred orientation of asphalt molecules, using only a $\theta/2\theta$ scan may not show the complete picture; therefore, a 2θ scan was also done for all the samples.

In a $\theta/2\theta$ scan, both θ and 2θ vary; and whenever the Bragg equation is satisfied, it gives a diffraction peak. The Bragg equation is

$$\lambda n = 2d \sin$$

where λ = wavelength

d = interplaner spacing

θ = angle of incidence.

In a 2θ scan, θ is fixed and 2θ varies. If there is any preferred orientation of molecules, the diffraction peak appears when the Bragg equation is satisfied, and the orientation can be calculated (1).

Results obtained with $\theta/2\theta$ scans are presented in Figures 21-23. Figure 21, which compares the two asphalts AC-5 and AC-20 used in this study, indicates that molecules of both asphalts are arranged in the horizontal direction with an average separation of 4.7 Å. Both peaks have a breadth of about 9.8 Å at half maximum intensity, which indicates the same size of minute clusters of molecules. The main difference between the two asphalts is in the height of the shoulder to the left of the peak. This shoulder is due to low-angle scattering of x-rays and is a measure of the size and abundance of dispersed particles of asphaltenes dispersed in resinous and oily fractions of asphalts (53).

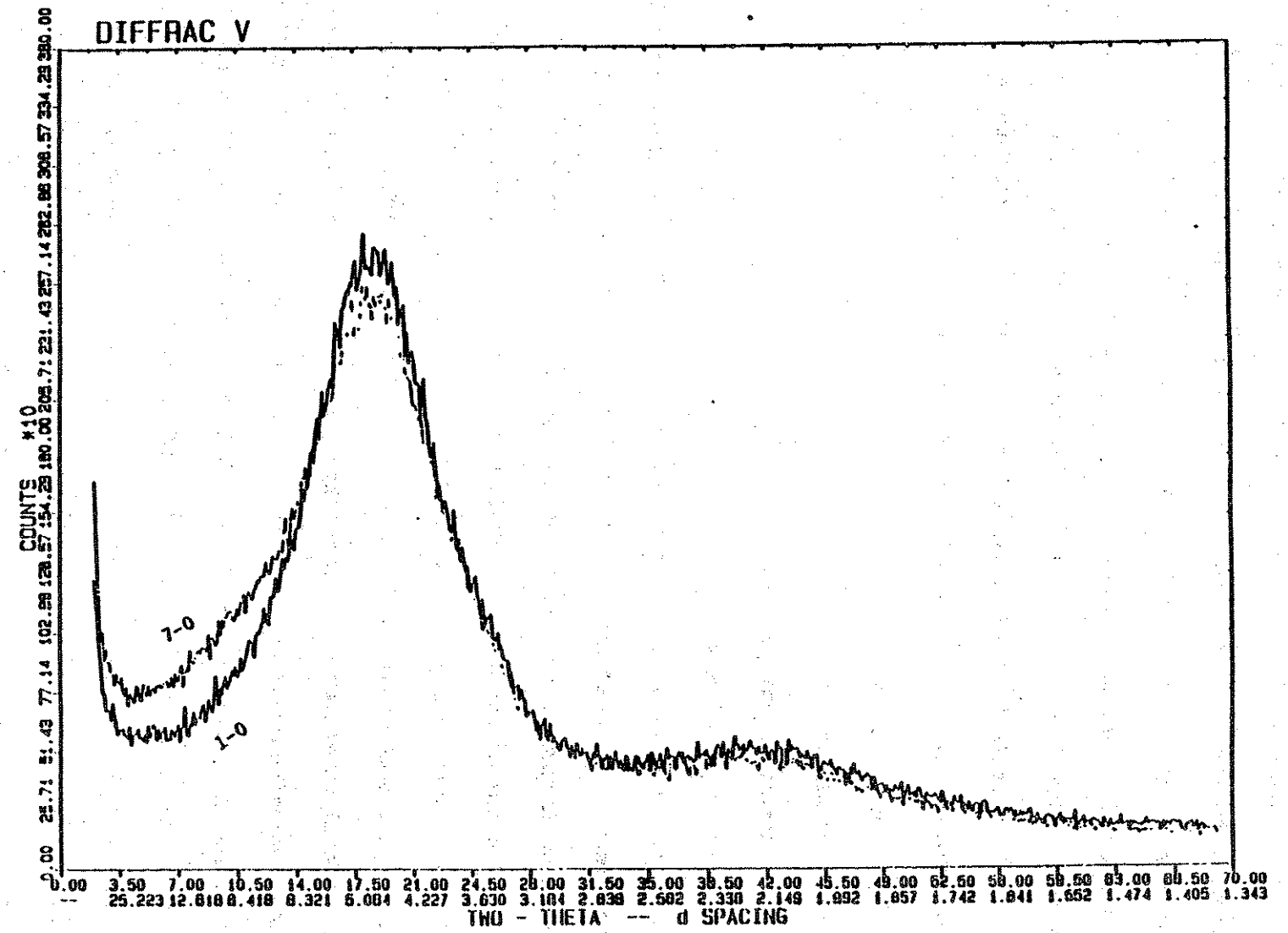


Fig. 21. Theta/two-theta scan. AC-5 versus AC-20.

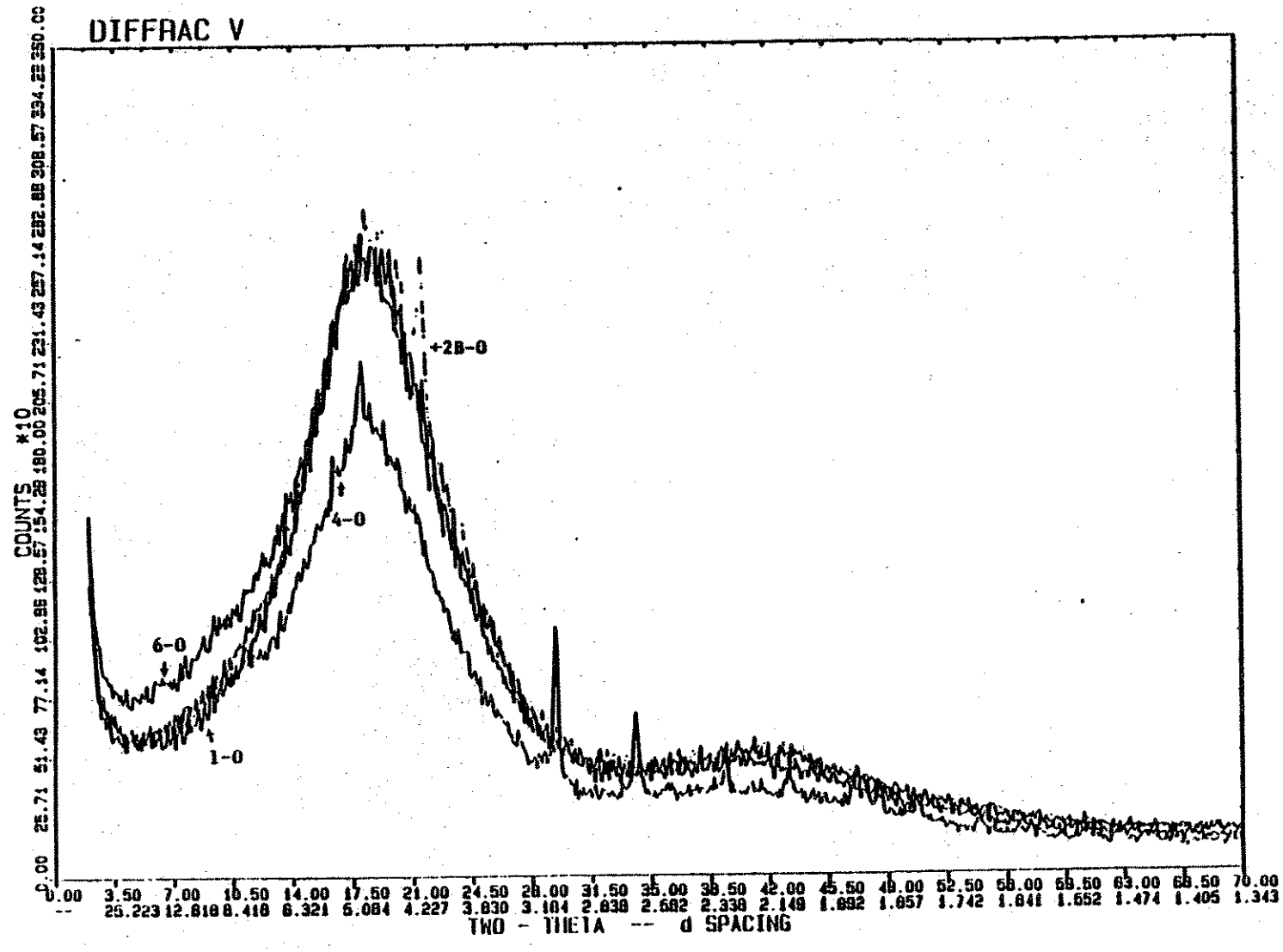


Fig. 22. Theta/two-theta scan, AC-5 with additives.

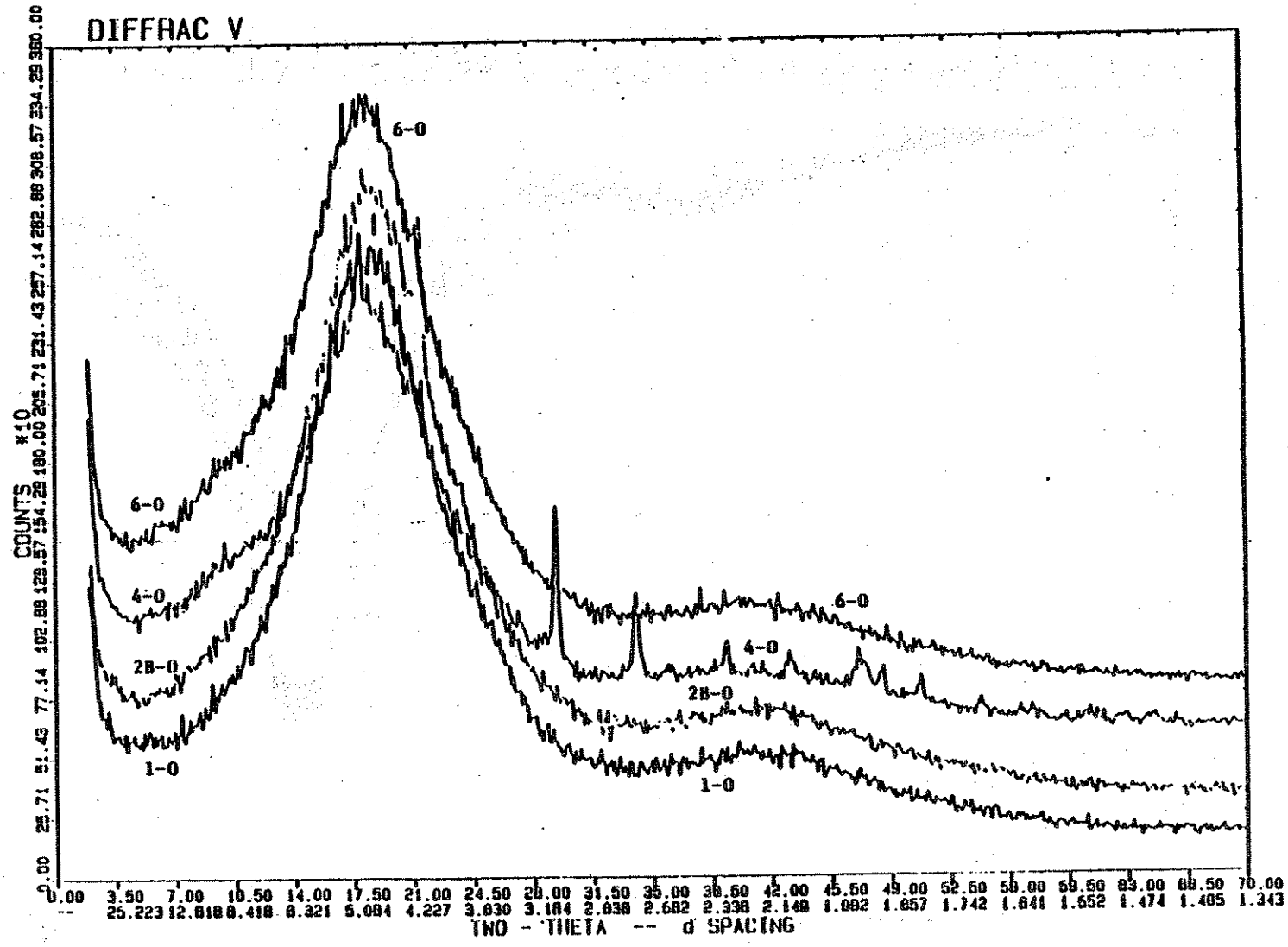


Fig. 23. Theta/two-theta scan, AC-5 with additives
vertical scale offsets).

According to Williford (53), the higher the shoulder the better the asphalt. Effects of additives, for example, lime, Asphadur, and SBS, on AC-5 are compared in Figs. 22 and 23. As can be seen from Fig. 22, the most significant effect is demonstrated by Styrelf in raising the low-angle scattering shoulder. The reduced intensity of the sample containing lime is probably due to absorption of the copper radiation by calcium. The crystalline peaks observed with this sample correspond to lime crystals and indicate that the lime did not chemically react with the component of asphalt. The sample containing Asphadur also produced a sharp crystalline peak (d-spacing of 4.1 Å). Since a diffraction pattern of Asphadur alone could not be obtained at the present time, it is not yet possible to state whether this peak corresponds to Asphadur or to a reaction product.

The 2θ scans performed indicated that major alignment of molecules with about 4.7 Å separation occurred in the horizontal direction. When θ angle was fixed at 5, 10, and 15 degrees, the peaks were flattened out, peak intensities were reduced, and noncrystalline peak positions were shifted. These results support the hypothesis that a horizontal orientation is preferred. Figures 24 and 25 show 2θ scans for samples containing lime and Asphadur. The reduction of intensities and broadening of the peaks of not only the asphalt matrix but also of the crystalline peaks suggest that even the crystals of Asphadur and lime are also oriented in the matrix, possibly by attaching themselves to asphalt molecules. This may explain the observations made in viscosity studies.

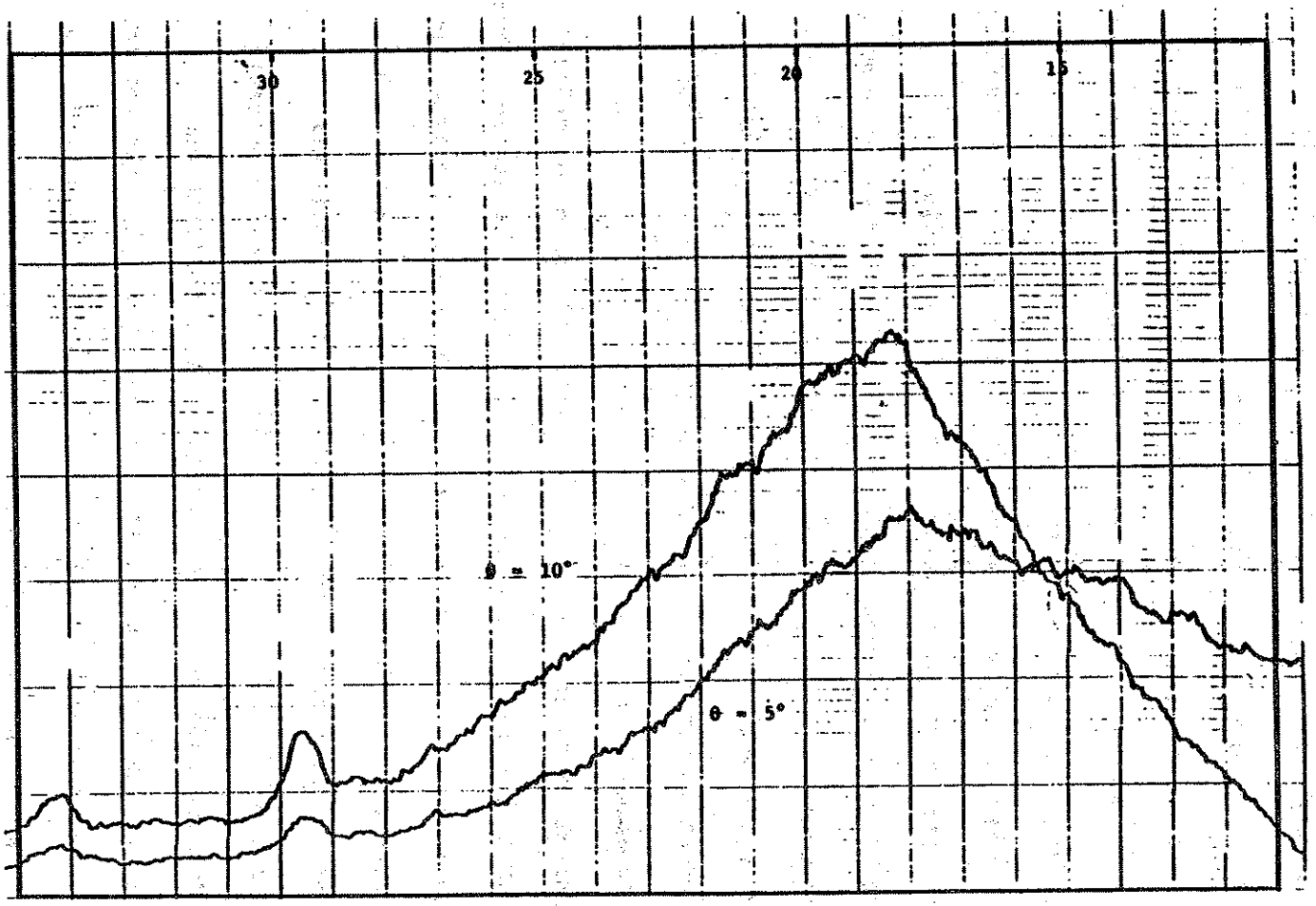


Fig. 24. Two-theta scan, lime (5%) in AC-5.

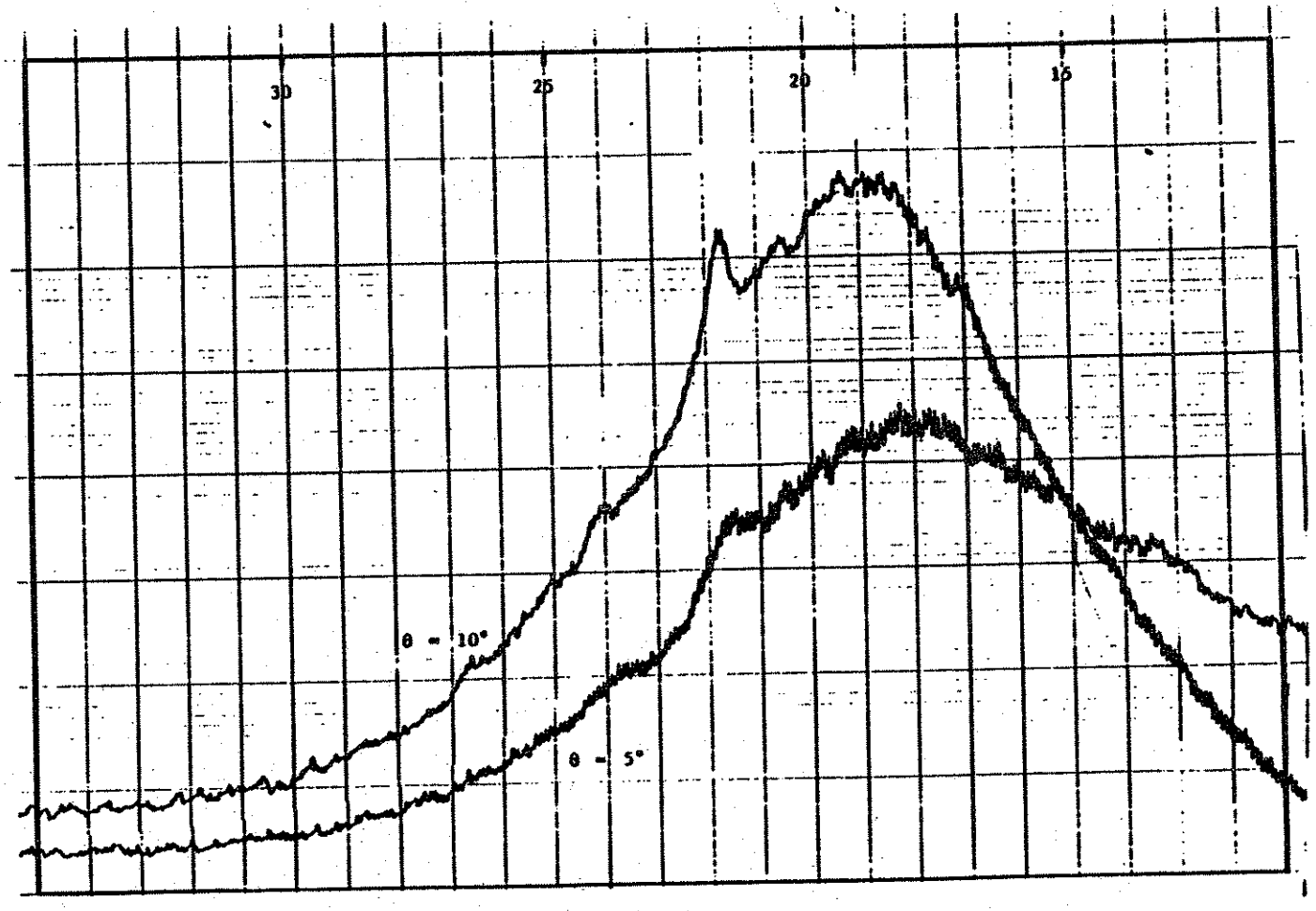


Fig. 25. Two-theta scan, Asphadur (4%) in AC-5.

From the above discussion, we can conclude that the introduction of the additives did change the structure and behavior of the asphalt. Increasing low-angle scattering and preferred orientation of the particles are to be noted. We expect that identification of additives and their effects on asphalts can be rapidly and economically determined by x-ray diffraction techniques based on low-angle scattering intensities and the shape of the amorphous peaks.

In the future, we suggest that more comprehensive studies be undertaken using θ scans and especially diffraction in transmission mode (1) for a complete understanding of molecular make-up of asphalts and the effects of additives as related to their engineering performance.

3.3.4. Temperature Susceptibility

Asphalt cements of high-temperature susceptibility may contribute to rutting at high pavement temperatures and cracking at low pavement temperatures. One of the often-quoted benefits of polymer additives is the reduction of temperature susceptibility of paving asphalts.

Temperature susceptibility of an asphalt can be evaluated by using the Shell Bitumen Test Data Chart (BTDC) (15), the Penetration Index (PI) (52), the Pen-Vis Number (PVN) based on viscosity at 60° C or viscosity at 135° C (33), the viscosity-temperature susceptibility (VTS), and the Asphalt Class Number (CN) (4). The basic rheological data as plotted on BTDC are shown in Figs. 12 and 13; and the derived PI, PVN, VTS and CN of the binder blends studied are given in Table 5.

The CN shows the difference between measured and predicted penetration at 25° C. A small negative or positive CN value indicates a Class S (straight run with a straight line, temperature-viscosity-

Table 5. Temperature susceptibility.

MATERIAL	SAMPLE No.	CN	PIm	VTS	PVN,60	PVN,135
AC-5	1-0	9.28	-1.336	3.618	-0.832	-1.012
AC-5+4% ASPHADUR	2b-0	5.82	-0.673	3.420	-0.387	-0.327
AC-5+6% ASPHADUR	3b-0	-25.97	0.347	3.499	1.829	1.080
AC-5+5% LIME	4-0	-22.45	-0.939	4.318	0.281	-1.475
STYRELF IN AC-5	6-0	10.50	-0.286	3.217	-0.375	0.071
AC-20	7-0	6.46	-1.105	3.675	-0.854	-1.073
AC-20+4% ASPHADUR	8b-0	-36.10	-0.601	3.827	1.415	0.152
AC-20+6% ASPHADUR	9b-0	30.24	-1.247	3.089	-0.830	-0.047
AC-20+5% LIME	10-0	0.75	-1.354	3.708	-0.578	-0.935
STYRELF IN AC-20	12-0	26.63	-1.245	3.292	-1.244	-0.695
AC-5	1-R	13.56	-1.748	3.546	-1.084	-1.034
AC-5+4% ASPHADUR	2b-R	-285.19	0.390	c	c	-0.249
AC-5+6% ASPHADUR	3b-R	c	-1.239	c	c	c
AC-5+5% LIME	4-R	c	-0.516	c	c	c
STYRELF IN AC-5	6-R	-1.55	-0.033	3.514	-0.135	-0.304
AC-20	7-R	22.11	0.814	3.178	-0.860	-0.222
AC-20+4% ASPHADUR	8b-R	c	-0.695	c	c	c
AC-20+6% ASPHADUR	9b-R	c	-0.078	c	c	c
AC-20+5% LIME	10-R	c	-0.493	c	c	c
STYRELF IN AC-20	12-R	-12.12	-0.454	3.071	-1.116	-0.227

a : partially dissolved.
b : totally dissolved.
c : could not be determined due to absence of viscosity data.
CN : class number.
PIm : measured penetration index.
VTS : Viscosity-temperature susceptibility.
PVN,60 : Penetration-viscosity number @ 60 C.
PVN,135 : Penetration-viscosity number @ 135 C.
0 : original.
R : thin film oven test residue.

penetration plot) asphalt. High positive CN values indicate Class W (waxy) asphalts, and high negative CN values indicate Class B (blown) asphalts. Either case reflects substantially high- and low-temperature susceptibility. On the basis of CN, Asphadur (except 6% in AC-20) and lime decreased the temperature susceptibility; and SBS increased the temperature susceptibility, especially in AC-20.

According to the PI, all additives decreased the temperature susceptibility of AC-5, but increased the temperature susceptibility of AC-20, except Asphadur at 4% (Fig. 26). In general, temperature susceptibility (VTS) at a high-temperature range (60° C to 135° C) seemed to be decreased because of polymer modification but increased because of hydrated lime (Fig. 27).

On the basis of the PVN, data indicated decreases in temperature susceptibility because of additives. The exceptions were the effects of lime on AC-5, based on PVN from viscosity at 135° C and the effect of SBS on AC-20, based on PVN from viscosity at 60° C. Both of these estimates showed increases in temperature susceptibility (Fig. 28).

When all the indices were considered, all the additives appeared to decrease the temperature susceptibility of the asphalts studied, especially for AC-5 and at higher temperature ranges. Temperature susceptibility of asphalts can be reduced by (a) increasing viscosity at high temperatures, (b) decreasing viscosity at low temperatures, and (c) increasing viscosity at high temperatures substantially more than the viscosity increase at low temperatures. The apparent decrease in temperature susceptibility of polymer-modified asphalts in this study resulted from a combination of mechanisms.

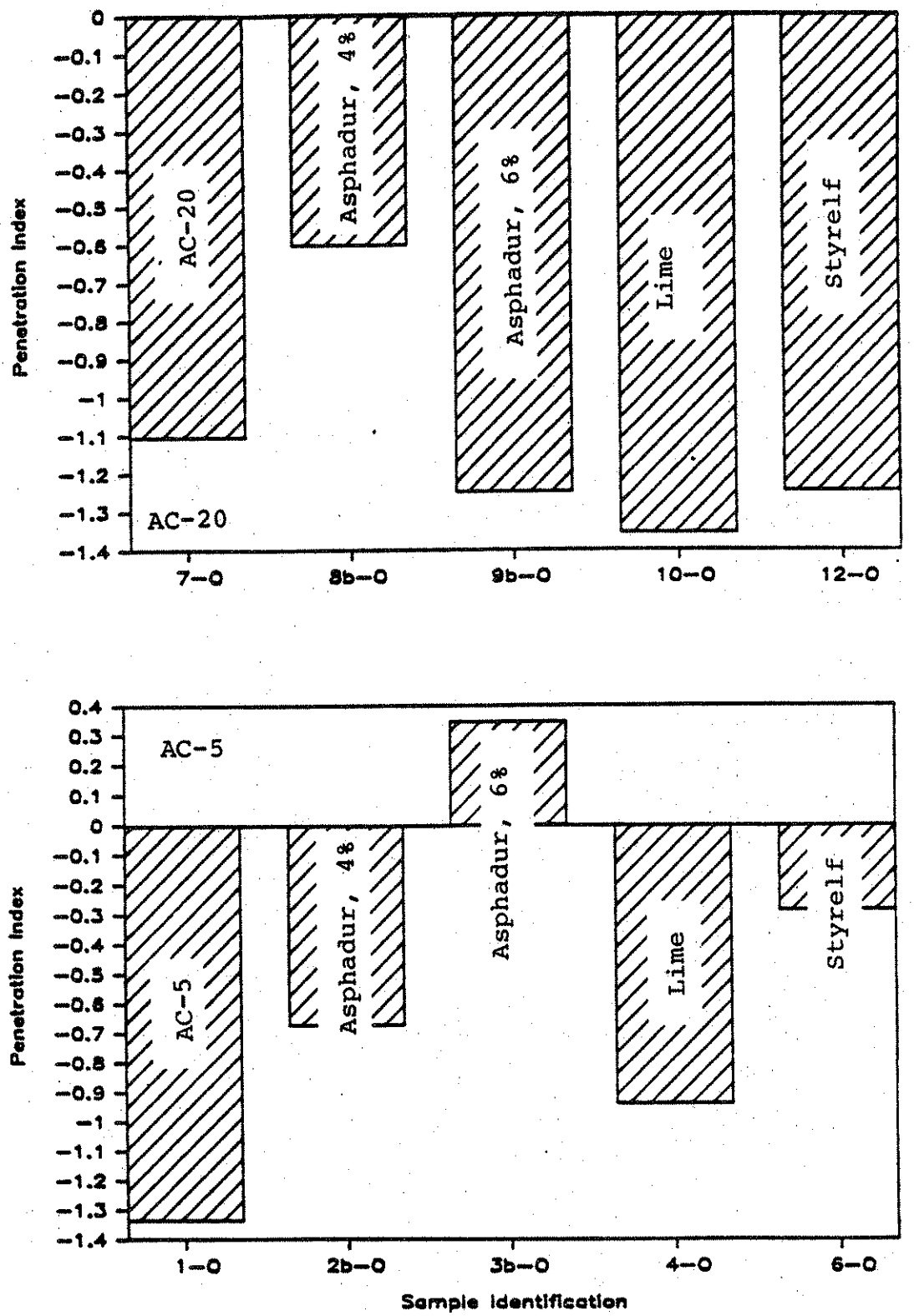


Fig. 26. Penetration index.

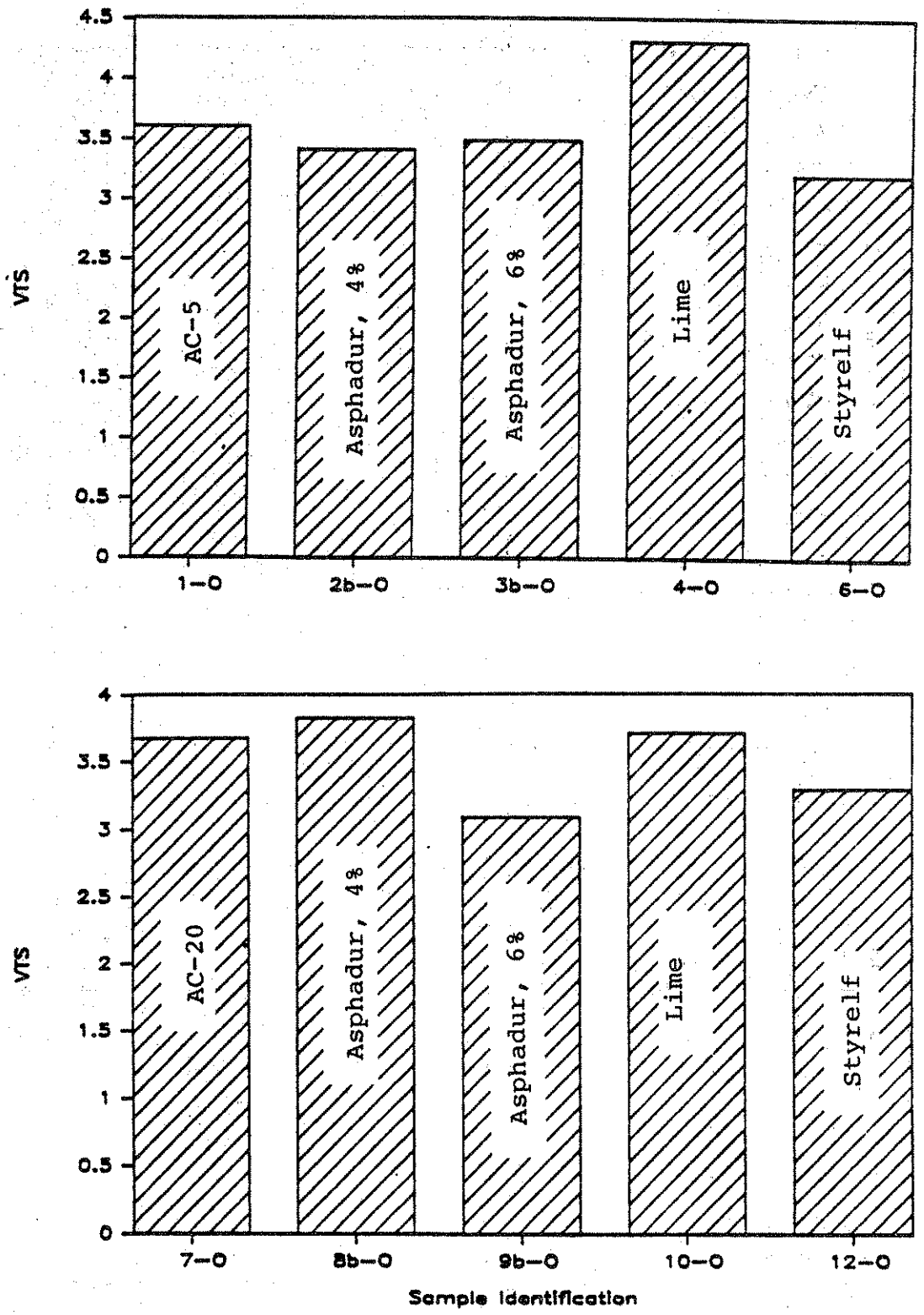
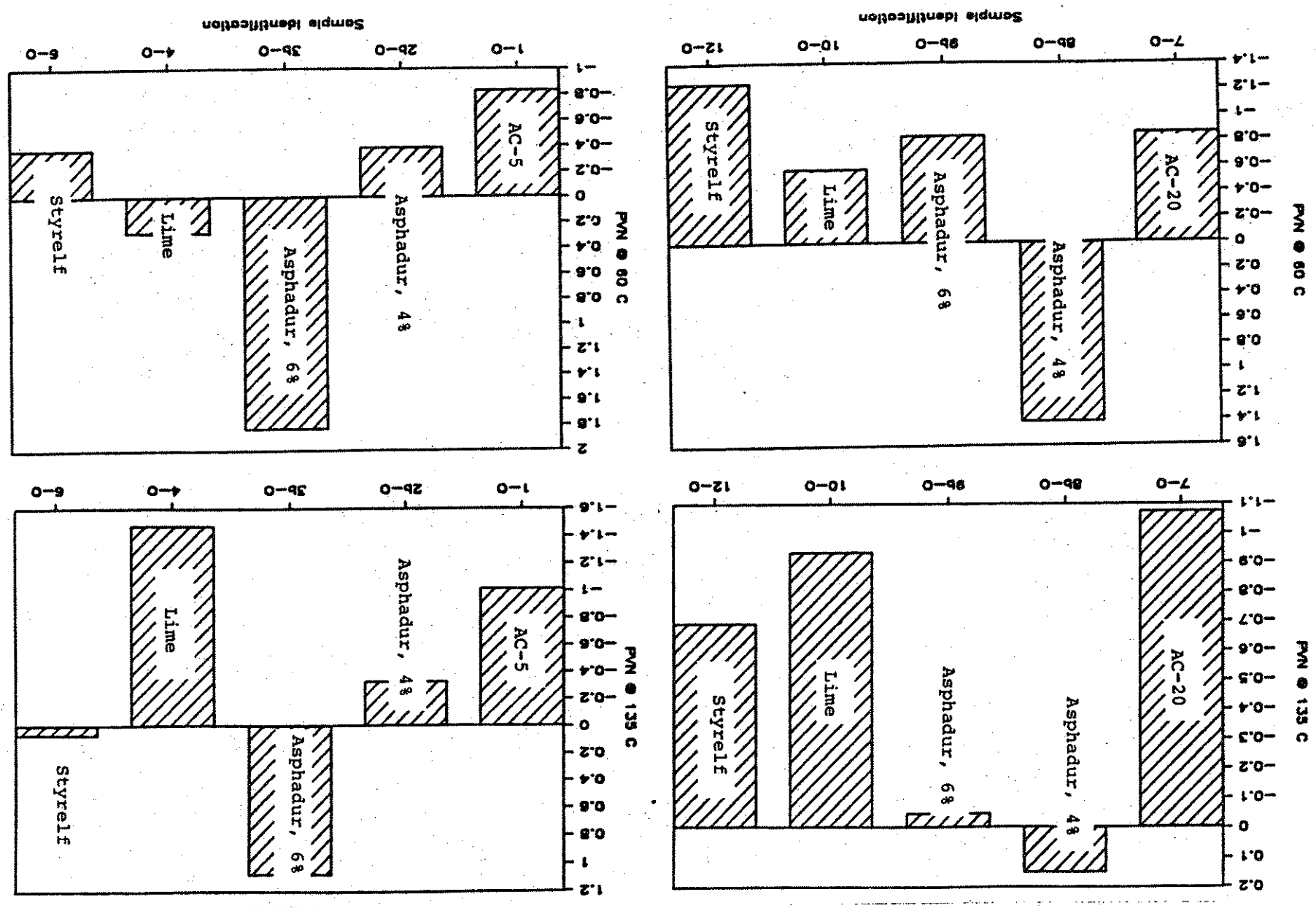


Fig. 27. Viscosity-temperature susceptibility.



a. AC-5

b. AC-20

Fig. 28. Penetration-viscosity number (PVN).

Haas (13) recently suggested a minimum PVN to avoid low-temperature cracking. If we use his suggestion and assume a minimum design temperature of -23° C (-10° F) for Iowa, the required minimum PVN would be -0.5 and 1.4, respectively. On the basis of these criteria, asphalts AC-5 and AC-20, used in this study without additives, would be considered susceptible to low-temperature cracking; and AC-5 with either Asphadur or SBS would be crack resistant.

3.3.5. Potential for Cracking and Rutting

Other factors being equal, increases in viscosity at the 60° C to 135° C range will benefit the rutting resistance of asphalt pavements. On the basis of substantial increases in viscosity at 60° C and 135° C (Table 2) and a decrease in temperature susceptibility (Table 5), we may infer that both Asphadur and SBS should improve the rutting resistance of asphalts.

Reduced temperature susceptibility, for example, increases in PVN (Table 5), would lead one to expect improved low-temperature cracking resistance of polymer-modified asphalts. Low-temperature asphalt stiffness has been correlated with pavement cracking associated with nonload conditions. The effects of additives on low-temperature behavior of asphalts can be evaluated either by estimating the temperature at which asphalt reaches a certain critical or limiting stiffness or by comparing the stiffness of asphalts at low temperatures (long loading times) (3).

Table 6 presents the results of estimated low-temperature cracking properties of binders involving two asphalts with three additives. The

properties include cracking temperature (CT), temperature corresponding to asphalt thermal cracking stress of 72.5 psi (5 x 10 Pa), based on penetrations at 5° C and 25° C, temperature of equivalent asphalt stiffness of 20,000 psi at 10,000 sec loading time (TES), estimated stiffness at -23° C and 10,000 sec loading time, and stiffness at -29° C and 20,000 sec loading time. The following can be observed:

- Softer grade AC-5 had a lower cracking temperature and reached a critical stiffness of 20,000 psi at a lower temperature than harder asphalt AC-20 (Fig. 29).
- Harder asphalt AC-20 benefitted more from additives than softer asphalt AC-5. Lowered cracking temperatures occurred in AC-20 in every case, but in AC-5 lime and Asphadur increased the predicted cracking temperature (Fig. 29).
- On the basis of temperatures predicted to reach critical stiffness of 20,000 psi (TES), only Asphadur at 6% and Styrelf showed beneficial effects on AC-5.
- Stiffness at low temperatures and long loading times increased in every case when additives were used. However, on the basis of critical cracking stiffness of 20,000 psi criterion, only Asphadur and lime in AC-20 will be expected to crack at -29° C (-20° F).

Data in Table 6 and the above observations must be viewed with caution because the limiting stiffness criteria for asphalt cements may or may not be satisfactory for additive-modified asphalts.

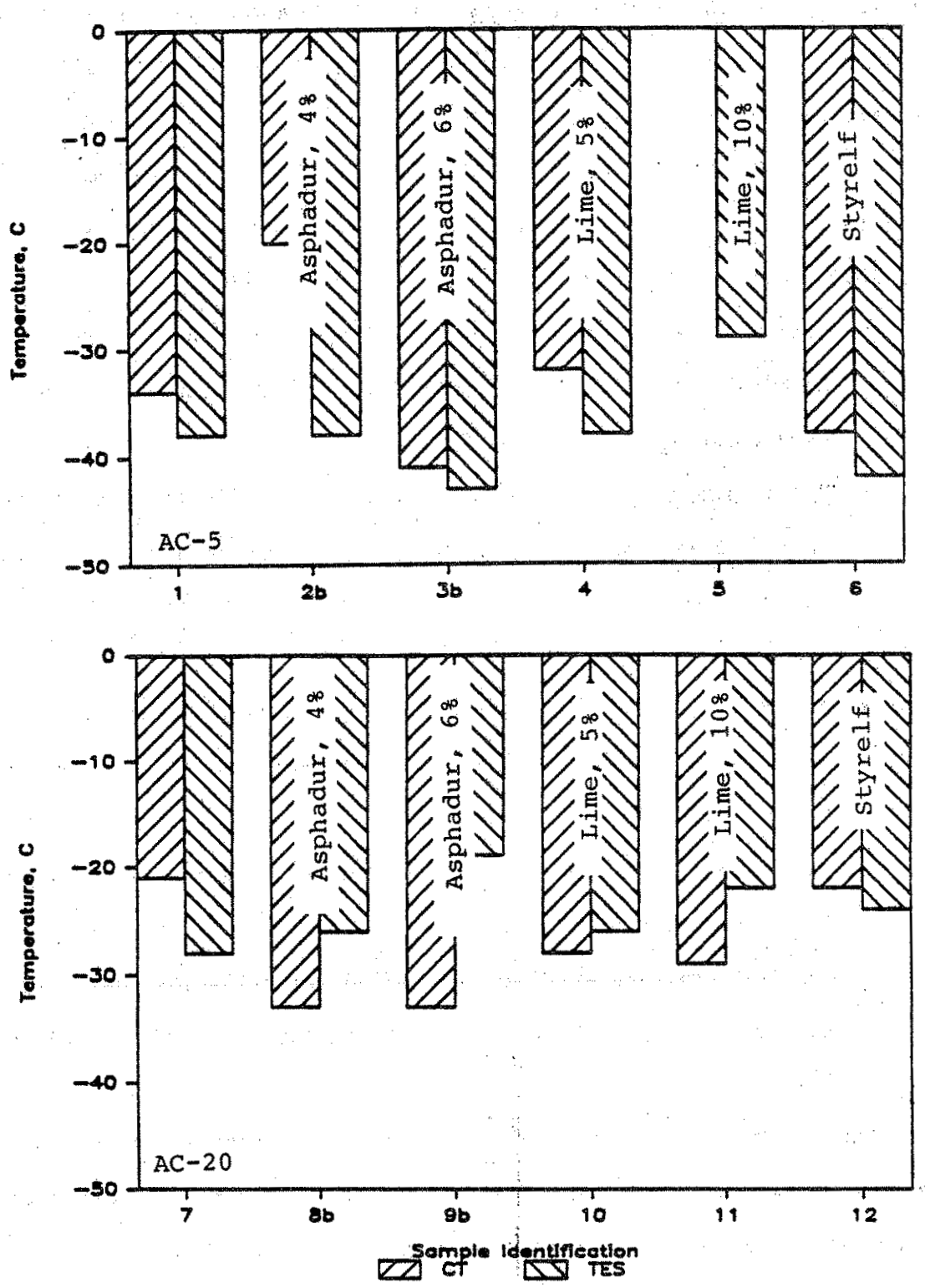


Fig. 29. Low-temperature cracking properties.

Table 6. Low-temperature cracking properties.

MATERIAL	SAMPLE No.	CT,C	TES,20ksi C	S,-23,10Ks ksi	S,-29,20Ks ksi
AC-5	1-O	-34.00	-38.00	0.508	1.890
AC-5+4% ASPHADUR	2b-O	-20.00	-38.00	0.798	2.900
AC-5+6% ASPHADUR	3b-O	-41.00	-43.00	0.725	1.450
AC-5+5% LIME	4-O	-32.00	-38.00	0.725	2.900
STYRELF IN AC-5	6-O	-38.00	-42.00	0.435	1.450
AC-20	7-O	-21.00	-28.00	0.435	1.450
AC-20+4% ASPHADUR	8b-O	-33.00	-26.00	10.200	21.800
AC-20+6% ASPHADUR	9b-O	-33.00	-19.00	43.500	72.500
AC-20+5% LIME	10-O	-28.00	-26.00	5.800	13.100
STYRELF IN AC-20	12-O	-22.00	-24.00	17.400	36.600
AC-5	1-R	-24.00	-31.00	4.350	11.600
AC-5+4% ASPHADUR	2b-R	c	-31.00	17.400	29.000
AC-5+6% ASPHADUR	3b-R	-45.00	-18.00	43.500	72.500
AC-5+5% LIME	4-R	-34.00	-27.00	10.200	21.800
STYRELF IN AC-5	6-R	-30.00	-29.00	5.800	10.200
AC-20	7-R	c	-33.00	4.350	8.700
AC-20+4% ASPHADUR	8b-R	c	-16.00	43.500	102.000
AC-20+6% ASPHADUR	9b-R	c	-17.00	145.000	174.000
AC-20+5% LIME	10-R	c	-18.00	43.500	72.500
STYRELF IN AC-20	12-R	c	-56.00	29.000	58.000

a : patially dissoolved.
b : totally dissolved.
c : outside nomograph range, but higher than -20 C.
CT,C : cracking temperature in C.
TES,20ksi,C : temperature of equivalent stiffness @ 20 ksi.
S,-23,10ks : stiffness @ -23 C, 10,000 sec.
S,-29,20ks : stiffness @ -29 C, 20,000 sec.
O : original.
R : thin film oven test residue.

4. EFFECTS OF ADDITIVES ON THE PROPERTIES OF ASPHALT CONCRETE MIXTURES--PHASE II

4.1. Materials

Seven series of asphalt concrete mixtures were prepared with the two asphalt cements studied in Phase I (AC-5 and AC-20) and in conjunction with five additives and two aggregates (limestone and gravel). In addition to the additives and polymer-modified asphalt used in Phase I of the study (Asphadur, hydrated lime, and Styrelf), two additional types of polymer-modified asphalts (PACs) were included. These were PAC-5 and PAC-20 from Koch Asphalt Company of St. Paul, Minnesota, and PAC-5 and PAC-20 from Jebro Inc. of Sioux City, Iowa. These PACs were identified by the suppliers as neoprene-modified asphalts and styrene-butadiene-rubber latex-modified asphalts, respectively. Both PACs were prepared at respective plants and containing about 2% to 3% solids. As described in the previous chapter, Styrelf binders as received and used in this study were SBS-modified AC-5 and AC-20 asphalts. Asphadur and lime were added to the mixes during mixing. The limestone aggregate (LS) consisted of 60% 3/4-in. crushed limestone and 40% sand, both from Hardin County, Iowa. The gravel aggregate (G) consisted of 55% 1/2-in. natural gravel, 30% 1/2-in. crushed gravel, and 15% sand, all fom Sac County, Iowa. The gradations of the aggregate blends are shown in Fig. 30.

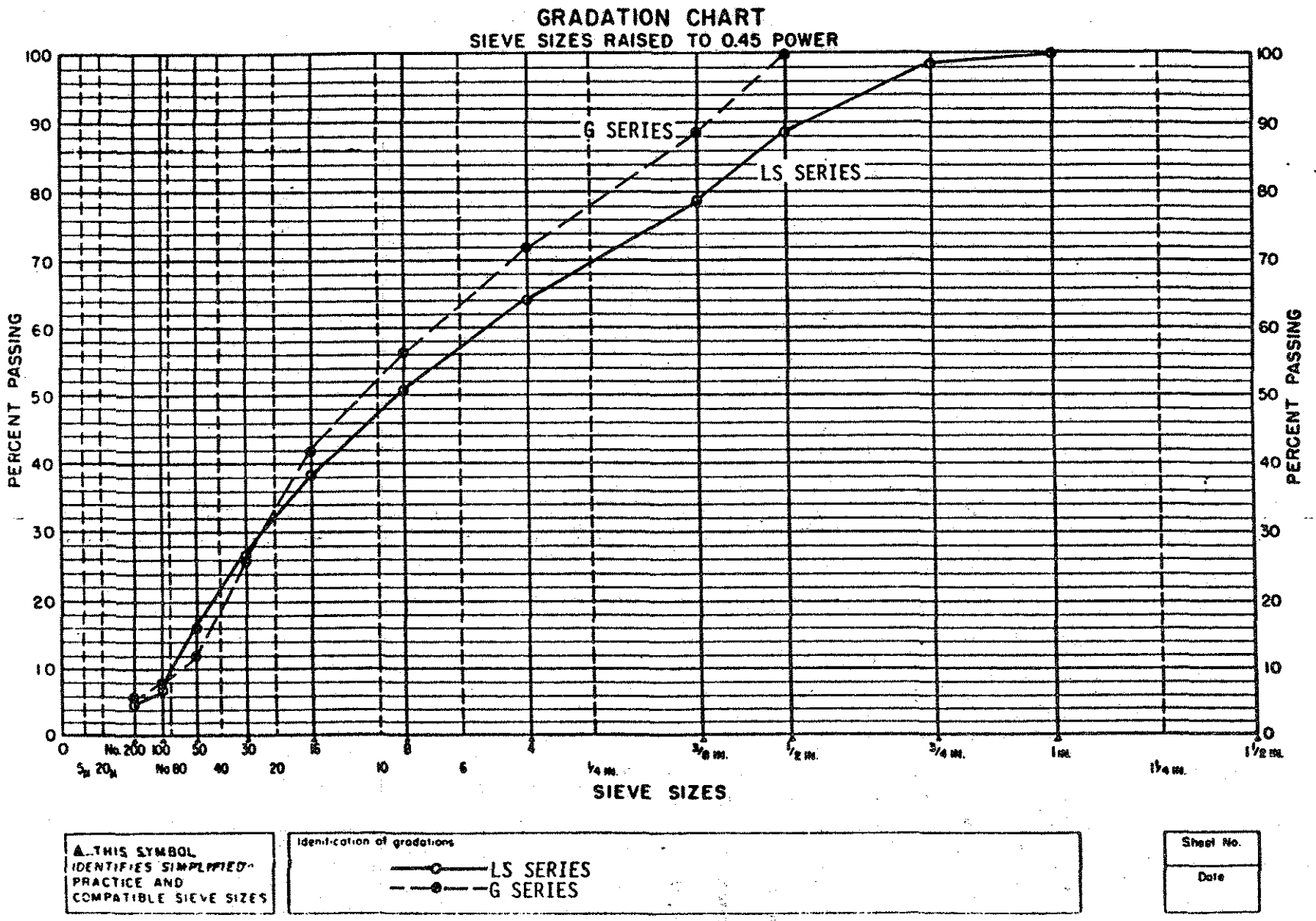


Fig. 30. Aggregate gradations.

4.2. Procedures

Seven series of 72 batches of mixes were prepared and tested, including 12 control mixes containing no additives (Table 7). For each aggregate-binder combination, three mixes were made at 1% binder content increments bracketing the optimum asphalt content estimated by the Marshall method of mix design. The additives were introduced into the mixtures with methods as close to field conditions as possible.

Mixes of 50 lbs each were mixed in a heated twin-shaft pug-mill mixer. Mixing procedures for controls (mixes C1 to C12), mixes containing Styrelf (mixes S1 to S12), mixes containing neoprene-modified PAC-5 (mixes K1 to K6), mixes containing SBR-modified PAC-5, and mixes containing hydrated lime (mixes LL1 to LL12 and LH1 to LH11) were as follows: Place aggregates at 325 +/- 10° F in pug-mill mixer and dry mix for 10 sec. Add binder at 275 +/- 10° F, mix for 30 sec and discharge. Hydrated lime, at 1% (LL series) and 2% (LH series) by weight of aggregate, was added to the heated aggregates before the addition of asphalt for the wet-mixing cycles. The same mixing procedure was followed for mixes containing PAC-20 (mixes J7 to J12 and K7 to K12) except that aggregates were heated to 340° F and binders were added at 290° F. For the AH series, asphalt cements at 400° F were added to aggregates at 450° F. After the wet-mixing of 20 sec, Asphadur, at 6% by weight of asphalt, was then added to the mixture; and mixing continued for an additional 30 sec to complete the mixing cycle.

Table 7. Mix identification - Phase II.

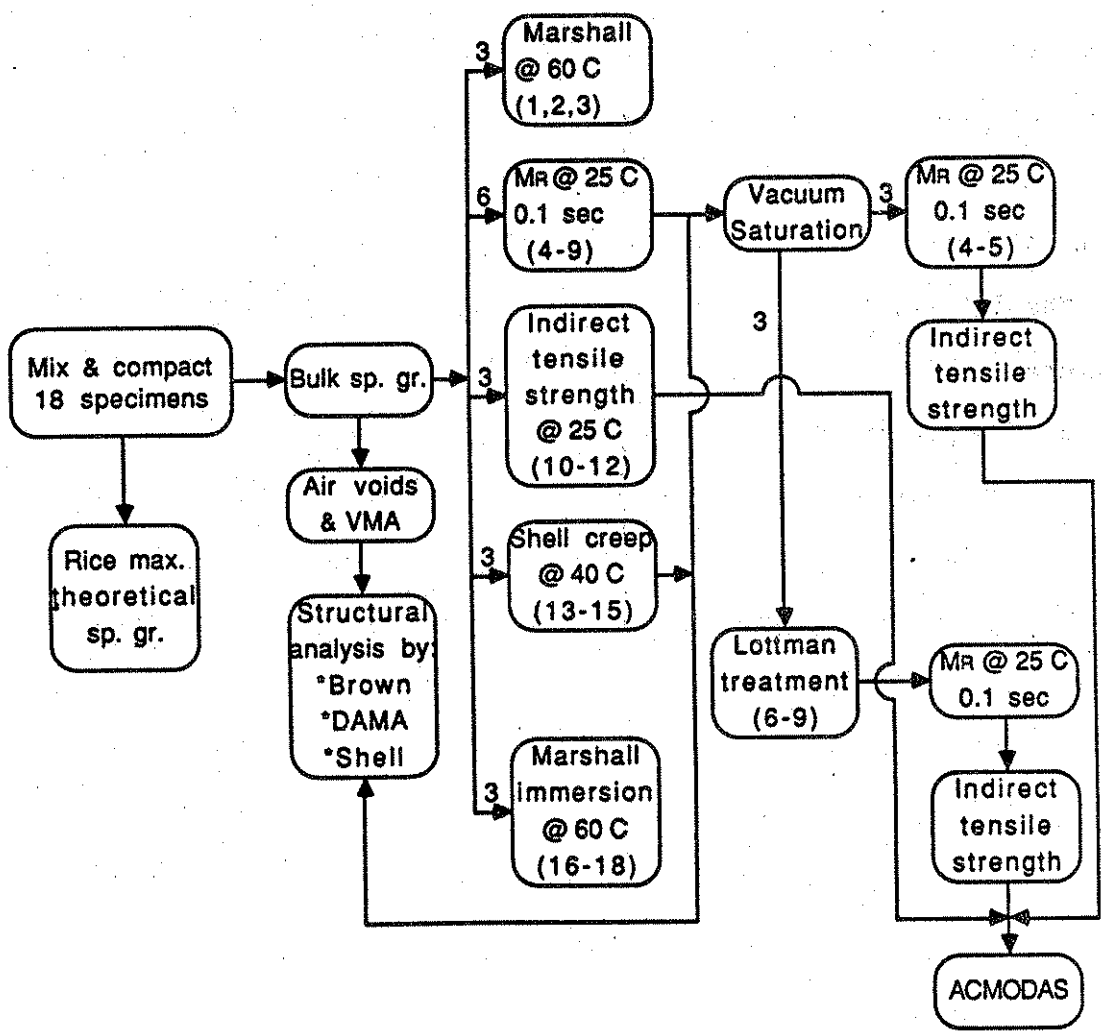
SERIES	AC GRADE	AC-5						AC-20					
	AC CONTENT	OPT-1		OPT		OPT+1		OPT-1		OPT		OPT+1	
	AGG. TYPE	LS	G	LS	G	LS	G	LS	G	LS	G	LS	G
C	CONTROL	1	2	3	4	5	6	7	8	9	10	11	12
AH	ASPHADUR-6%	1		3		5		7		9		11	
LL	LIME-1%	1	2	3	4	5	6	7	8	9	10	11	12
LH	LIME-2%	1		3		5		7		9		11	
S	STYRELF (SBS)	1	2	3	4	5	6	7	8	9	10	11	12
K	NEOPRENE	1	2	3	4	5	6	7	8	9	10	11	12
J	SBR	1	2	3	4	5	6	7	8	9	10	11	12

Total number of batches : 72.

Eighteen Marshall specimens were prepared from each batch. Compaction was accomplished by a mechanical Marshall compactor with 50 blows per side at a mix temperature of 275° F for all mixes except for mixes J7 to J12 and K7 to K12, which were compacted at 290° F and mixes AH1 to AH12, which were compacted at 375° F.

The following tests were performed on the mixtures and the compacted specimens, as shown in Fig. 31:

- Sample height and bulk specific gravity (ASTM D 2726)
- Theoretical maximum specific gravity (ASTM D 2041)
- Marshall stability and flow, air and VMA (ASTM D 1559)
- Marshall stability and flow after specimens immersed in water at 140° F for 24 hrs (45, 49)
- Indirect (splitting) tensile strength at 77° F and a loading rate of 2 in. per minute (21)
- Indirect tensile resilient modulus at 77° F and a frequency of 0.33. hz. measured with a Retsina Mark IV resilient modulus device (41)
- Shell uniaxial compression creep test at 104° F (40° C) at a stress level of 14.5 psi (0.1 MPa) for a loading time of 2 hrs (51)
- Indirect tensile strength and resilient modulus after vacuum-saturation (42,45) and after an accelerated Lottman conditioning procedure (27,28).



HR-278 Phase II Test Program

Fig. 31. Mixture evaluation flow chart.

4.3. Results and Discussion

4.3.1. Marshall Properties

Marshall properties (stability, flow, voids, and bulk specific gravity) of the 72 mixes are given in Table 8. Marshall stability results are shown in Fig. 32(a), and the results of Marshall stiffness or Marshall quotient, defined as ratio between stability and flow, are shown in Fig. 32(b). As expected, stability values of mixes containing AC-20 were higher than corresponding mixes containing AC-5, and stability values of mixes made with limestone aggregate (LS) were higher than corresponding mixes made with gravel (G). With the exception of Series J (SBR modified AC-5) with gravel aggregate, all other mixes at optimum asphalt content of about 6% would have met design criteria for heavy traffic in terms of stability (1500 lbs +) and flow (8-16). There were significant increases in stability because of the addition of Asphadur (AH) and Styrelf (S) as compared to control mixes (C), slight increases in stability for neoprene mixes (K), and no significant differences because of other additives. One of the reasons for increased stability for AH and S mixes was that polymers added to AC-5 or AC-20 base asphalts resulted in a higher viscosity binder. However, PAC-5 and PAC-20 binders used in K and J mixes were polymer-modified binders in the AC-5 and AC-20 viscosity ranges.

It is significant that Asphadur and Styrelf increased the stability of AC-5 mixes to that of AC-20 mixes without additives. This makes it possible to use softer AC-5 with these additives for both low-temperature cracking resistance and high-temperature stability requirements.

Table 8a. Mix properties, LS/AC-5.

Series	AC % by wt of Mix	VMA (%)	air (%)	Gmb	Marshall stab. (lb)	Marshall flow (.01 in.)	Marshall stiffness	Marshall-Immersion stab. (lb)	Marshall-Immersion flow (.01 in.)	RMS
C	opt-1 5.213	16.97	6.84	2.270	2058	8.8	233.1	2293	9.9	1.114
	opt 6.103	16.46	4.12	2.306	1708	11.5	148.5	2128	10.8	1.246
	opt+1 6.977	16.68	2.23	2.314	1858	12.2	152.7	2392	13.2	1.287
AH	opt-1 5.213	16.16	6.73	2.293	3367	9.7	348.2	4930	10.6	1.464
	opt 6.103	16.93	5.57	2.293	3825	8.5	450.0	6443	9.6	1.684
	opt+1 6.977	16.61	3.19	2.324	2675	14.3	187.7	3020	15.2	1.129
LL	opt-1 5.164	14.39	3.22	2.340	2158	12.2	177.3	2347	10.6	1.087
	opt 6.047	14.95	1.70	2.346	2117	11.7	181.4	2837	10.2	1.340
	opt+1 6.912	16.04	0.83	2.338	1567	14.5	108.0	1877	11.7	1.198
LH	opt-1 5.116	14.48	2.99	2.336	2658	10.3	257.3	2847	10.1	1.071
	opt 5.991	15.03	1.47	2.343	1875	12.7	148.0	2595	11.8	1.384
	opt+1 6.849	16.20	0.72	2.332	1392	15.7	88.8	1670	14.5	1.200
S	opt-1 5.213	16.04	6.76	2.296	2875	9.8	292.5	3243	9.7	1.128
	opt 6.103	16.92	5.61	2.342	2050	15.7	130.8	2650	13.7	1.293
	opt+1 6.977	16.26	2.71	2.333	1775	15.8	112.1	2222	14.0	1.252
K	opt-1 5.213	17.27	6.90	2.262	1667	8.8	188.7	2407	10.3	1.444
	opt 6.103	15.79	3.07	2.324	2083	13.5	154.3	2883	15.0	1.384
	opt+1 6.977	17.64	3.04	2.296	1400	11.2	125.3	1708	15.0	1.220
J	opt-1 5.213	17.18	8.56	2.265	1617	8.2	197.9	2020	7.4	1.249
	opt 6.103	16.31	5.44	2.310	2142	11.3	189.0	--	--	--
	opt+1 6.977	17.68	4.88	2.294	1333	11.0	121.2	2225	11.8	1.669

-- : Data not available.
RMS : Marshall stability ratio.

Table 8b. Mix properties, G/AC-5.

Series	AC %	by wt of Mix	VMA (%)	air % (%)	Gmb	Marshall stab. (lb)	Marshall flow (.01 in.)	Marshall stiffness	Marshall-Immersion stab. (lb)	Marshall-Immersion flow (.01 in.)	RMS
C	opt-1	5.213	20.18	9.20	2.250	1517	9.0	168.5	1102	11.6	0.727
	opt	6.103	19.68	6.51	2.286	1750	9.0	194.4	1215	9.8	0.694
	opt+1	6.977	19.65	4.34	2.300	1333	8.3	160.1	1488	9.9	1.116
LL	opt-1	5.164	16.36	5.77	2.357	1583	10.7	148.4	1808	10.2	1.142
	opt	6.047	19.51	7.21	2.289	1450	9.0	161.1	1613	8.2	1.112
	opt+1	6.912	18.86	4.34	2.329	1583	9.7	163.7	1395	9.7	0.881
S	opt-1	5.213	19.66	9.42	2.265	1775	8.5	208.8	1597	10.2	0.900
	opt	6.103	19.01	6.55	2.305	1475	8.3	177.1	1633	13.7	1.107
	opt+1	6.977	19.19	4.61	2.321	1392	14.3	97.1	1178	10.8	0.846
K	opt-1	5.213	18.80	6.94	2.289	1833	10.3	177.5	2225	13.3	1.214
	opt	6.103	18.25	4.14	2.326	1783	11.0	162.1	1988	14.7	1.115
	opt+1	6.977	18.87	2.71	2.330	1550	14.0	110.7	2037	14.7	1.314
J	opt-1	5.213	19.49	9.25	2.270	1325	15.0	88.3	1240	10.4	0.936
	opt	6.103	18.13	5.55	2.330	1325	9.5	139.5	1735	12.2	1.309
	opt+1	6.977	19.19	4.62	2.321	1233	10.5	117.5	1658	10.8	1.344

Table 8c. Mix properties, LS/AC-20.

Series		AC % by wt of Mix	VMA (%)	air % (%)	Gmb	Marshall stab. (lb)	Marshall flow (.01 in.)	Marshall stiffness	Marshall-Immersion stab. (lb)	Marshall-Immersion flow (.01 in.)	RMS
C	opt-1	5.213	16.79	6.33	2.275	2550	9.3	273.3	3693	11.6	1.448
	opt	6.103	17.26	4.83	2.284	2483	12.0	206.9	2650	11.8	1.067
	opt+1	6.977	16.57	2.00	2.325	1975	18.2	108.7	3153	20.5	1.596
AH	opt-1	5.213	15.50	4.83	2.311	3783	12.7	298.6	8380	12.7	2.215
	opt	6.103	16.89	4.38	2.294	5067	12.5	405.4	6130	11.0	1.210
	opt+1	6.977	16.83	2.29	2.317	3633	16.2	224.7	7892	10.8	2.172
LL	opt-1	5.164	15.58	4.47	2.307	3092	11.0	281.1	2990	10.9	0.967
	opt	6.047	14.62	3.38	2.334	4284	15.5	276.4	2902	12.5	0.677
	opt+1	6.912	16.15	1.06	2.335	4522	14.3	315.5	2777	14.0	0.614
LH	opt-1	5.116	14.47	3.32	2.337	2783	13.8	201.3	3193	10.7	1.147
	opt	5.991	15.18	2.09	2.339	3125	14.0	223.2	3292	13.0	1.053
	opt+1	6.849	16.00	1.02	2.337	1825	20.3	89.8	2888	15.5	1.582
S	opt-1	5.213	16.01	5.53	2.297	3717	11.7	318.5	4208	11.8	1.132
	opt	6.103	16.55	4.05	2.304	3238	15.2	213.5	1463	12.5	0.452
	opt+1	6.977	16.79	2.25	2.319	2467	19.5	126.5	3227	16.8	1.308
K	opt-1	5.213	15.65	4.45	2.306	2683	16.8	159.4	3053	12.8	1.138
	opt	6.103	15.49	2.29	2.331	2242	19.5	115.0	2600	17.5	1.160
	opt+1	6.977	17.06	1.81	2.311	1658	21.7	76.5	2363	15.6	1.425
J	opt-1	5.213	17.39	6.97	2.259	2217	9.5	233.3	2925	9.5	1.320
	opt	6.103	16.49	3.85	2.310	2650	13.0	203.8	--	--	--
	opt+1	6.977	17.45	2.86	2.300	1883	12.7	148.6	3213	14.7	1.706

Table 8d. Mix properties, G/AC-20.

Series	AC %		VMA (%)	air % (%)	Gmb	Marshall stab. (lb)	Marshall flow (.01 in.)	Marshall stiffness	Marshall-immersion stab. (lb)	Marshall-immersion flow (.01 in.)	RMS
		by wt of Mix									
C	opt-1	5.213	19.17	7.96	2.279	2167	9.8	220.4	1878	13.4	0.867
	opt	6.103	19.65	6.48	2.287	1700	11.2	152.2	1850	10.8	1.088
	opt+1	6.977	19.20	3.92	2.321	1792	12.3	145.3	2367	13.5	1.321
LL	opt-1	5.164	19.18	8.18	2.277	2475	11.3	218.4	--	--	--
	opt	6.047	18.65	5.54	2.314	2283	12.3	185.2	--	--	--
	opt+1	6.912	19.03	3.96	2.324	2567	12.0	213.9	--	--	--
S	opt-1	5.213	19.49	8.74	2.270	2525	10.2	248.3	2277	11.2	0.902
	opt	6.103	19.40	6.57	2.294	1925	12.0	160.4	2170	12.7	1.127
	opt+1	6.977	18.34	3.24	2.346	2567	14.3	179.1	2565	12.0	0.999
K	opt-1	5.213	18.42	7.80	2.300	2358	14.2	166.4	2377	15.0	1.008
	opt	6.103	18.32	5.55	2.324	2250	12.2	184.9	2467	13.3	1.096
	opt+1	6.977	18.36	3.44	2.345	2183	18.5	118.0	2638	18.0	1.208
J	opt-1	5.213	18.55	8.81	2.296	2025	10.3	196.0	2583	13.8	1.276
	opt	6.103	19.73	8.04	2.284	1950	11.3	172.1	2338	15.2	1.199
	opt+1	6.977	18.62	4.64	2.338	1758	16.5	106.6	2260	17.9	1.285

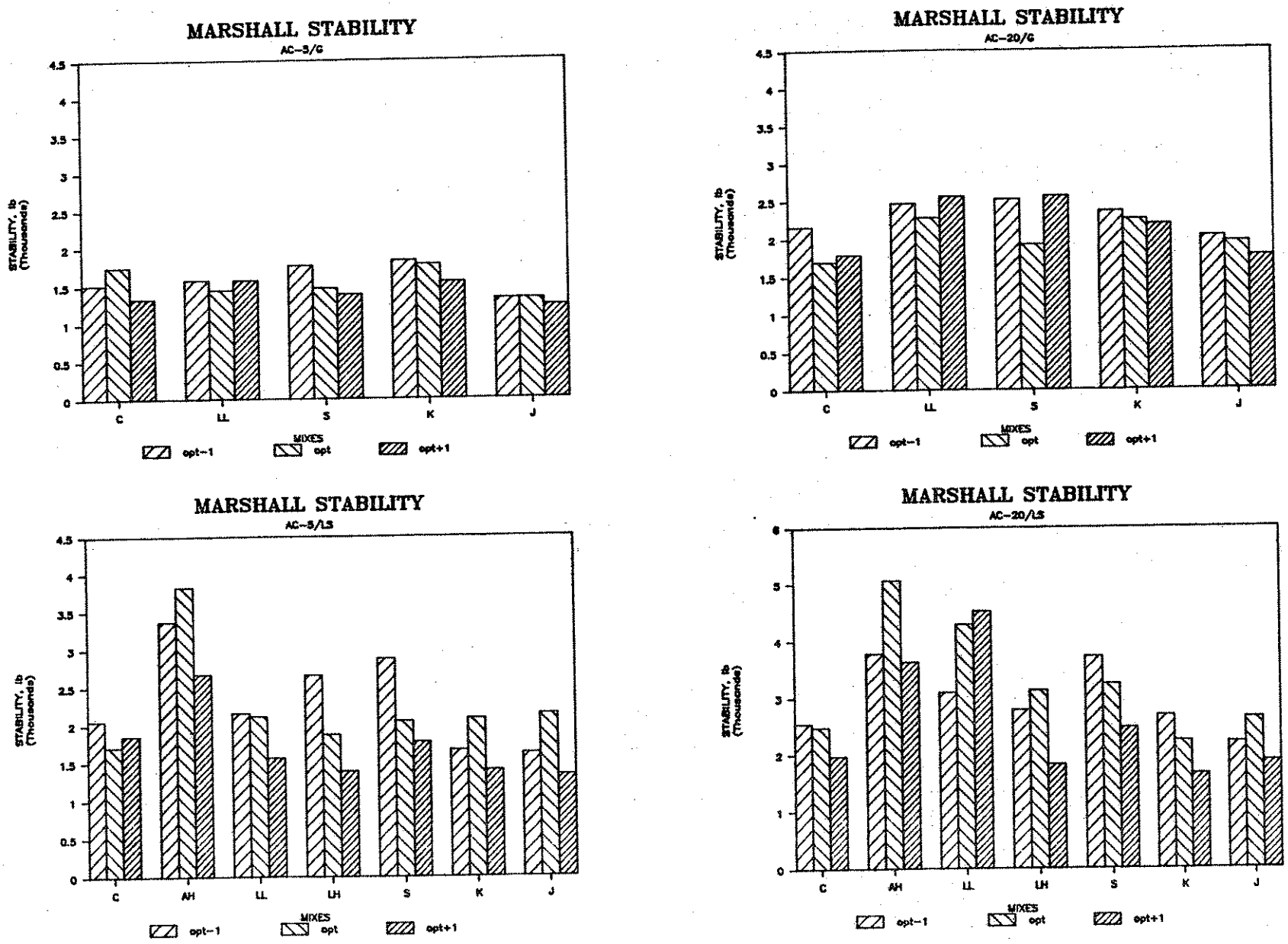


Fig. 32a. Marshall stability.

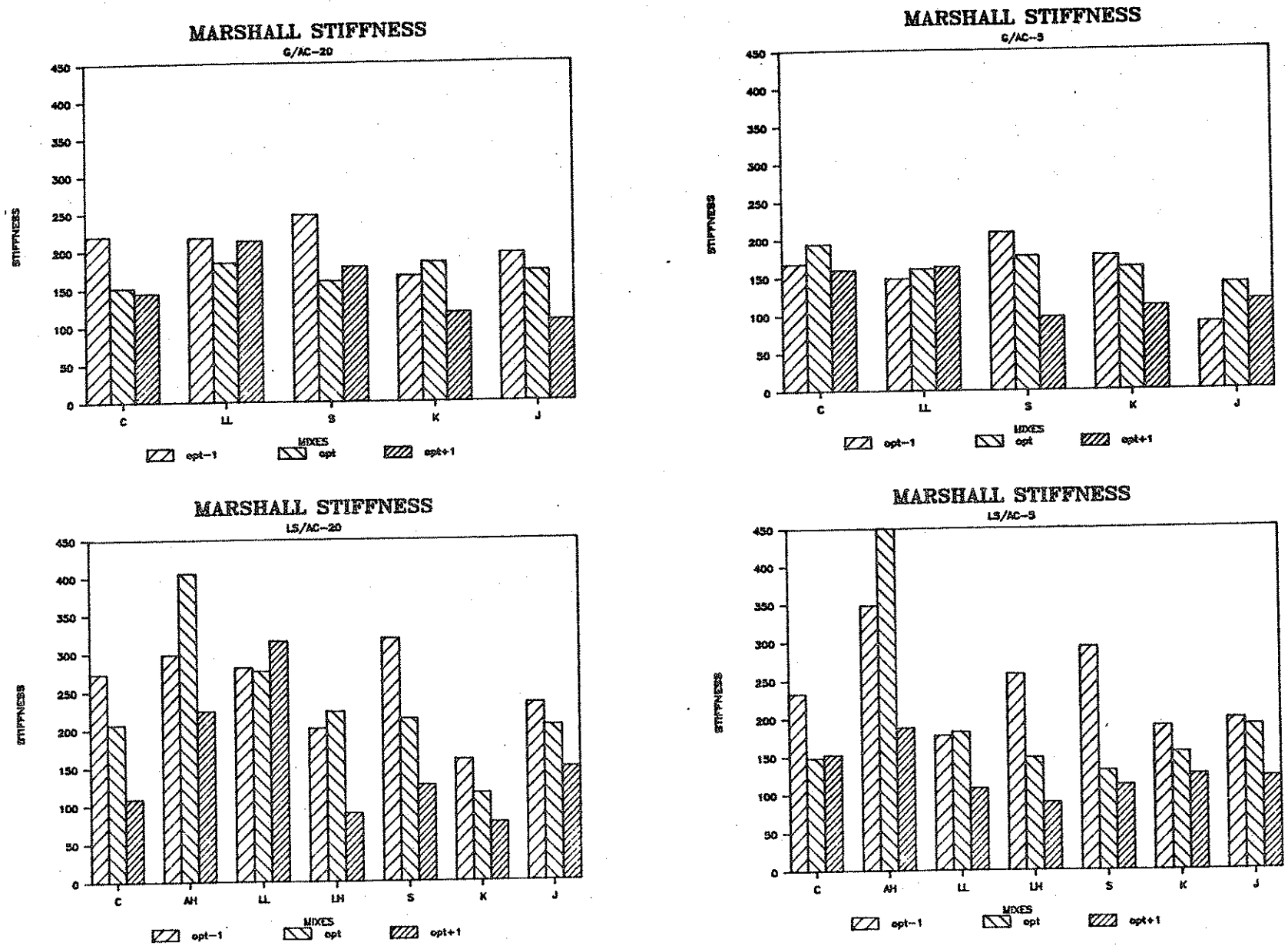


Fig. 32b. Marshall stiffness.

Marshall stiffness or Marshall quotient has been used in the United Kingdom and South Africa as a criterion in mix design and has been correlated to rut depth. For example, in South Africa, a minimum value of Marshall stiffness at 140° F (60° C) of 1 to 2 kN/mm (5700 to 11400 lbs/in.) has been suggested to control excessive permanent deformation or rutting (6, 30). Marshall stiffness, stability in pounds divided by flow in 0.01 in., of the mixes are shown in Fig. 32(b). No significant additive effects can be observed except large increases in stiffness because of Asphadur. All mixes exceeded the minimum stiffness value needed to prevent excessive rutting.

4.3.2. Resilient Modulus

The results of the resilient modulus tests are given in Table 9. No significant additive effects are seen except large increases are due to Asphadur (AH) and somewhat low values are observed in mixes containing SBR (J). Their effects as manifested in moisture damage and structural capacity will be discussed in the following sections.

4.3.3. Tensile Strengths

Indirect tensile strength results are given in Table 9 and plotted in Fig. 33. Asphadur increased tensile strength significantly; SBS increased the strength slightly; and SBR decreased the strength somewhat. The effects of other additives were not obvious.

4.3.4. Moisture Damage

Resistance to and effects of additives on moisture-induced damage of asphalt concrete mixtures were evaluated by using Marshall immersion

Table 9a. Indirect tensile strength and resilient modulus, LS/AC-5.

Mixes		% Sat.	Moist P	INDIRECT TENSILE STRENGTH ITSB (psi)	ITSAV (psi)	RV	ITSAL (psi)	RL	RESILIENT MODULUS (*100000) MRB (psi)	MRAV (psi)	MRV	MRAL (psi)	MRL
	opt-1	92.24	2.804	132.2	172.4	1.303	116.3	0.879	3.16	4.54	1.436	2.19	0.693
C	opt	73.47	1.308	112.1	149.6	1.334	105.9	0.944	2.37	2.52	1.065	1.55	0.656
	opt+1	108.46	1.192	96.3	108.6	1.128	104.3	1.083	1.63	2.32	1.423	1.14	0.699
	opt-1	78.11	2.287	276.4	224.6	0.813	192.1	0.695	10.90	7.45	0.683	5.35	0.491
AH	opt	79.52	1.939	258.0	266.8	1.031	270.3	1.045	16.30	13.85	0.850	10.01	0.614
	opt+1	65.99	0.982	199.8	164.7	0.824	187.3	0.937	6.32	4.25	0.672	5.46	0.864
	opt-1	58.91	0.807	151.0	111.0	0.735	161.7	1.071	3.30	1.72	0.520	3.73	1.130
LL	opt	115.06	0.830	140.7	137.4	0.977	151.0	1.073	2.59	2.71	1.046	2.40	0.927
	opt+1	156.90	0.560	109.0	94.7	0.862	74.6	0.679	1.58	1.37	0.867	1.09	0.690
	opt-1	95.55	1.222	142.0	173.0	1.218	150.4	1.059	4.08	4.15	1.016	3.50	0.859
LH	opt	111.60	0.700	128.0	135.1	1.048	125.2	0.972	2.71	2.28	0.842	2.81	1.036
	opt+1	156.81	0.483	94.1	104.6	1.111	87.7	0.931	1.23	1.19	0.966	1.03	0.833
	opt-1	77.03	2.266	145.1	195.3	1.345	147.7	1.017	3.54	3.79	1.071	2.03	0.573
S	opt	55.40	0.853	131.4	175.0	1.338	162.5	1.237	2.36	2.19	0.928	2.01	0.852
	opt+1	66.13	0.767	118.8	121.5	1.023	147.0	1.237	1.59	1.92	1.208	1.48	0.931
	opt-1	103.23	3.159	139.9	127.2	0.909	110.2	0.788	2.62	1.50	0.573	1.76	0.672
K	opt	101.23	1.332	106.9	117.2	1.096	111.5	1.043	1.21	1.26	1.041	1.28	1.058
	opt+1	107.01	1.420	95.1	105.7	1.112	88.3	0.929	1.59	1.76	1.110	1.01	0.639
	opt-1	73.45	2.776	97.6	89.0	0.912	94.2	0.965	2.10	0.97	0.462	1.25	0.595
J	opt	63.49	1.499	87.8	100.3	1.142	92.8	1.058	1.13	1.33	1.177	1.11	0.982
	opt+1	75.72	1.621	82.6	77.3	0.936	78.1	0.946	1.24	1.47	1.185	0.75	0.602

% Sat. : % Saturation.
Moist P : Moisture pickup, % wt..
ITSB : Indirect tensile strength before treatment.
ITSAV : Indirect tensile strength after vacuum saturation.
ITSAL : Indirect tensile strength after Lottman treatment.
RV : Ratio, ITSAV/ITSB.
RL : Ratio, ITSAL/ITSB.
MRB : Resilient modulus before treatment.
MRAV : Resilient modulus after vacuum saturation.
MRAL : Resilient modulus after Lottman treatment.
MRV : Ratio, MRAV/MRB.
MRL : Ratio, MRAL/MRB.

Table 9b. Indirect tensile strength and resilient modulus, G/AC-5.

Mixes		% Sat.	Moist P	INDIRECT TENSILE STRENGTH ITSB (psi)	ITSAV (psi)	RV	ITSAL (psi)	RL	RESILIENT MODULUS (*100000) MRB (psi)	MRAV (psi)	MRV	MRAL (psi)	MRL
	opt-1	98.23	3.995	97.6	118.4	1.213	69.7	0.714	2.03	2.25	1.105	1.78	0.875
C	opt	100.77	2.867	80.5	128.3	1.450	100.4	1.134	1.94	2.17	1.123	2.17	1.120
	opt+1	103.64	1.954	92.5	97.9	1.058	103.6	1.120	2.15	2.27	1.056	1.15	0.535
	opt-1	54.40	1.343	119.1	138.0	1.159	110.5	0.928	2.66	2.29	0.861	1.56	0.586
LL	opt	85.49	2.661	112.4	105.1	0.934	88.0	0.782	5.15	1.78	0.346	1.47	0.285
	opt+1	77.79	1.446	95.5	93.0	0.974	87.0	0.911	1.25	1.09	0.872	1.11	0.888
	opt-1	79.39	3.616	103.8	136.7	1.317	92.7	0.893	2.07	2.37	1.145	1.26	0.609
S	opt	82.76	2.352	126.7	124.3	0.981	126.5	0.998	1.49	1.39	0.933	1.34	0.899
	opt+1	63.69	1.257	125.6	151.3	1.205	121.3	0.966	0.76	0.97	1.280	0.82	1.081
	opt-1	95.12	2.875	137.8	166.0	1.204	125.1	0.908	2.02	1.98	0.980	1.78	0.881
K	opt	105.60	1.880	124.9	202.7	1.623	125.3	1.003	1.70	2.22	1.308	1.52	0.893
	opt+1	133.60	1.560	108.3	124.7	1.152	122.5	1.132	1.19	1.53	1.286	1.01	0.845
	opt-1	84.63	3.450	66.6	68.8	1.034	48.6	0.730	1.00	0.89	0.887	0.49	0.486
J	opt	69.17	1.648	73.2	81.6	1.115	69.2	0.945	1.03	0.87	0.846	0.82	0.794
	opt+1	82.94	1.655	77.1	82.5	1.070	85.0	1.102	0.71	0.66	0.928	0.71	1.007

Table 9c. Indirect tensile strength and resilient modulus, LS/AC-20.

Mixes		% Sat.	Moist P	INDIRECT TENSILE STRENGTH ITSB (psi)	ITSAV (psi)	RV	ITSAL (psi)	RL	RESILIENT MODULUS (*100000) MRB (psi)	MRAV (psi)	MRV	MRAL (psi)	MRL
	opt-1	81.88	2.282	291.2	279.7	0.961	156.6	0.538	10.67	8.49	0.796	5.44	0.510
C	opt	85.51	1.808	251.5	282.2	1.122	166.8	0.663	11.35	9.59	0.845	6.65	0.586
	opt+1	54.70	0.471	236.7	226.1	0.955	226.3	0.956	5.55	3.99	0.719	4.82	0.868
	opt-1	71.61	1.495	383.8	388.7	1.013	342.3	0.892	17.30	14.93	0.863	9.87	0.571
AH	opt	88.01	1.674	397.7	344.8	0.867	313.0	0.787	19.90	24.00	1.206	11.98	0.602
	opt+1	82.10	0.808	385.8	422.2	1.095	427.6	1.108	18.60	11.25	0.605	11.50	0.618
	opt-1	94.27	1.825	156.6	309.1	1.974	257.8	1.646	13.00	10.10	0.777	8.53	0.656
LL	opt	51.72	0.748	220.3	275.4	1.251	294.1	1.335	8.85	6.45	0.729	6.94	0.784
	opt+1	107.36	0.487	261.7	264.6	1.011	295.4	1.129	7.50	5.43	0.724	7.42	0.989
	opt-1	59.31	0.039	273.5	331.6	1.212	171.1	0.626	8.66	8.59	0.992	7.57	0.874
LH	opt	72.73	0.649	245.4	308.9	1.259	321.0	1.308	8.38	7.50	0.894	8.84	1.055
	opt+1	95.80	0.417	188.9	259.4	1.374	262.8	1.391	7.27	5.60	0.770	6.81	0.937
	opt-1	70.47	1.695	270.7	328.9	1.215	151.9	0.561	8.85	9.51	1.075	2.08	0.235
S	opt	83.98	1.479	254.2	303.5	1.194	186.0	0.732	6.16	8.87	1.440	2.91	0.472
	opt+1	102.88	1.080	253.9	348.2	1.371	249.0	0.981	4.23	9.50	2.246	5.77	1.364
	opt-1	79.06	1.527	225.5	221.7	0.983	182.1	0.807	4.94	4.00	0.810	3.69	0.747
K	opt	93.80	0.922	173.8	169.7	0.977	188.5	1.085	2.71	2.45	0.904	3.39	1.251
	opt+1	104.70	0.818	165.6	134.0	0.809	155.0	0.936	1.44	1.39	0.965	1.39	0.965
	opt-1	84.78	2.627	154.0	154.5	1.004	130.6	0.848	3.42	3.87	1.132	1.76	0.515
J	opt	85.79	1.433	167.6	182.9	1.091	157.8	0.942	3.69	3.60	0.976	2.40	0.650
	opt+1	123.10	1.550	146.2	184.8	1.264	149.0	1.019	2.76	3.44	1.246	2.22	0.804

Table 9d. Indirect tensile strength and resilient modulus, G/AC-20.

Mixes		% Sat.	Moist P	INDIRECT TENSILE STRENGTH ITSB (psi)	ITSAV (psi)	RV	ITSAL (psi)	RL	RESILIENT MODULUS (*100000) MRB (psi)	MRAV (psi)	MRV	MRAL (psi)	MRL
	opt-1	82.46	2.873	201.7	244.8	1.214	120.5	0.597	6.26	9.16	1.462	6.84	1.091
C	opt	97.15	2.761	199.3	165.4	0.830	104.9	0.526	5.38	7.78	1.446	5.41	1.006
	opt+1	79.69	1.339	220.8	288.5	1.307	180.5	0.818	6.80	8.72	1.282	5.06	0.744
	opt-1	94.69	3.395	228.2	203.7	0.893	115.6	0.506	11.90	9.61	0.808	5.18	0.435
LL	opt	77.17	1.847	264.3	262.3	0.992	241.6	0.914	9.38	7.59	0.809	7.56	0.806
	opt+1	107.05	1.815	225.1	249.0	1.106	168.4	0.748	8.65	6.26	0.724	4.32	0.499
	opt-1	80.96	3.107	231.8	297.8	1.285	156.9	0.677	6.51	6.43	0.988	4.74	0.728
S	opt	75.94	2.167	316.2	309.5	0.979	169.4	0.536	7.82	7.31	0.935	4.15	0.531
	opt+1	90.00	1.244	300.5	345.2	1.149	224.3	0.746	6.80	6.46	1.077	4.06	0.677
	opt-1	73.71	2.490	171.7	240.0	1.398	146.2	0.851	4.65	5.84	1.256	3.42	0.735
K	opt	71.48	1.706	222.3	219.9	0.989	178.2	0.802	6.34	5.17	0.815	3.78	0.596
	opt+1	72.36	1.062	194.0	211.7	1.091	195.9	1.010	3.89	2.88	0.740	2.93	0.753
	opt-1	65.77	2.524	149.3	153.3	1.027	113.7	0.762	3.44	2.99	0.869	1.48	0.430
J	opt	62.24	2.179	146.9	180.6	1.229	135.1	0.920	2.38	2.56	1.076	2.03	0.853
	opt+1	57.39	1.140	137.2	128.2	0.935	140.0	1.021	2.33	1.94	0.833	1.92	0.824

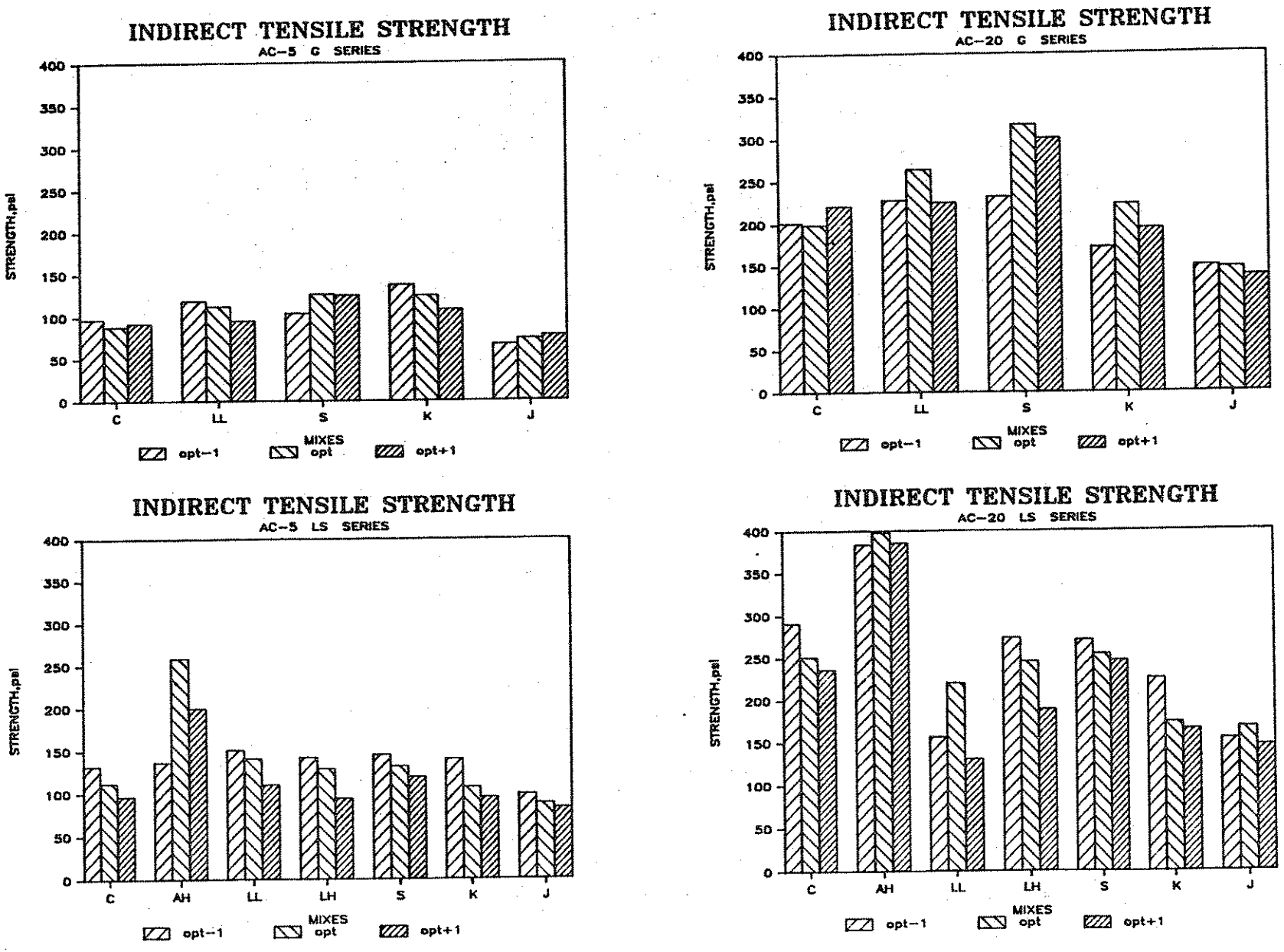


Fig. 33. Indirect tensile strength.

(24 hrs. at 140° F), retained tensile strength ratio and retained resilient modulus ratio after vacuum saturation and after Lottman-accelerated moisture conditioning (vacuum saturation followed by freezing and warm water soaking). (See Fig. 31.) The Lottman wet-to-dry tensile strength ratios were used in conjunction with the ACMODAS (Asphalt Concrete Moisture Damage Analysis System) computer program developed by Lottman and Leonard (28) to predict changes in fatigue life because of additives and to predict field life benefit-to-cost ratios for different additives.

4.3.4.1. Marshall Immersion

Marshall immersion stability results are given in Table 8, and the retained stability expressed as ratios are shown in Fig. 34. The only asphalt-aggregate combination with additives that showed improved stability ratios was gravel with AC-5; here the mixes without additives (control) would have a problem meeting the usual criterion of minimum ratio of 0.85.

4.3.4.2. Tensile Strength

Indirect tensile strengths after vacuum-saturation and after Lottman-accelerated conditioning are given in Table 9. Also given were percent resistance pick-up by weight and degree of saturation of vacuum-saturated samples. The degree of saturation, expressed as percent, was calculated by dividing the volume of moisture pick-up by the volume of air content. The retained tensile strengths, expressed as ratios, are shown in Fig. 35.

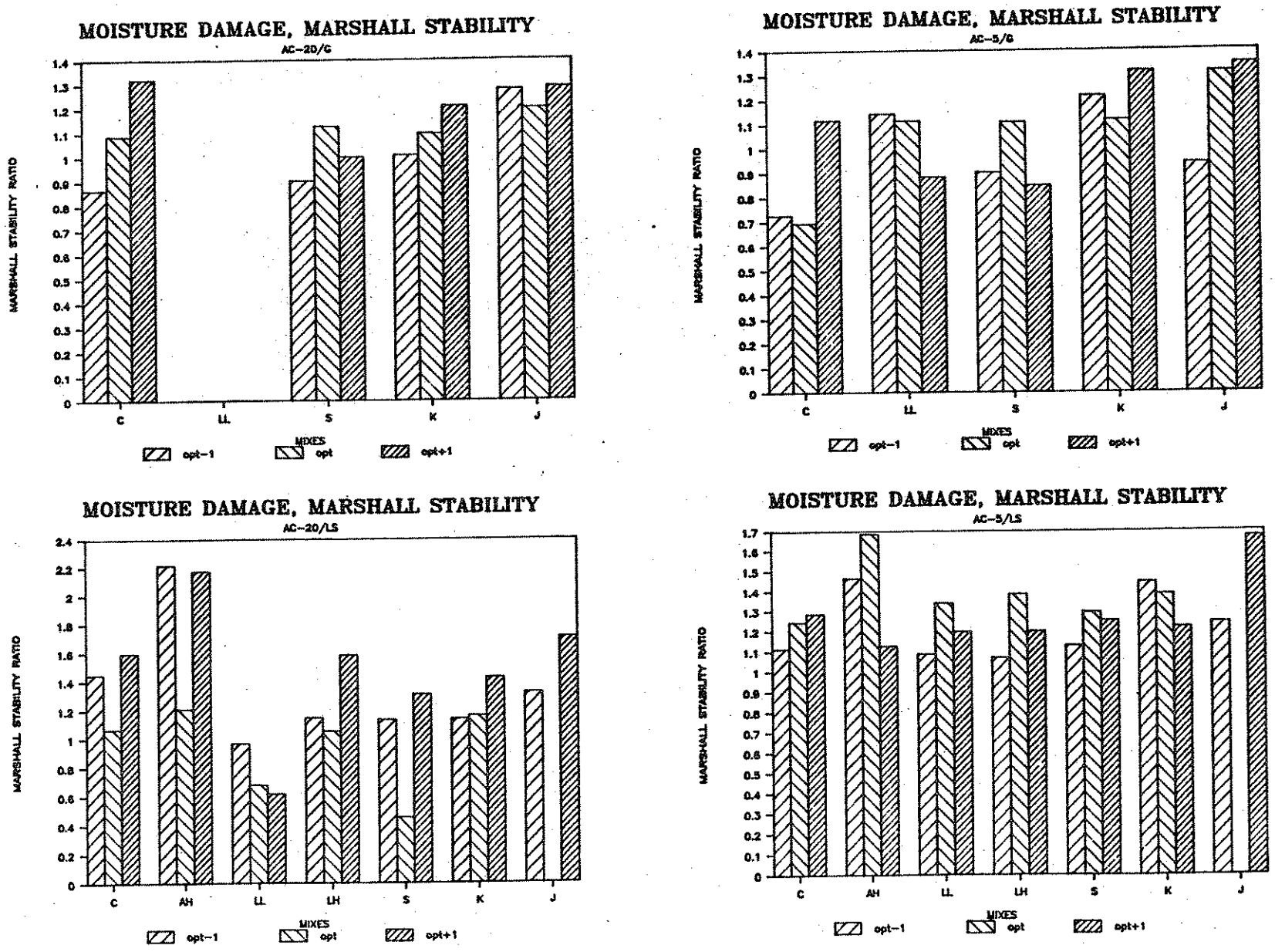


Fig. 34. Moisture damage, Marshall immersion stability.

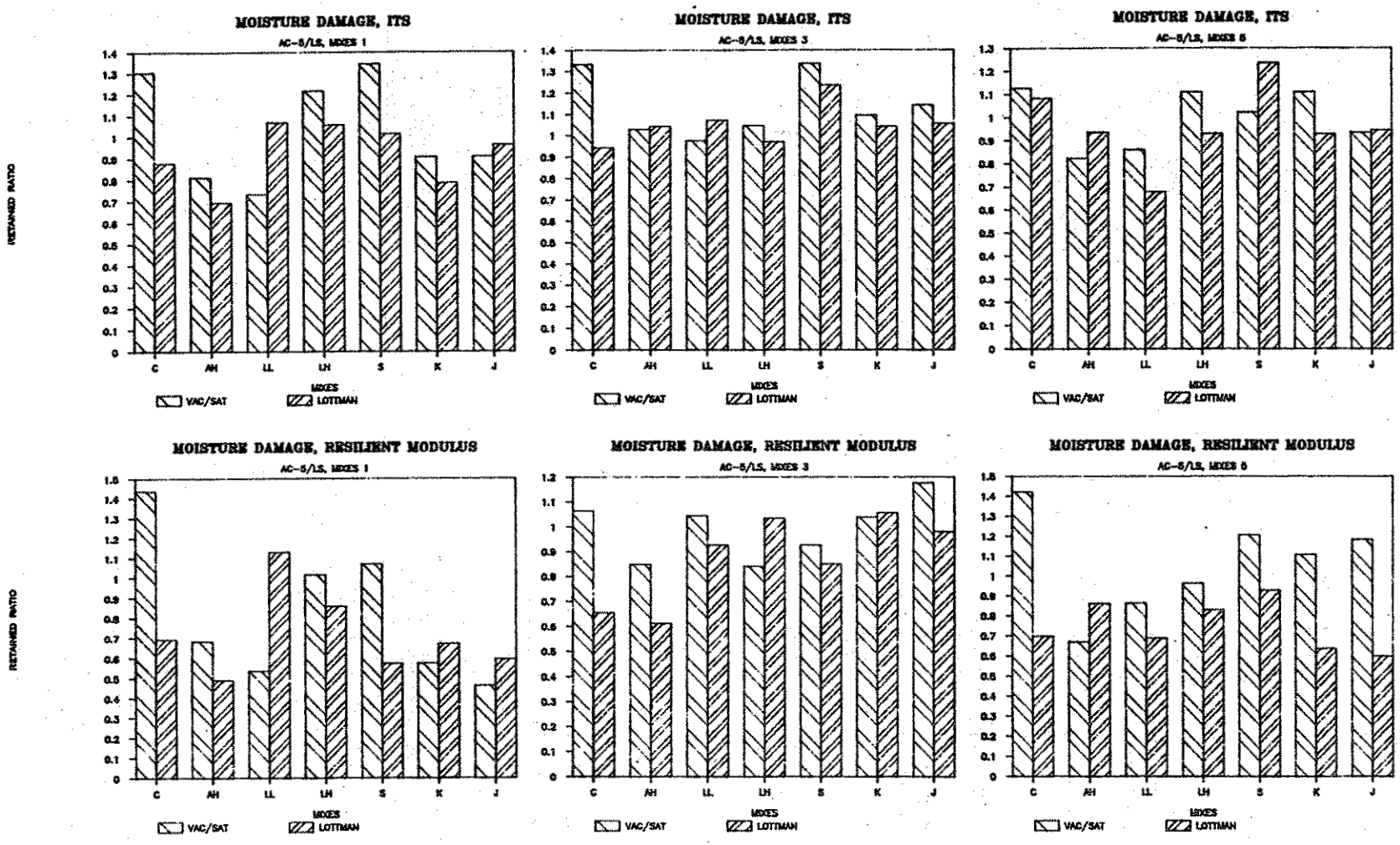


Fig. 35a. Moisture damage, ITS, and resilient modulus, AC-5/LS.

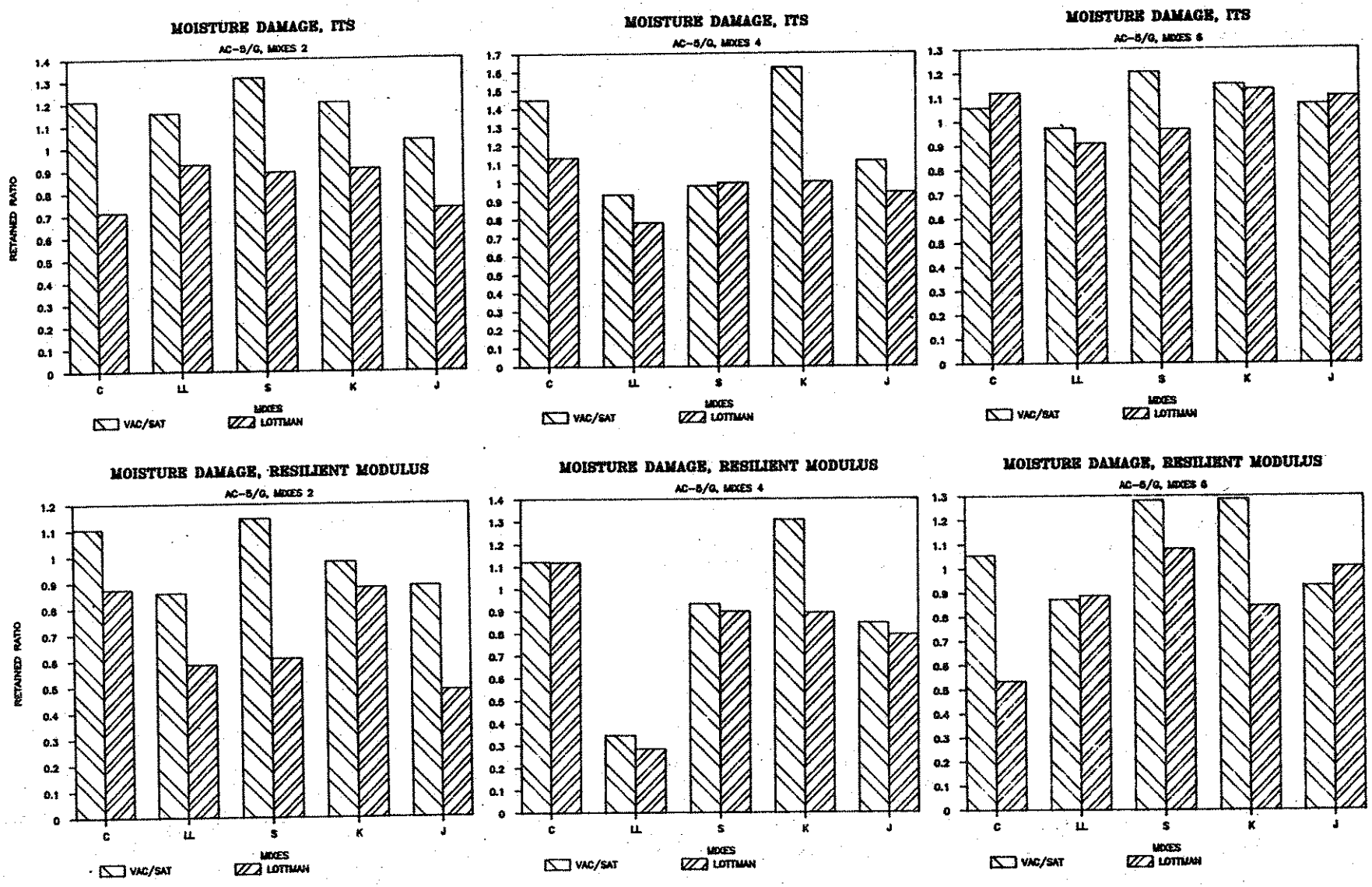


Fig. 35b Moisture damage, ITS, and resilient modulus, AC-5/G.

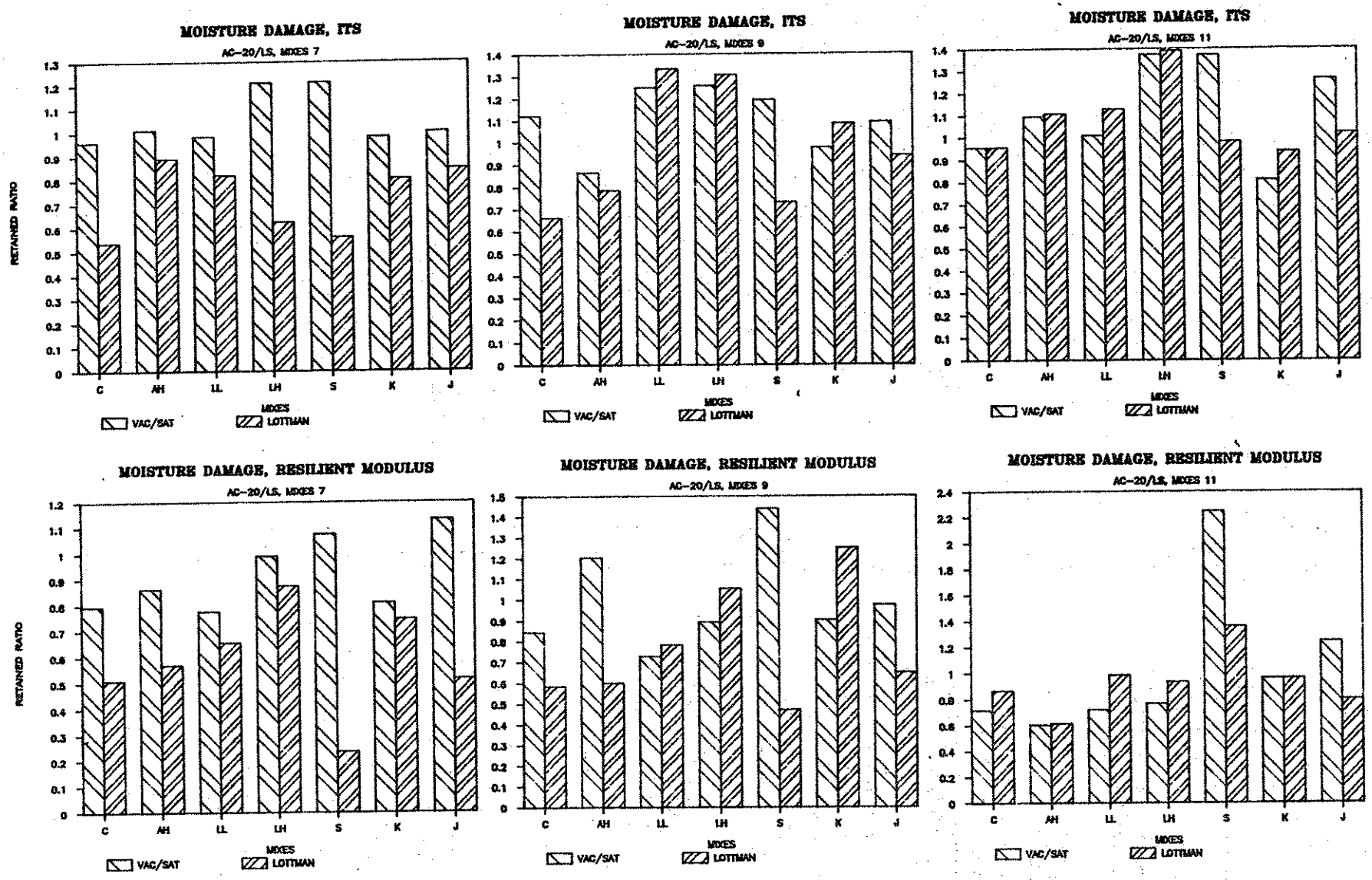


Fig. 35c. Moisture damage, ITS, and resilient modulus, AC-20/LS.

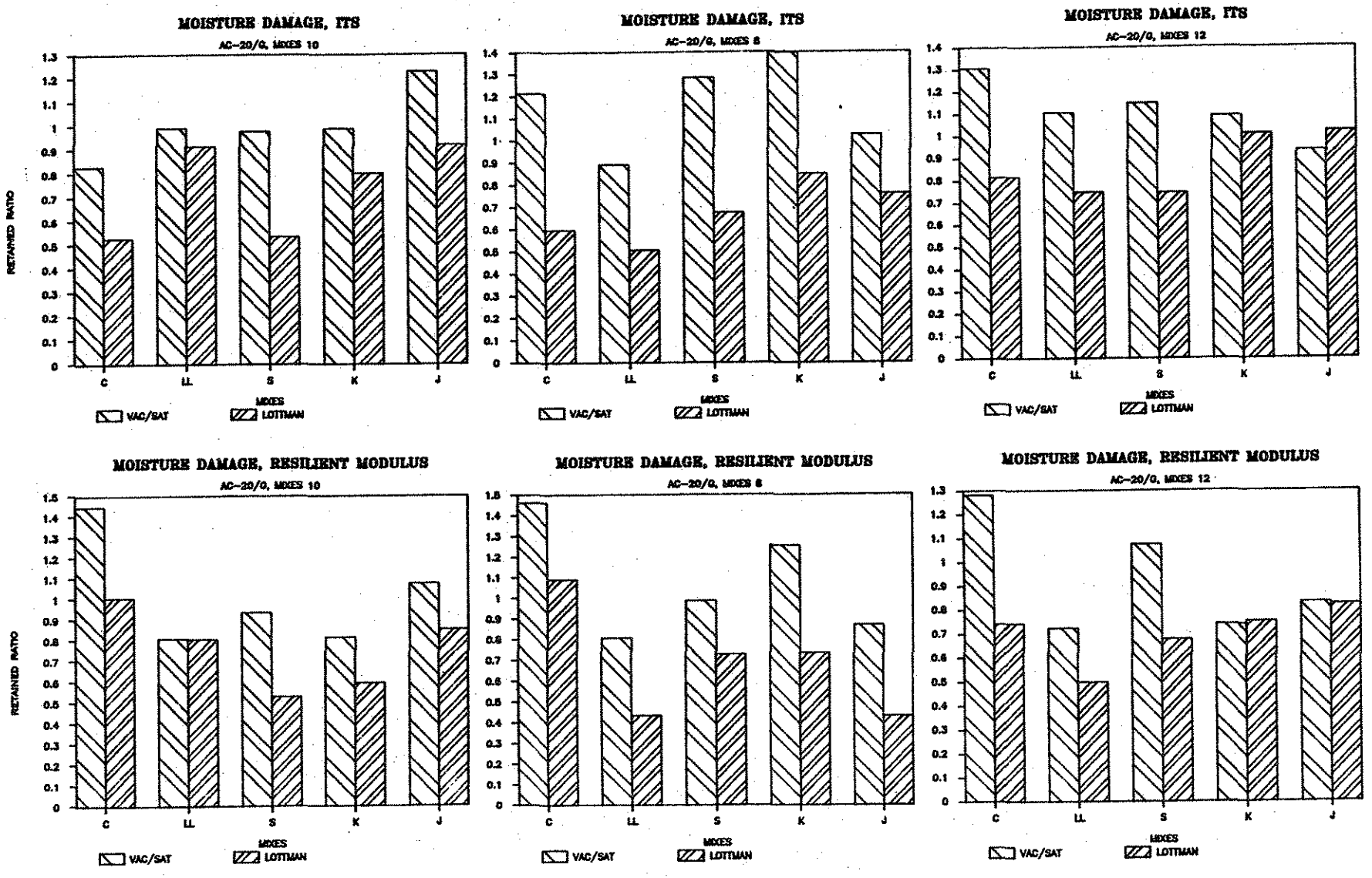


Fig. 35d. Moisture damage, ITS, and resilient modulus, AC-20/G.

With a few exceptions, the tensile stength ratios after Lottman treatment were lower than those after simple vacuum saturation. The retained ratios ranged from about 0.50 to 1.4. The moisture pick-up ratios ranged from 0.4% to 4.0%. All except two mixes had percent saturation exceeding the recommended 55% (49). In several samples the degree of saturation was greater than the theoretical 100% because of (1) small moisture pick-up values, (2) small air content values, and (3) the different number of specimens examined for (1) and (2). The moisture pick-up values were based on an average of 3 to 6 specimens, but the air content values were determined for an average of 15 to 18 specimens. The following observations can be made.

- AC-5/Limestone: Lime, SBS, and SBR seemed to have improved the moisture resistance determined by the Lottman procedure; but no additives showed improvements based on vacuum-saturation treatment.
- AC-5/Gravel: No significant effect.
- AC-20/Limestone: Lime, SBS and SBR reduced moisture damage while Asphadur and neoprene showed improvement only by the Lottman procedure.
- AC-20/Gravel: Whereas SBS and neoprene showed beneficial effects, lime and SBR made little difference in retained tensile strength ratios.

4.3.4.3. Resilient Modulus

Resilient modulus data for mixes before and after moisture treatments are given in Table 9 and shown in Fig. 35. In the majority of the mixes, the resilient modulus ratios were parallel to and were

lower than those of tensile strength ratios. In other words, they were most sensitive to moisture-induced damage. Again, as in the tensile strength ratios, Lottman conditioning resulted in lower retained ratios; and no additives showed consistent improvements for all asphalt-aggregate combinations and with all binder contents, although AC-20/limestone mixes seemed to have benefitted by the additives more often than other mixes. Contrary to previous beliefs, gravel mixes did not show more moisture susceptibility than corresponding limestone mixes, and hydrated lime did not improve moisture resistance in all cases.

4.3.4.4. Life Benefit-to-Cost Ratio

Dry and wet accelerated-conditioned indirect tensile strength data were used to calculate the field dry-wet lives and the percent changes from all-dry design life because of moisture damage. The subroutine LCO of the ACMODAS program was used for all control (C) mixtures. From dry and wet strengths of treated mixes and the predicted field dry-wet life of corresponding control mixes, field dry-wet lives and the percent changes from the all-dry design life of additive-treated mixtures were calculated with the subroutine LBC. By using the same LBC subroutine, the field life benefit-to-cost ratios were calculated for scenarios where the costs of the additive-treated mixes were 5%, 10% and 20% higher than the corresponding control mixes (cost ratios of additive-treated mixtures of 1.05, 1.10 and 1.20). The pavement and environmental data assumed were:

Regional factor: 1 (severe)

Field all-dry design life: 16 years

Percent allowable reduction of all-dry design life: 10

Field dry stage time: 4 years

The percent changes from all-dry design life and the life benefit-to-cost ratios for additives cost ratios of 1.05, 1.10 and 1.20 were plotted in Fig. 36a (LS/AC-5), 36b (G/AC-5), 36c (LS/AC-20) and 36d (G/AC-20). The only consistent trend that can be deduced from the analysis is the decreased benefit-to-cost ratio as the cost of additive is increased. The effects of additives in terms of changing the design life and benefit-to-cost ratio with respect to moisture-induced damage depend on the asphalt-aggregate combination as well as asphalt content. While limestone (LS)/AC-20 mixes seemed to have benefitted by all additives, no significant differences can be seen for mixes containing AC-5. Neoprene (K) and SBR (J) improved the moisture resistance of AC-20 mixes but not AC-5 mixes.

At an additive cost ratio of 1.05, 63% of the 60 mixes containing additives had life benefit-to-cost ratios of greater than one. At an additive cost ratio of 1.20, only 37% of the mixes had benefit-to-cost ratios greater than one. Ranking of the additives based on percent of mixes containing the respective additives with a life benefit-to-cost ratio exceeding one is as follows: high lime (LH), 83%; SBR (J), 75%; Asphadur (AH), 67%; SBS (S) and neoprene (K), 58%; low lime content (LL), 50%.

4.3.5. Fatigue Resistance

Fatigue resistance of asphalt concrete mixes can be determined experimentally by repeated flexure, direct tension, or diametral tensile tests, either at controlled-strain or controlled-stress mode. However,

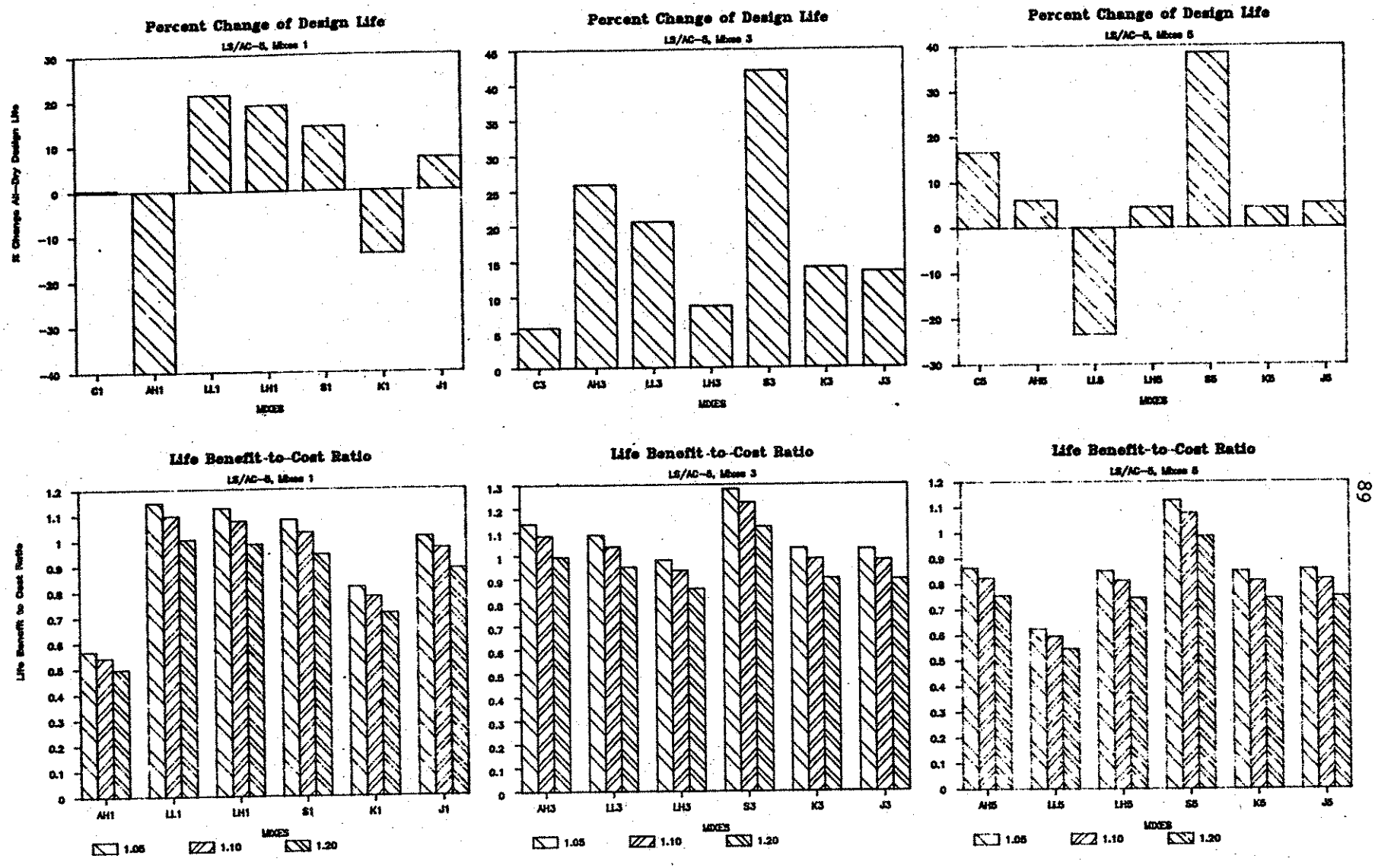


Fig. 36a. Percent change of design life and benefit-to-cost ratio, AC-5/LS.

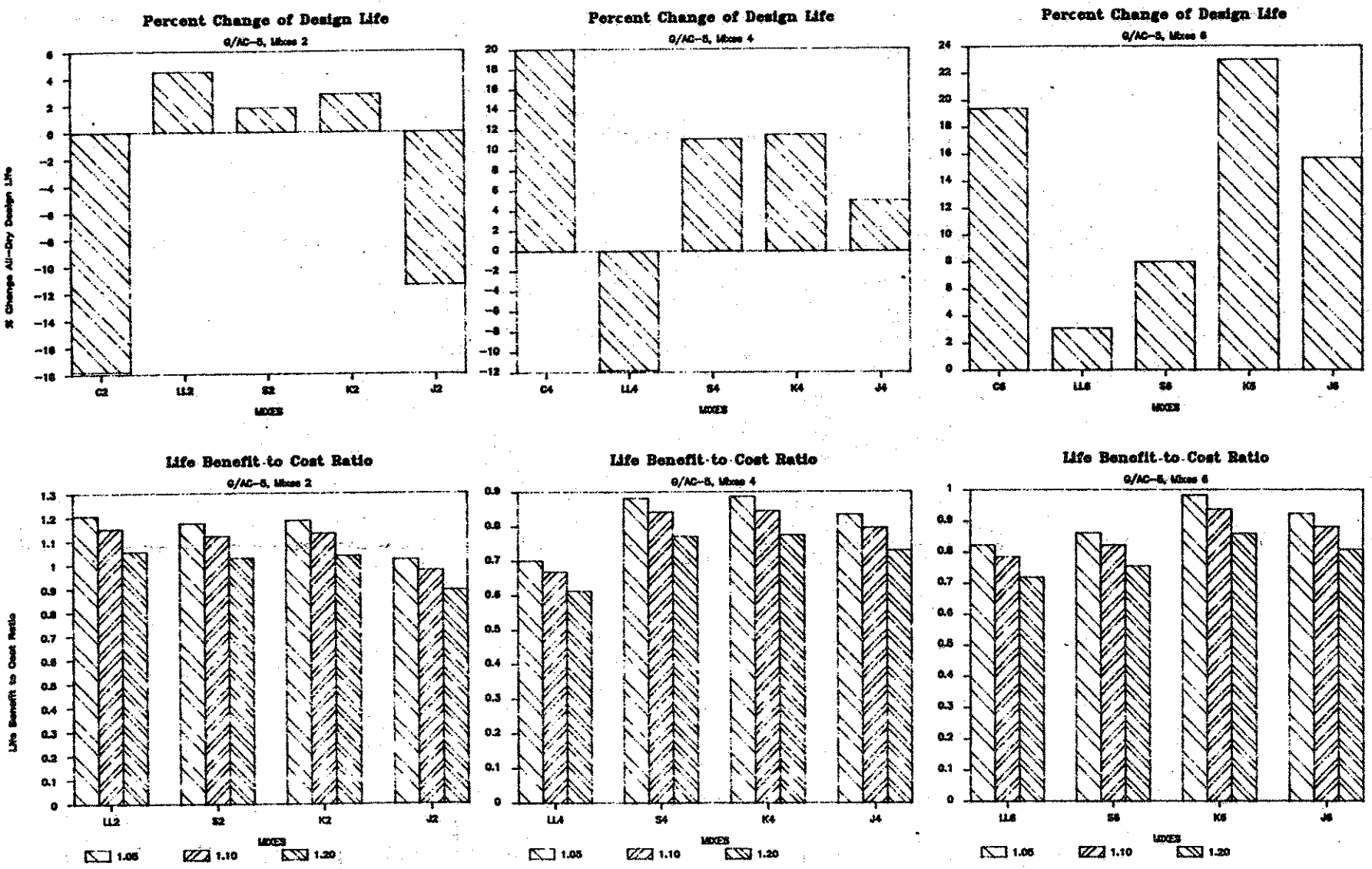


Fig. 36b. Percent change of design life and benefit-to-cost ratio, AC-5/G.

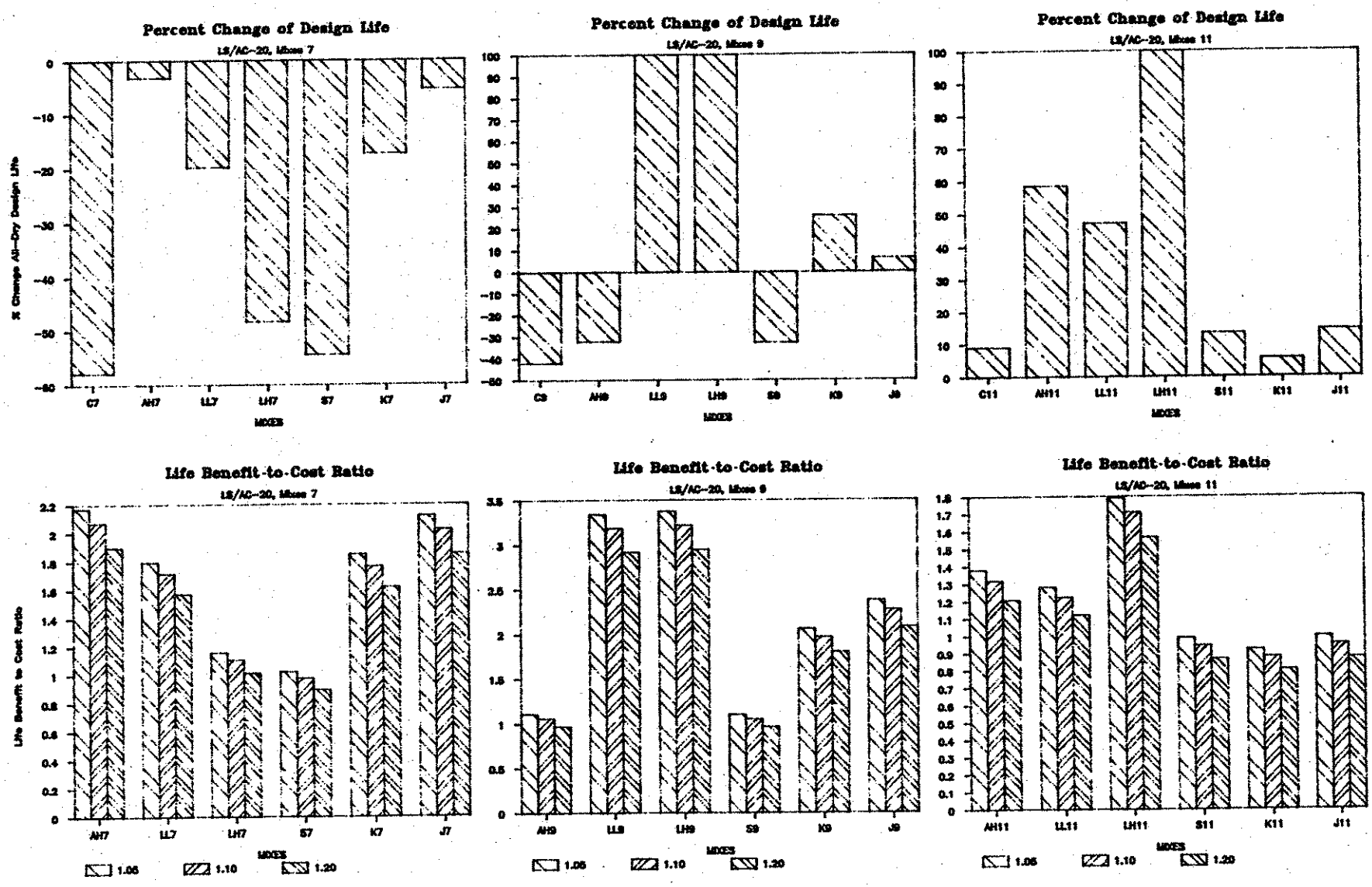


Fig. 36c. Percent change of design life and benefit-to-cost ratio, AC-20/LS.

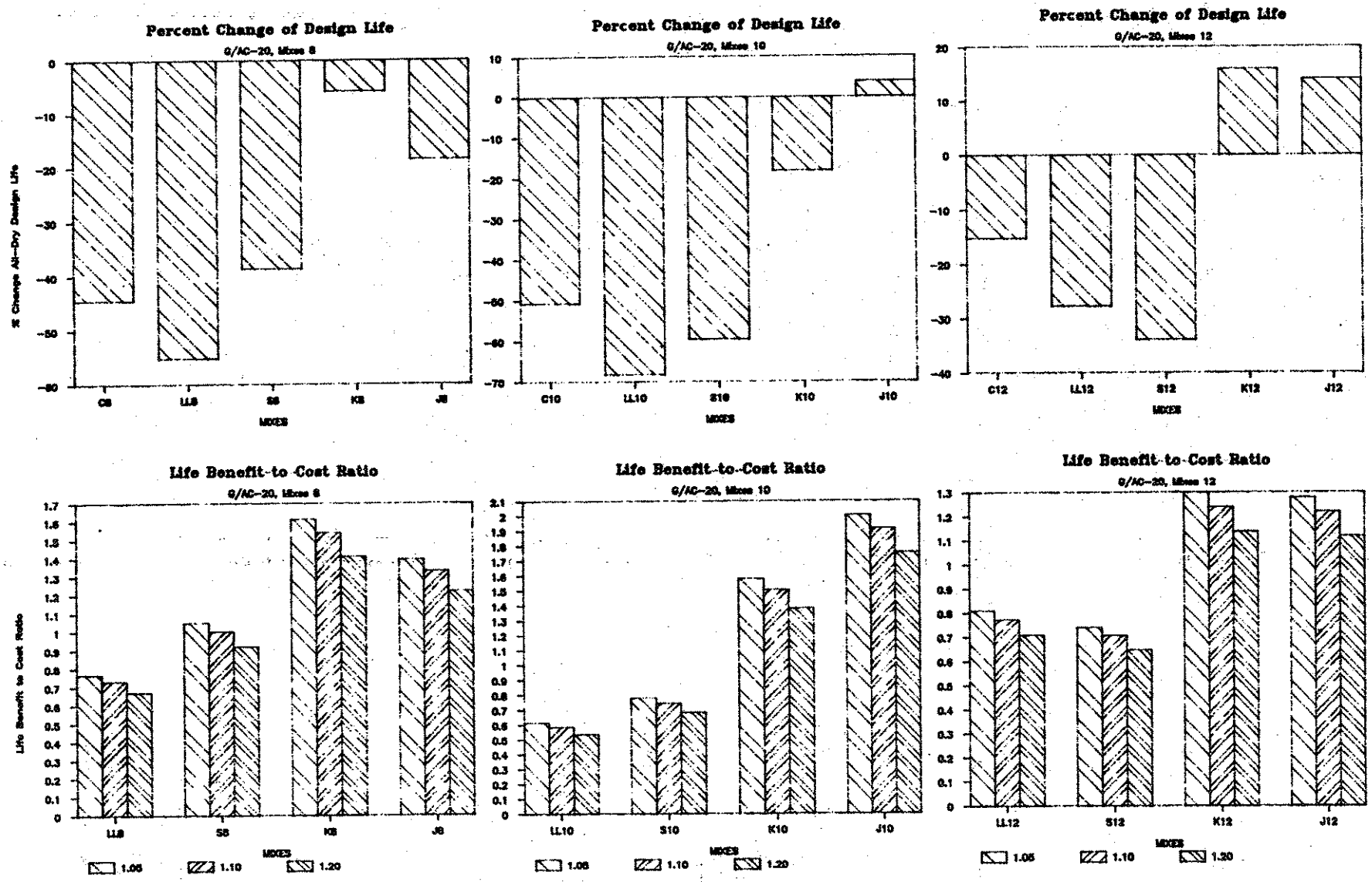


Fig. 36d. Percent change of design and benefit-to-cost ratio, AC-20/G.

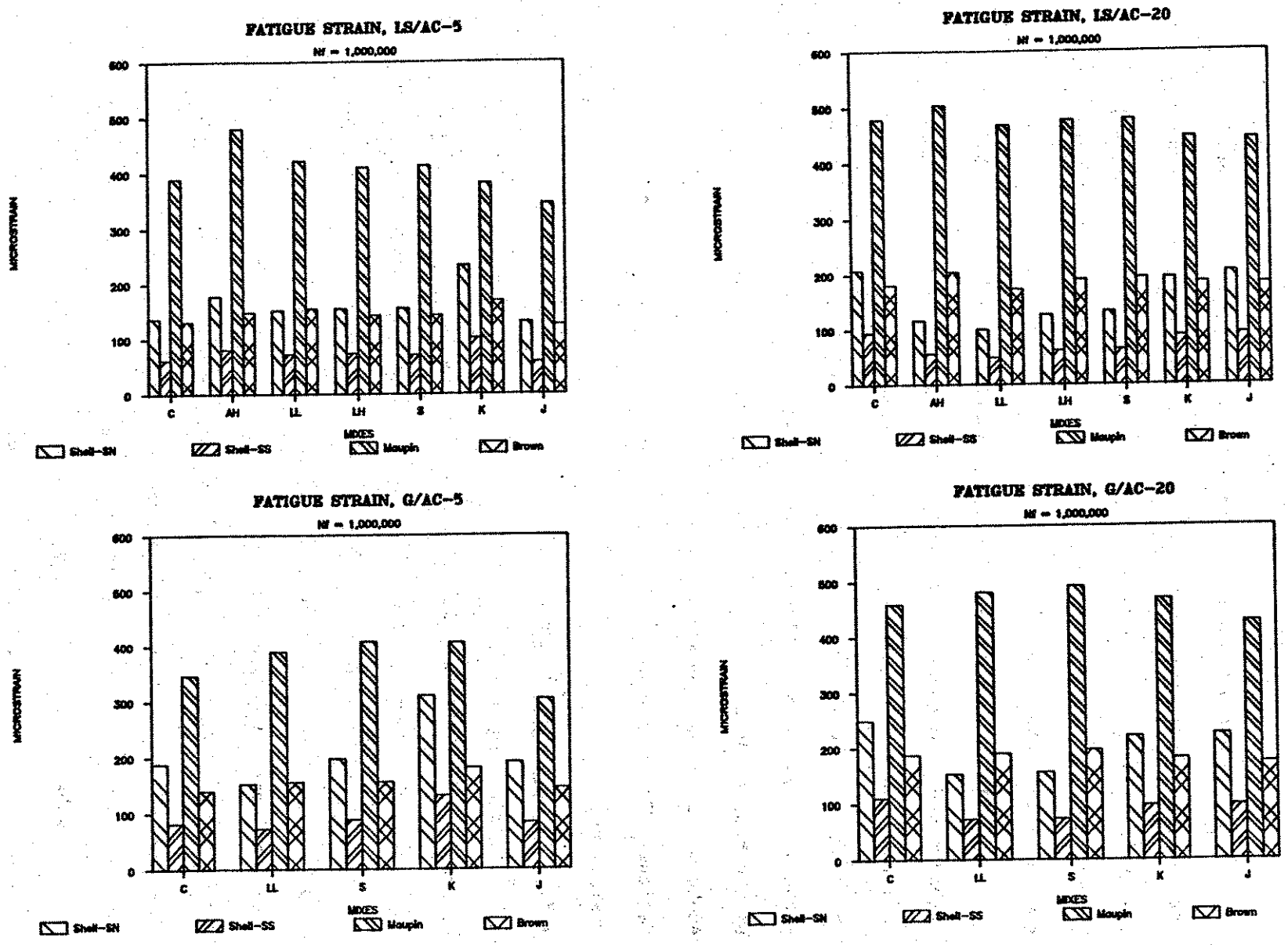
fatigue experiments are extremely time-consuming and expensive and require a minimum of 42 specimens per mix (a minimum of 7 specimens per each of 3 stress levels at each of 2 temperatures). As an alternative, three indirect methods were used to compare the fatigue properties of the mixes studied. They were based on the fatigue life and allowable tensile strain relationships of existing fatigue data. The fatigue relationships used were:

- The Shell France method (5) is based on 150 fatigue curves for both constant stress and constant strain tests. Fatigue life is a function of the stiffness of the mix, the penetration index, and the percent by volume of bitumen. The stiffness of the mix is determined from the volume percent of bitumen, the volume percent of aggregate, and the stiffness of bitumen that is obtained from van der Poel nomograph (52) on the basis of the penetration index and softening point of the bitumen, temperature, and loading time.
- The Brown (University of Nottingham) method (7) is based on 50 fatigue curves conducted at 10° C in controlled-stress tests. The fatigue life depends on the softening point and the volume percent of bitumen.
- The Maupin method (32) is based on relationships between constant-strain fatigue tests and indirect tensile strength.

The relative fatigue resistance of different mixes were compared on the basis of calculated allowable tensile strains for a fatigue life of one million cycles. The results of fatigue analyses are given in Table 10 and shown in Fig. 37.

Table 10. Results of fatigue analyses, microstrain.

Mix	SHELL-SN	SHELL-SS	MAUPIN	BROWN
LS/AC-5				
C	137.04	62.25	389.91	131.14
AH	177.94	80.79	479.99	148.72
LL	152.36	72.56	422.44	155.91
LH	155.50	73.79	410.68	143.24
S	156.32	71.71	413.43	143.43
K	233.70	102.23	382.10	169.38
J	130.40	58.45	345.43	125.39
G/AC-5				
C	188.37	82.23	347.05	139.55
LL	152.36	72.56	390.34	155.91
S	197.86	88.55	408.37	155.64
K	310.46	130.86	406.33	181.37
J	191.34	83.66	304.57	144.43
LS/AC-20				
C	208.45	94.50	478.02	180.81
AH	116.10	55.98	503.61	204.17
LL	100.33	49.69	468.09	173.08
LH	126.87	62.19	476.28	190.40
S	133.03	64.20	478.76	194.23
K	194.12	88.45	446.58	185.79
J	204.61	92.24	442.79	183.20
G/AC-20				
C	249.75	110.11	459.64	187.35
LL	152.99	72.58	481.40	190.58
S	156.73	73.54	492.29	197.05
K	221.70	97.15	468.81	182.02
J	225.18	97.46	427.80	174.22



a. AC-5

Fig. 37. Fatigue strain.

b. AC-20

Strain values determined by the Shell nomograph that is based on the controlled-stress mode and by the Brown (Nottingham) nomograph are comparable. Strains determined by the Shell constant-strain fatigue curves were lower, and those calculated from the Maupin expressions were consistently higher.

No significant effects resulted because of additives, except that Asphadur (AH) and neoprene (K) seemed to have increased the fatigue resistance for AC-5 mixes; and Asphadur, lime (LL and LH), and Styrelf (S) decreased the fatigue resistance for AC-20 mixes based on Shell methods. Also, higher allowable strains were obtained for AC-20 mixes by the Maupin and Brown methods, but lower strains were obtained for AC-20 mixes by Shell nomographs, especially for contolled-strain fatigue. Types of aggregates made little difference in fatigue resistance.

4.3.6. Rutting Resistance

The effect of additives on the resistance to permanent deformation or rutting of the asphalt concrete mixes studied were evaluated by the Shell procedure (43) by using the results of uniaxial creep tests. The creep tests were performed at 40° C and at a stress level of 14.5 psi (100 kPa) for 2 hrs after conditioning or preloading of 1.45 psi (10 kPa) for 2 min. Typical strain-time creep curves are shown in Fig. 38. The results of creep tests for each mix were plotted in terms of the stiffness of the mix (Smix) versus the stiffness of the bitumen (Sbit) curves. The effects of aggregate type (LS vs G), asphalt grade (AC-5 vs AC-20), asphalt content, and type of additives on the creep curves are shown in Figures 39, 40, 41, and 42 respectively.

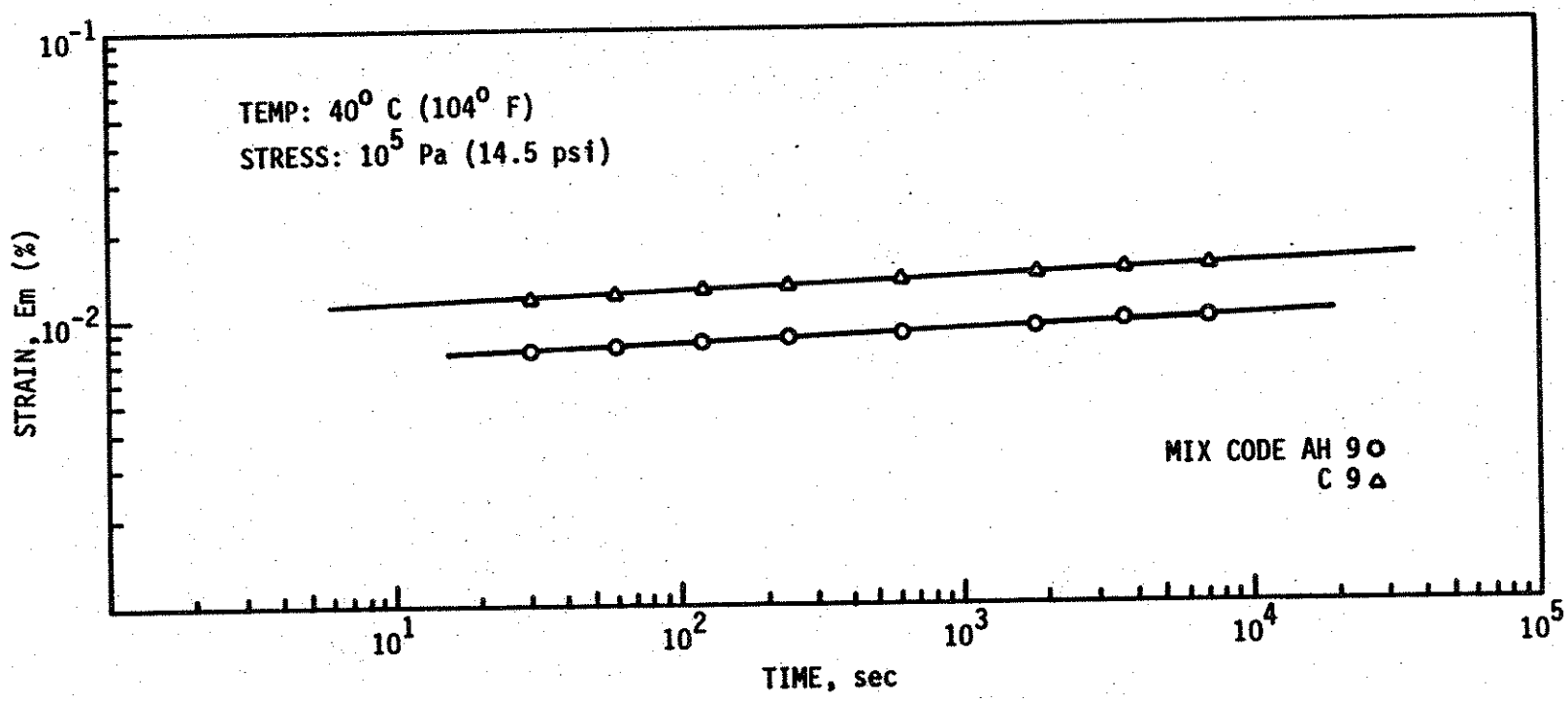


Fig. 38. Typical strain versus time curves, mixes C9 and AH9.

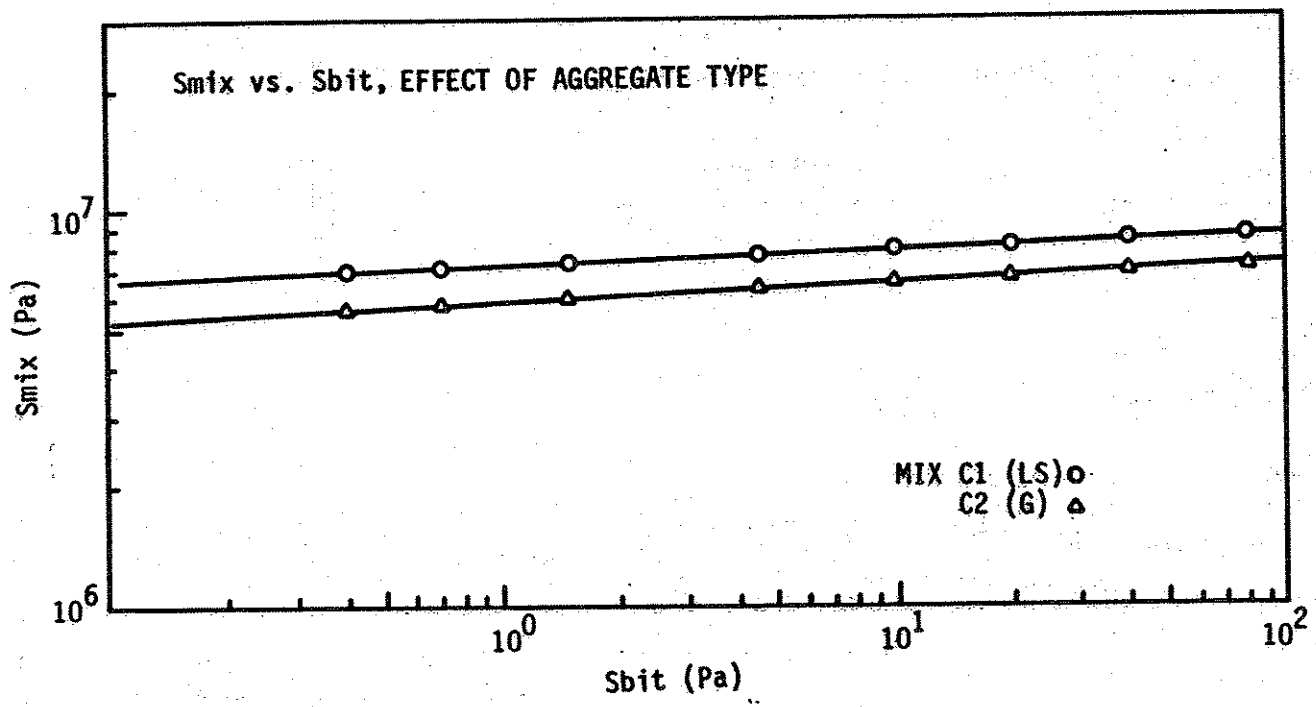


Fig. 39. Effect of aggregate type on Smix versus Sbit curves, Mixes C1 and C2.

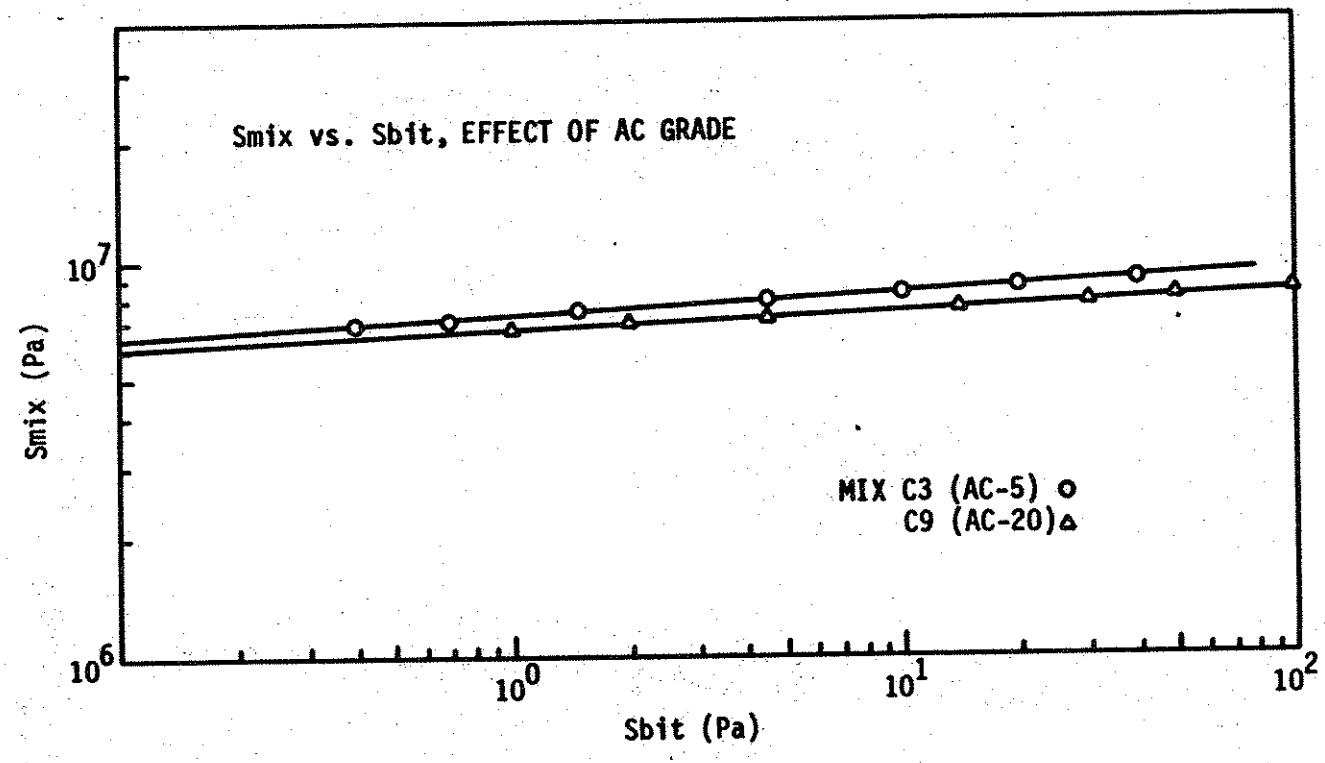


Fig. 40. Effect of AC grade on Smix versus Sbit curves, Mixes C3 and C9.

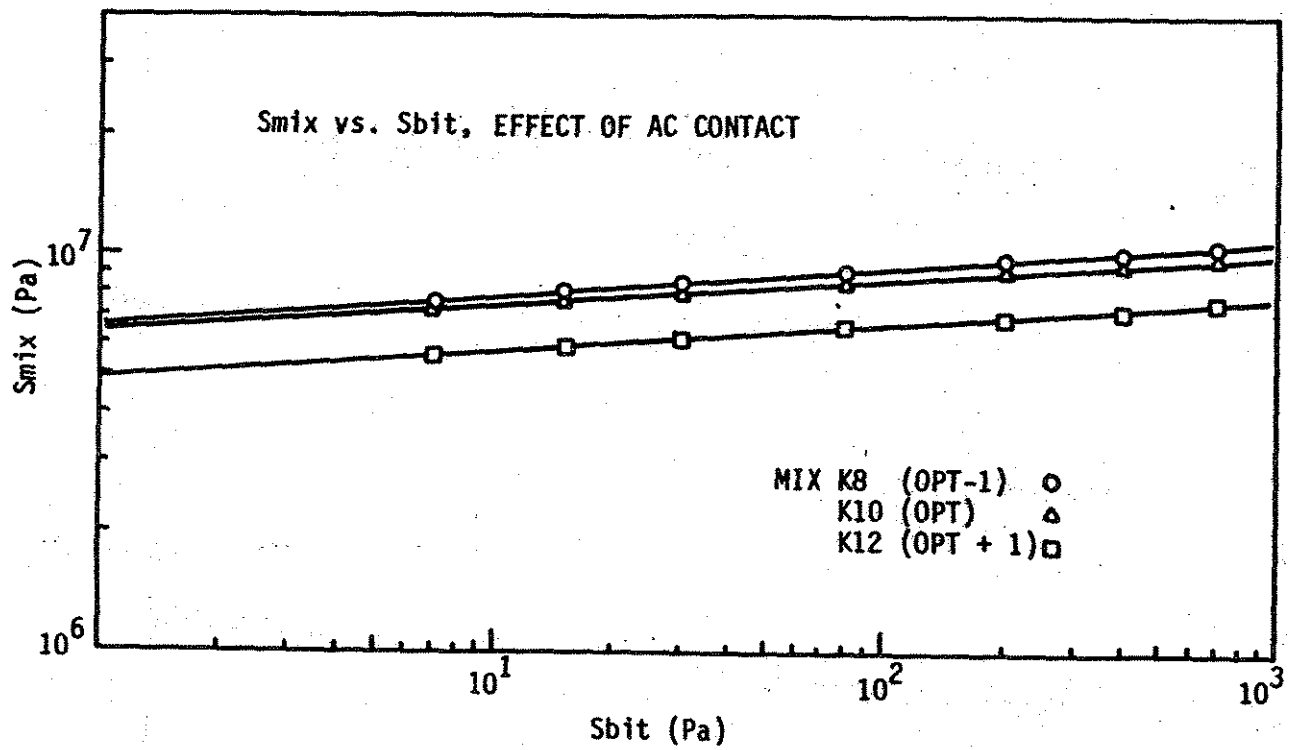


Fig. 41. Effect of AC content on Smix versus Sbit curves, Mixes K8, K10, and K12.

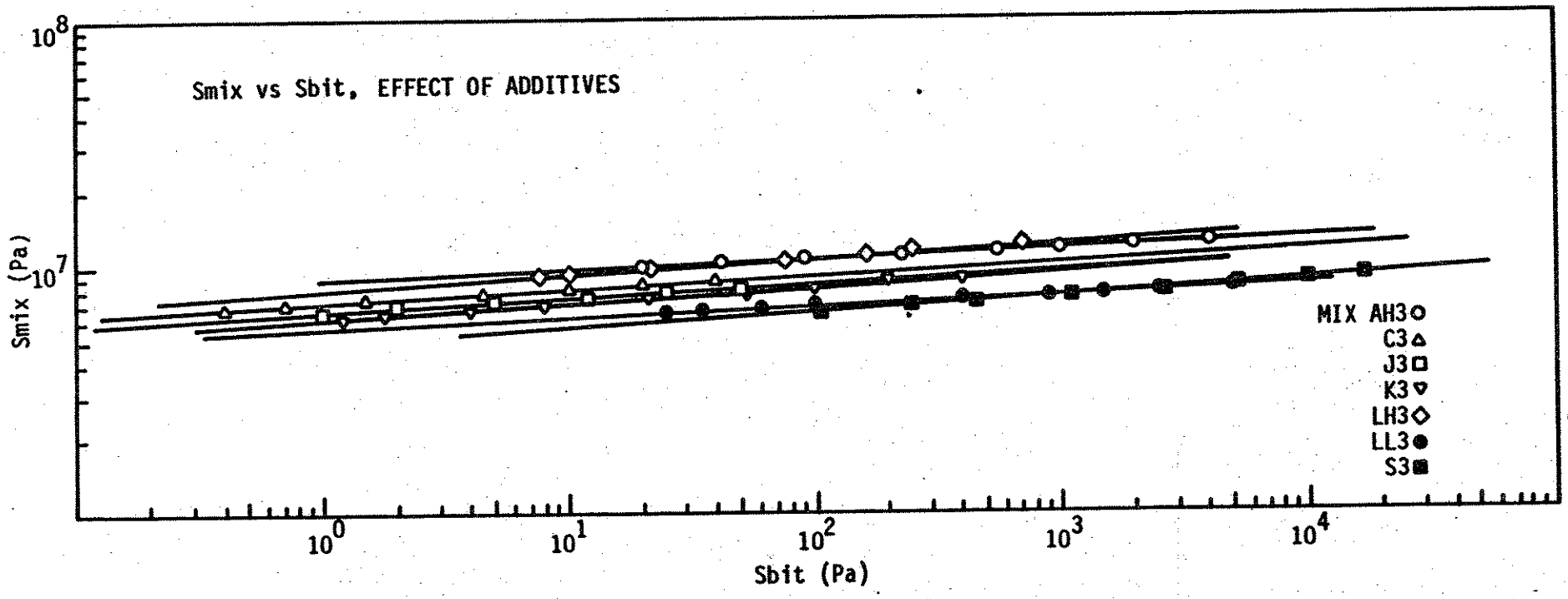


Fig. 42. Effect of additives on Smix versus Sbit curves.

To compare rutting resistance of various mixes, we calculated rut depths or permanent deformations occurring in the asphalt concrete layer. To make these calculations, we followed the Shell procedure for a standard pavement structure of asphalt concrete with a surface course 130 mm thick (subdivided into three layers of 40, 40 and 50 mm) on top of a subgrade of CBR of 2.5 (E3 = 25 mPa). The design life was 20 years. The traffic was assumed to be 100 (18 kip SAL) per lane per day with a growth of 3%. The mean monthly air temperatures (MMAT) for Iowa were used and resulted in effective mean annual air temperatures (MAATeff) of 19° C (66° F) for AC-5 and 20° C (68° F) for AC-20.

The estimated rut depths occurring in the 130 mm (5 in.) asphalt concrete layer and calculated from creep data based on the Shell procedure are shown in Fig. 43. As we expected, raising the binder content and using softer binders resulted in larger rut depths. There was little difference in the type of aggregates used. Asphadur appeared to be the most effective additive in reducing rutting or permanent deformation in the mix. Other additives had no significant effects. With additives such as Asphadur, and perhaps hydrated lime, the rut depths of softer grade AC-5 mixes can be reduced to those of AC-20 without additives. These results seemed to confirm data provided by Marshall stiffness.

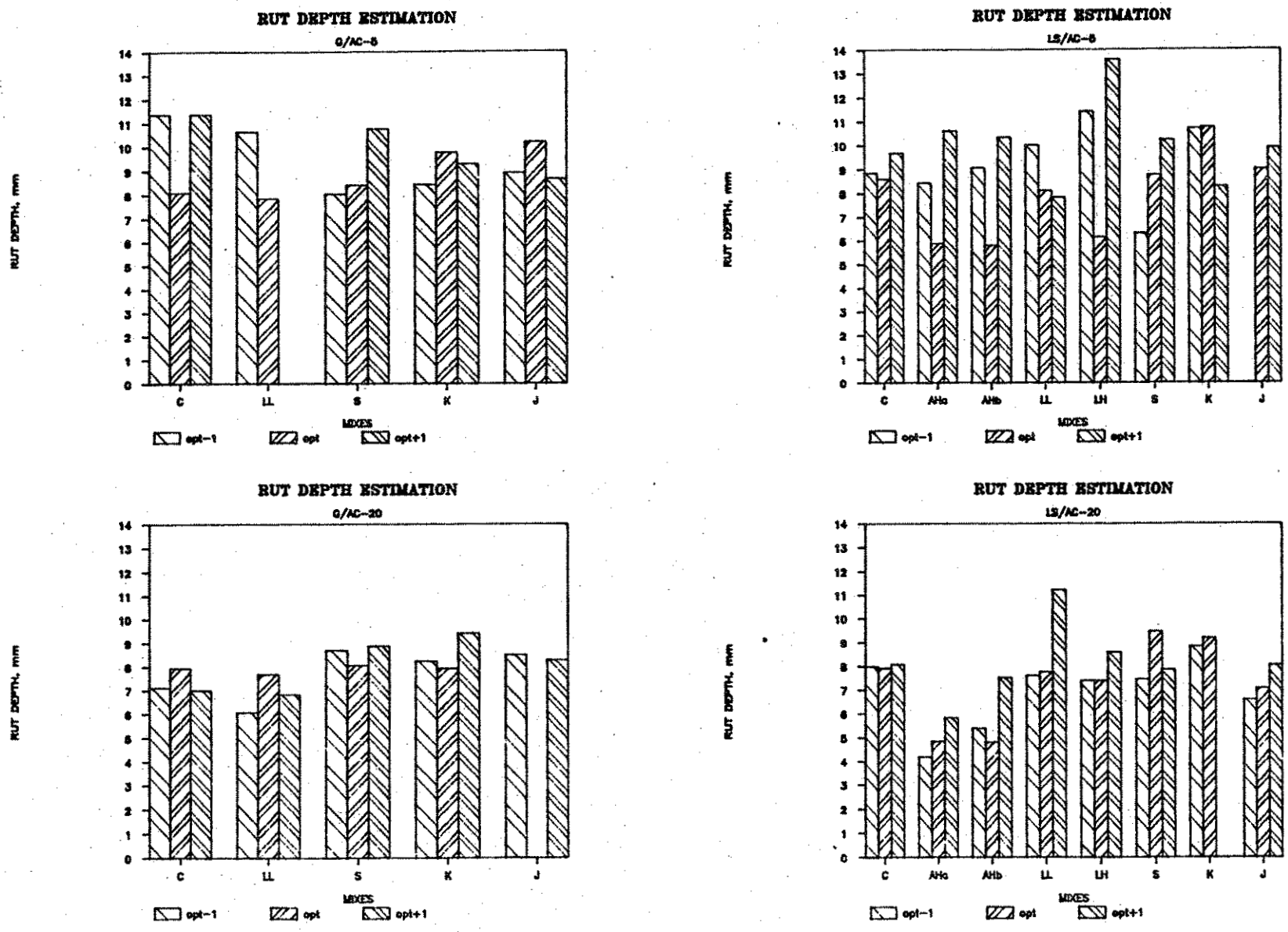


Fig. 43. Rut depth estimation by Shell procedure.

5. STRUCTURAL AND PERFORMANCE EVALUATION—PHASE III

In addition to evaluating the effects of additives on the properties of the asphalt cements (Phase I) and on the properties of asphalt concrete mixtures (Phase II), the effects of additives on structural and performance characteristics of the mixtures containing the additives as surface courses in pavements were evaluated. In the final analysis, it is the effect of these additives on the mixtures as a structural layer in the pavement that ultimately determines the benefits and usefulness of the additives.

Two pavement design and analysis methods, both based on elastic-layered theories, were used: the Asphalt Institute method (44) and the University of Nottingham (Brown) method (7).

5.1. The Asphalt Institute Method

The computer program DAMA (Chevron) was used to compute pavement lives for the 24 mixes at optimum binder contents in full-depth asphalt pavements of 4 and 8 in. on subgrades of CBR of 3% (subgrade modulus of 4,500 psi) and 8% (subgrade modulus of 12,000 psi). A mean annual air temperature (MAAT) of 60° F, appropriate for Iowa conditions, was used. The traffic was assumed to be 1,000 equivalent 18 kips SAL per month. It was also assumed that the pavements were opened to traffic in July. The resilient moduli of the mixes determined in Phase II were used in the analyses. A total of 96 computer runs were performed.

The results of computer analyses are tabulated in Table 11. A sample of the computer printout for Mix S3 (Styrelf at the optimum binder content with AC-5 and limestone) of 4 in. and subgrade modulus of 4500 psi (CBR of 8) is given in Appendix F.

The results presented in Table 11 are given in terms of surface deflection (Dz), tensile strain in the asphalt layer (Et), compressive strain in the subgrade (Ec), number of standard loads to cause fatigue failure (Nf), and number of standard loads to cause rutting failure (Nr). The strain and deflection values are the averages of their respective monthly values at the critical response point (at the center of one tire of the dual-tire system of an 18 kip single axle load) over a 12-month period.

To show the additive effects, we compared these five responses to the respective responses of the corresponding control mixes and expressed as ratios. Figure 44 shows these ratios at optimum binder contents (Mixes 3, 4, 9 an 10).

While increased asphalt concrete thickness and subgrade modulus reduced the strains and deflections and increased the numbers of loads to failure, the relative effects of the additives did not change. For the same asphalt, limestone mixes performed better than the gravel mixes; for the same aggregate, AC-20 mixes performed better than the AC-5 mixes. Asphadur improved the structural capacities of all mixes. Hydrated lime increased the structural capacities of gravel mixes, while SBR (J) decreased the structural capacities of all mixes. Styrelf (SBS) and neoprene (K) improved the behavior of gravel mixes with AC-20, but had little effect on the other mixes as compared to the responses of control mixes with no additives.

Table 11. Results of DAMA structural analyses.

H1 = 4 in.

SGE,ksi	DZ,/1000in. 4.5	DZ,/1000in. 12	ET,microstrain 4.5	ET,microstrain 12	EC,microstrain 4.5	EC,microstrain 12	Nf,xE06 4.5	Nf,xE06 12	Nr,xE06 4.5	Nr,xE06 12
Mixes 3										
C	55.80	25.80	736	485	1760	1100	0.064	0.264	0.001	0.005
AH	34.20	16.70	193	148	558	383	0.350	0.917	0.149	0.882
LL	54.80	25.50	702	466	1687	1058	0.029	0.117	0.001	0.012
LH	54.07	25.16	675	451	1630	1029	0.407	1.619	0.001	0.013
S	55.78	25.89	737	486	1762	1103	0.122	0.502	0.001	0.004
K	64.62	29.73	1094	672	2514	1500	0.059	0.305	0.001	0.001
J	64.87	29.85	1104	676	2534	1509	0.012	0.064	0.001	0.001
Mixes 4										
C	58.30	27.00	833	538	1970	1200	0.021	0.092	0.001	0.003
LL	53.39	21.89	653	313	1584	738	0.021	0.148	0.001	0.052
S	61.80	28.49	971	565	2257	1368	0.014	0.065	0.001	0.002
K	60.16	24.79	904	576	2114	1293	0.057	0.263	0.001	0.002
J	66.88	30.75	1195	719	2725	1603	0.015	0.080	0.001	0.001
Mixes 9										
C	37.73	18.21	253	189	700	473	0.349	0.993	0.056	0.352
AH	32.40	15.80	166	128	492	340	1.045	2.623	0.259	1.478
LL	40.38	19.35	304	223	819	547	0.415	1.260	0.028	0.188
LH	40.90	19.58	315	230	843	563	1.097	3.370	0.025	0.167
S	48.85	21.04	391	280	1016	668	0.218	0.725	0.012	0.080
K	54.08	25.16	677	452	1633	1030	0.233	0.926	0.001	0.013
J	48.93	22.99	514	356	1285	830	0.147	0.534	0.002	0.032
Mixes 10										
C	45.80	21.70	429	303	1100	719	0.070	0.241	0.003	0.058
LL	39.72	19.06	291	214	789	528	2.181	0.651	0.033	0.220
S	41.66	19.91	331	241	881	586	0.106	0.332	0.021	0.141
K	43.98	20.90	383	275	999	658	0.118	0.391	0.012	0.085
J	55.68	25.85	733	484	1753	1097	0.012	0.046	0.001	0.005

H1 = 8 in.

SGE,ksi	DZ,/1000in. 4.5	DZ,/1000in. 12	ET,microstrain 4.5	ET,microstrain 12	EC,microstrain 4.5	EC,microstrain 12	Nf,xE06 4.5	Nf,xE06 12	Nr,xE06 4.5	Nr,xE06 12
Mixes 3										
C	33.60	16.90	313	229	709	484	0.851	2.536	0.052	0.328
AH	19.30	9.50	69	57	189	141	8.996	17.270	17.770	67.090
LL	32.87	16.54	297	219	675	465	0.395	1.148	0.064	0.393
LH	32.29	16.23	284	211	649	448	5.699	16.270	0.076	0.456
S	33.64	16.94	314	230	710	486	1.616	4.820	0.052	0.325
K	41.09	20.80	500	343	1078	700	0.631	2.374	0.003	0.072
J	41.28	20.92	506	346	1088	705	0.131	0.494	0.003	0.069
Mixes 4										
C	35.70	18.00	362	26	806	544	0.259	0.825	0.030	0.203
LL	26.76	13.40	174	136	422	303	0.760	1.832	4.943	2.405
S	38.60	19.48	434	405	950	627	0.156	0.542	0.015	0.112
K	37.19	18.77	399	283	880	587	0.681	2.271	0.021	0.148
J	43.13	21.88	557	374	1186	757	0.149	0.596	0.002	0.051
Mixes 9										
C	21.31	16.89	93	76	244	180	8.014	16.540	5.677	22.600
AH	18.20	9.01	58	49	165	123	28.570	52.760	33.340	123.800
LL	22.91	11.42	114	92	291	214	8.809	19.090	2.566	10.780
LH	23.24	11.59	118	95	302	215	22.900	50.070	2.197	9.341
S	25.39	15.38	151	120	373	270	4.110	9.537	0.851	3.926
K	32.32	16.26	284	211	650	449	3.253	9.298	0.075	0.453
J	28.53	14.30	207	159	491	348	2.427	6.156	0.256	1.333
Mixes 10										
C	26.40	13.30	168	132	410	294	1.272	3.037	0.564	2.708
LL	22.50	11.21	108	88	279	205	4.721	10.110	3.122	12.930
S	23.71	11.82	125	100	316	231	2.163	4.791	1.772	7.667
K	25.17	12.59	148	117	366	265	2.254	5.200	9.288	4.252
J	33.56	16.88	312	229	706	483	0.149	0.442	0.053	0.332

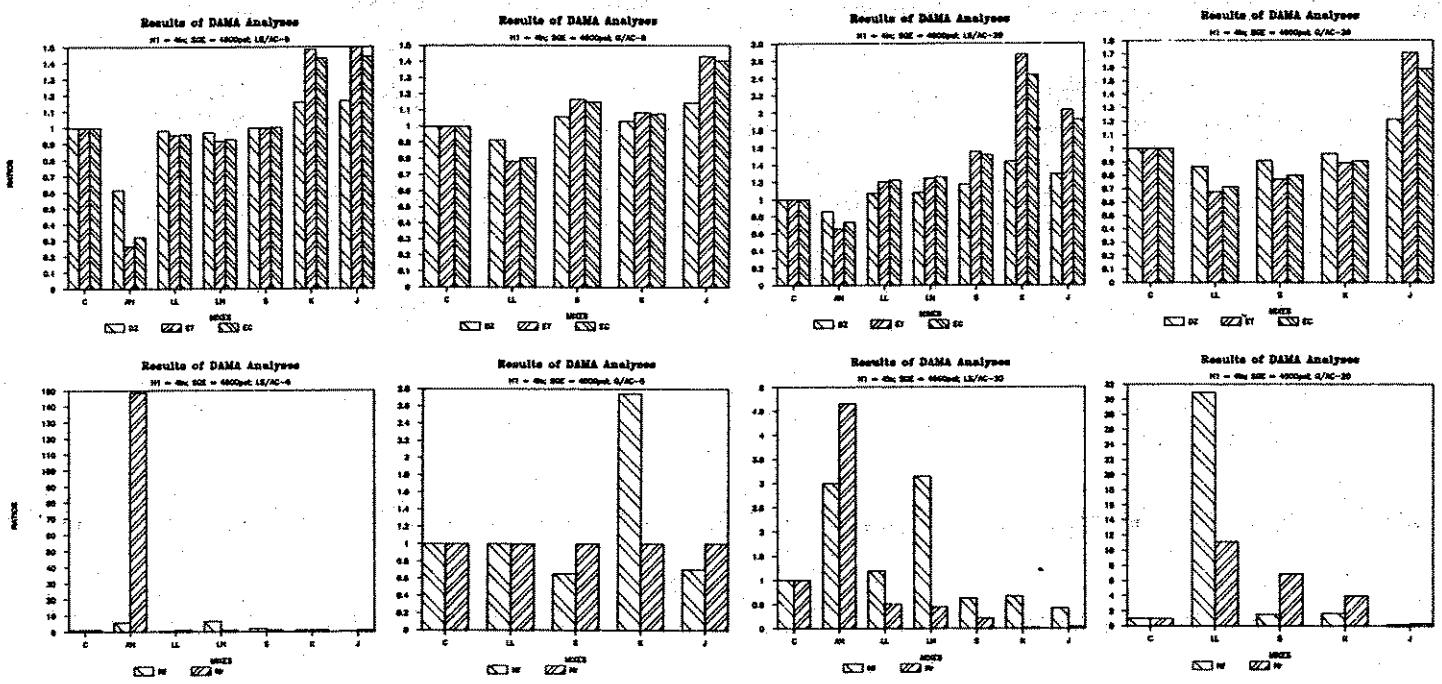


Fig. 44a. Structural analyses by DAMA procedure, H1 = 4 in., SGE = 4,5000 psi.

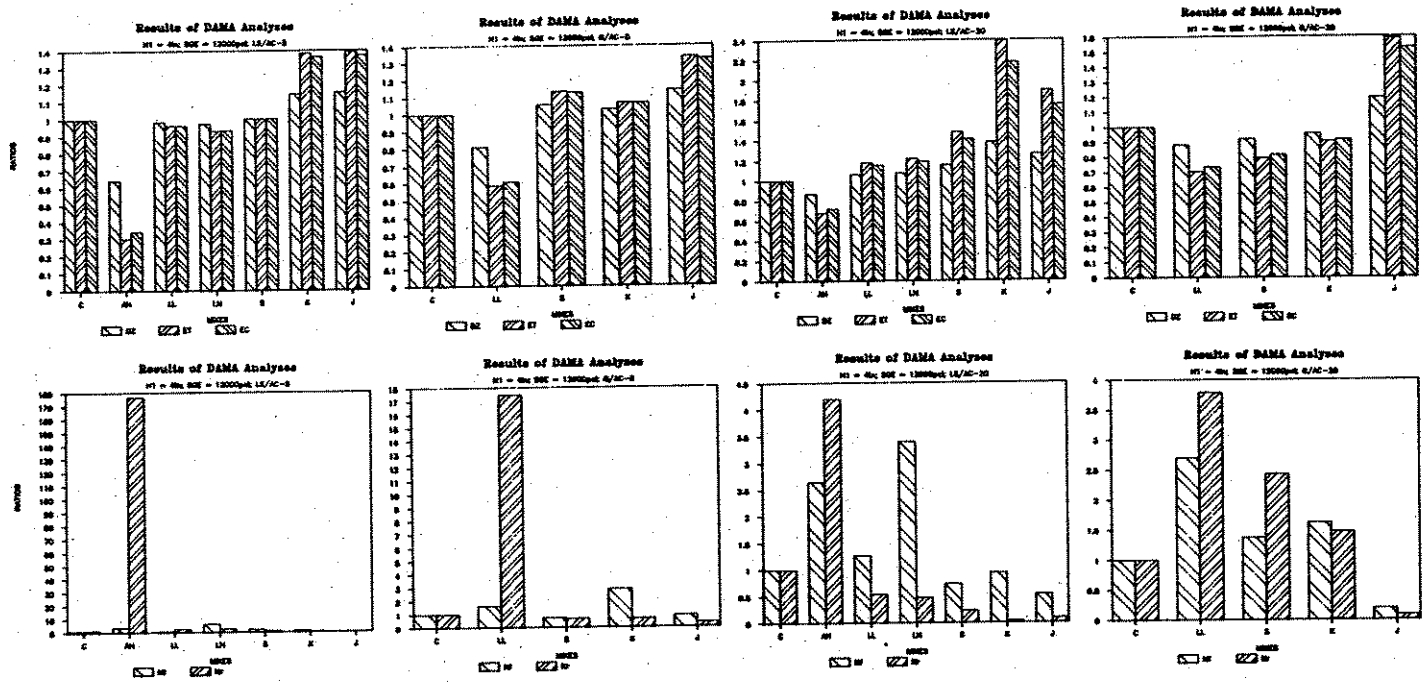


Fig. 44b. Structural analyses by DAMA procedure, H1 = 4 in., SGE = 12,000 psi.

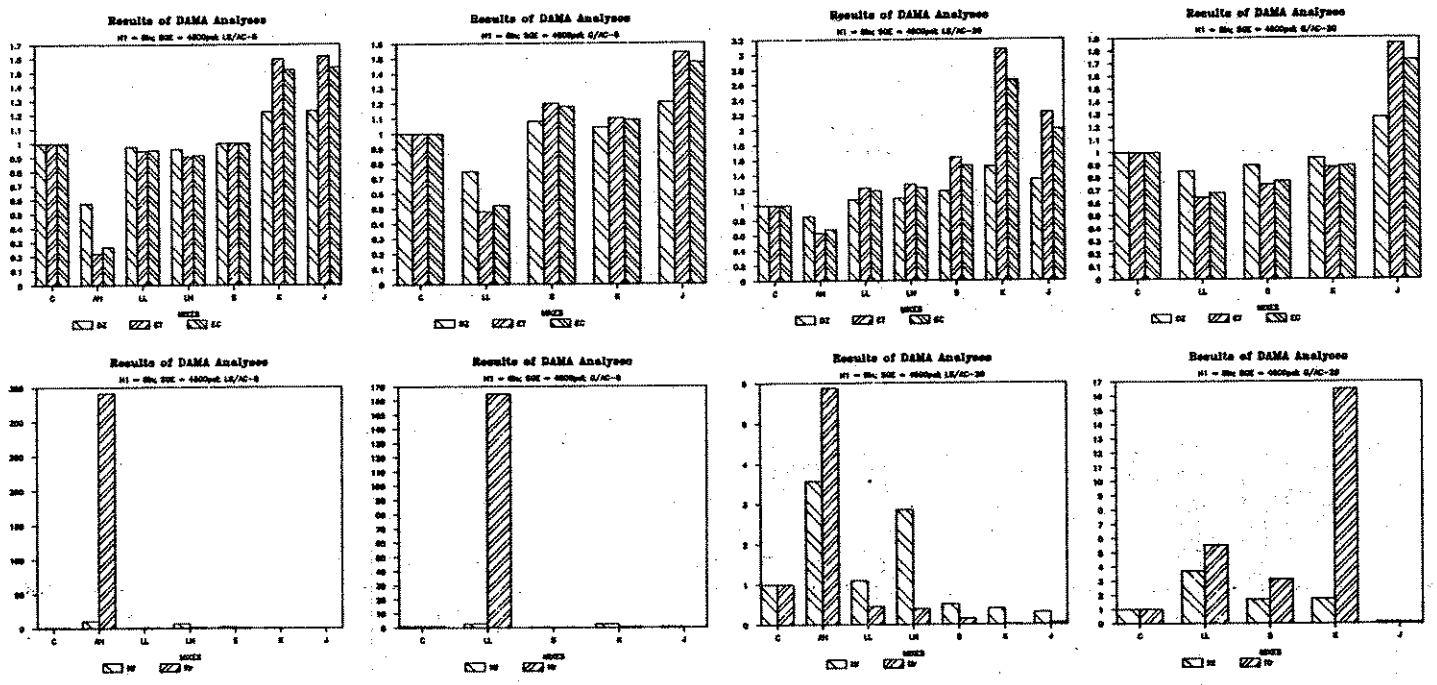


Fig. 44c. Structural analyses by DAMA procedure, H1 = 8 in., SGE = 4,500 psi.

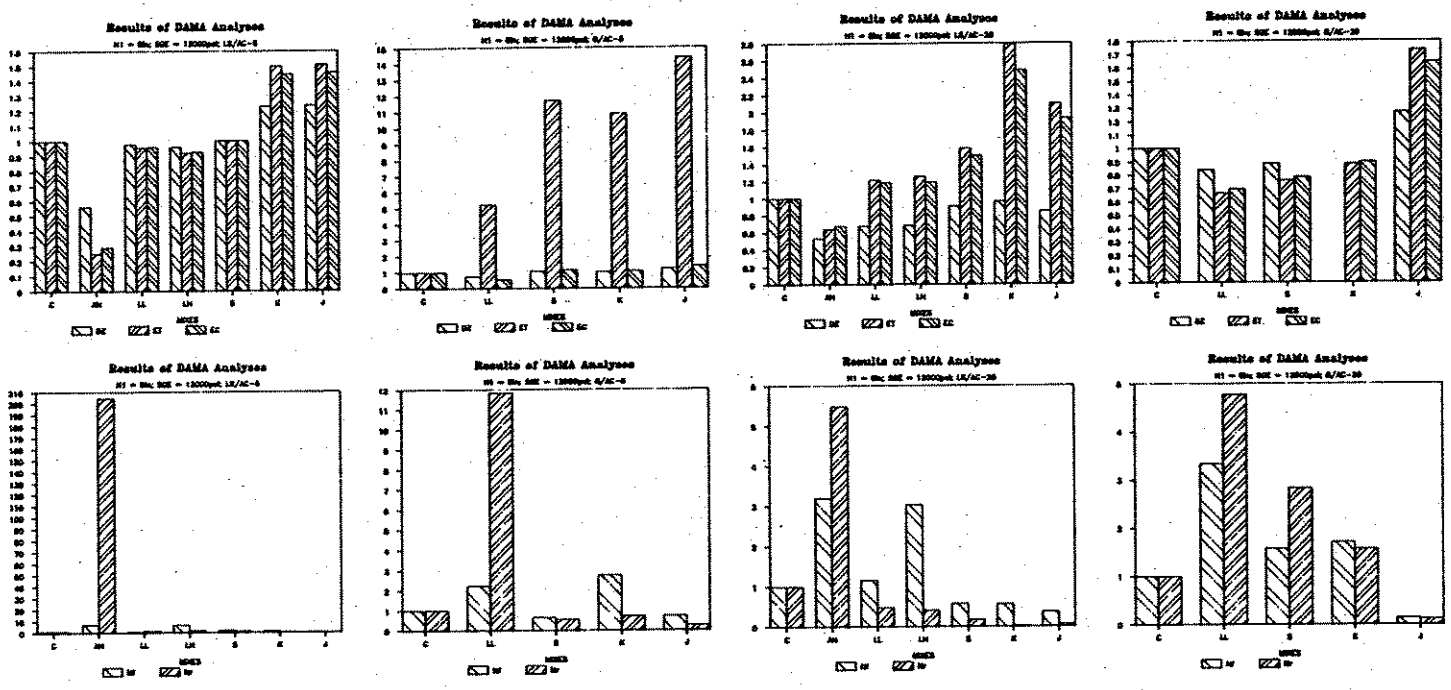


Fig. 44d. Structural analyses by DAMA procedure, H1 = 8 in., SGE = 12,000 psi.

5.2. The University of Nottingham (Brown) Method

In this method design charts were developed (based on the computer program BISAR for the analysis of multilayer elastic pavement system) for a three-layer pavement system consisting of an asphalt surface course with a fixed base course of 200 mm (8 in.) placed on a subgrade of varied subgrade modulus (CBR). The surface course is characterized by the stiffness modulus of the mix. The Poisson's ratio of the asphalt layer and that of the subgrade was assumed to be 0.4, and the Poisson's ratio of the base was assumed to be 0.3. The elastic modulus of the base layer was assumed to be twice that of the subgrade.

Critical subgrade strains and critical asphalt tensile strains were determined for all the mixes for each of four pavement sections. Pavement lives in terms of numbers of standard 40 kN wheel loads (18 kips SAL) to cause fatigue failure (Nf) and rutting failure (Nr) were computed for the mixes used as surface courses of 100 mm (4 in.) and 200 m (8 in.) on subgrade of 20 MPa (CBR of 2) and 70 MPa (CBR of 7) with a constant granular base of 200 mm (8 in.). The stiffness modulus of the mix was calculated from the stiffness of the binder (van der Poel nomograph), binder content by volume, and the volume percent of aggregate. A loading time of 0.02/sec. (corresponding to a traffic speed of 50/100 km/hr) and a temperature of 13° C (corresponding to MAAT of 10° C or 50° F for Iowa) were used in the determination of binder stiffness.

Table 12 gives the results of the structural analyses by the Brown (Nottingham) method in terms of numbers of standard loads required to cause fatigue failure (Nf) and rutting failure (Nr). As shown by the results of DAMA analyses, pavement lives increased with increasing thickness and subgrade modulus. Similarly, higher pavement lives were obtained for AC-20 than AC-5 mixes, and higher lives were obtained for limestone than gravel mixes.

The relative pavement lives for the four combinations of asphalt grades and aggregate types at optimum binder contents (Mixes 3, 4, 9 and 10) are shown in Fig. 45. Significant improvements were observed in fatigue resistance when Asphadur, hydrated lime and Styrelf (SBS) were added to the asphalts. These additives also provided moderate improvements in rutting resistance. Neoprene (K) and SBR (J), in general, reduced both fatigue and rutting resistance as compared to the control mixes. Asphadur, lime, and to some extent Styrelf increased the pavement lives of AC-5 mixes to equal or exceed those of corresponding AC-20 mixes without additives.

Table 12a. Summary of structural analyses by Brown method, LS/AC-5.

E3	20 MPa				70 MPa			
H,mm	100		200		100		200	
xE06	Nr	Nf	Nr	Nf	Nr	Nf	Nr	Nf
C-1	0.04	0.08	1.70	0.36	0.70	0.29	13.10	2.69
AHa-1	0.06	0.52	3.08	3.32	0.81	0.58	16.90	7.84
AHb-1	0.24	1.58	11.70	57.70	2.50	6.19	74.90	132.00
LL-1	0.21	0.82	13.10	23.30	2.05	3.11	58.10	54.50
LH-1	0.21	0.59	12.70	13.90	2.01	2.10	55.30	30.90
S-1	0.08	0.19	4.08	3.86	1.10	0.74	22.10	9.98
K-1	0.01	0.03	0.37	0.39	0.31	0.22	3.85	1.87
J-1	0.03	0.04	1.10	0.49	0.53	0.15	9.61	1.23
C-3	0.06	0.17	2.05	2.81	0.70	0.60	15.50	8.84
AHa-3	0.05	0.17	2.05	4.98	0.73	0.93	13.10	15.80
AHb-3	0.21	2.04	13.10	103.00	2.05	9.72	56.70	278.00
LL-3	0.18	0.87	8.31	44.90	1.55	5.21	45.80	116.00
LH-3	0.17	0.72	8.31	26.30	1.55	3.46	49.10	75.60
S-3	0.06	0.53	3.08	6.79	0.81	0.60	16.90	15.90
K-3	0.02	0.07	0.70	2.22	0.39	0.54	6.31	9.25
J-3	0.04	0.07	1.45	1.55	0.61	0.37	10.40	5.06
C-5	0.06	0.20	2.09	5.39	0.70	0.98	14.20	17.30
AHa-5	0.06	0.38	2.22	10.40	0.73	1.66	16.30	42.00
AHb-5	0.22	4.03	13.10	298.00	2.05	23.40	64.20	919.00
LL-5	0.12	0.60	4.89	48.20	1.48	5.50	32.90	144.00
LH-5	0.12	0.65	4.77	30.20	1.46	3.67	32.20	79.90
S-5	0.07	0.41	3.64	22.30	1.02	2.54	22.10	64.10
K-5	0.01	0.04	0.32	0.86	0.29	0.41	3.64	5.98
J-5	0.02	0.07	0.98	1.66	0.50	0.39	9.47	4.82

Table 12b. Summary of structural analyses by Brown method, G/AC-5.

E3	20 MPa				70 MPa			
H,mm	100		200		100		200	
xE06	Nr	Nf	Nr	Nf	Nr	Nf	Nr	Nf
C-2	0.02	0.04	0.57	0.55	0.37	0.52	4.89	6.10
LL-2	0.09	0.27	4.33	6.78	1.30	1.15	29.70	17.60
S-2	0.04	0.07	1.30	1.27	0.55	0.35	9.19	4.03
K-2	0.01	0.02	0.27	0.34	0.22	0.19	2.50	1.86
J-2	0.02	0.02	0.55	0.31	0.34	0.16	4.83	1.35
C-4	0.02	0.06	0.70	0.94	0.39	0.29	5.54	3.68
LL-4	0.04	0.14	1.70	3.86	0.70	0.69	13.10	11.90
S-4	0.04	0.12	1.42	3.04	0.57	0.61	9.61	12.50
K-4	0.01	0.03	0.31	0.57	0.22	0.29	2.77	3.68
J-4	0.02	0.06	0.71	1.12	0.40	0.32	5.69	4.32
C-6	0.02	0.05	0.70	1.54	0.39	0.43	5.54	6.84
LL-6	0.06	0.29	2.01	9.21	0.70	1.48	15.50	34.20
S-6	0.04	0.13	1.36	5.07	0.57	0.95	9.19	24.10
K-6	0.01	0.03	0.27	0.71	0.22	0.36	2.50	5.27
J-6	0.02	0.04	0.56	0.90	0.35	0.39	4.89	5.35

Table 12c. Summary of structural analyses by Brown method, LS/AC-20.

E3	20 MPa				70 MPa			
H,mm	100		200		100		200	
xE06	Nr	Nf	Nr	Nf	Nr	Nf	Nr	Nf
C-7	0.06	0.32	2.26	7.43	0.73	1.44	16.00	31.60
AHa-7	0.34	8.29	18.40	658.00	3.02	42.20	95.90	1570.00
AHb-7	0.33	10.30	18.40	930.00	2.98	52.10	95.90	2280.00
LL-7	0.34	6.70	18.40	300.00	3.02	23.00	95.90	678.00
LH-7	0.36	6.84	23.90	408.00	3.56	27.30	111.00	872.00
S-7	0.25	3.76	15.50	241.00	2.63	19.00	81.20	631.00
K-7	0.06	0.35	2.15	9.22	0.71	1.52	15.70	36.30
J-7	0.04	0.11	1.36	3.31	0.56	0.69	9.33	13.00
C-9	0.06	0.31	2.05	15.10	0.70	2.16	13.10	54.20
AHa-9	0.22	7.01	13.10	759.00	2.05	49.70	65.80	2320.00
AHb-9	0.21	7.17	13.10	873.00	2.05	60.60	62.60	2950.00
LL-9	0.37	7.63	26.80	474.00	3.85	29.90	114.00	1040.00
LH-9	0.34	9.27	18.40	868.00	3.08	51.00	98.60	1900.00
S-9	0.22	5.12	13.10	454.00	2.05	31.70	65.80	1480.00
K-9	0.06	0.54	2.22	19.00	0.73	2.64	16.30	85.80
J-9	0.04	0.30	1.70	2.68	0.70	2.01	13.10	50.30
C-11	0.06	0.67	2.77	48.40	0.81	4.92	18.40	185.00
AHa-11	0.22	11.60	13.10	1730.00	2.05	89.20	65.80	6480.00
AHb-11	0.21	12.20	13.10	2170.00	2.05	96.90	61.00	8160.00
LL-11	0.31	11.90	16.90	1470.00	2.77	69.10	85.70	4660.00
LH-11	0.25	9.93	15.50	1140.00	2.63	63.20	81.20	3440.00
S-11	0.21	7.66	13.10	950.00	2.05	51.50	61.00	3290.00
K-11	0.04	0.19	1.34	11.60	0.54	1.89	9.19	61.20
J-11	0.04	0.18	1.30	10.20	0.55	1.77	9.19	49.40

Table 12d. Summary of structural analyses by Brown method, G/AC-20.

E3	20 MPa				70 MPa			
H,mm	100		200		100		200	
xE06	Nr	Nf	Nr	Nf	Nr	Nf	Nr	Nf
C-8	0.03	0.10	1.10	4.28	0.53	0.74	9.61	15.40
LL-8	0.13	1.05	5.54	61.40	1.51	6.27	36.60	169.00
S-8	0.12	1.02	4.89	63.60	1.48	6.73	32.90	182.00
K-8	0.02	0.08	0.81	1.88	0.41	0.47	6.31	7.67
J-8	0.02	0.07	0.94	1.74	0.47	0.42	8.31	5.62
C-10	0.02	0.13	1.02	5.80	0.50	1.02	9.61	21.10
LL-10	0.16	2.13	7.22	199.00	1.55	13.90	40.90	591.00
S-10	0.12	1.69	4.89	142.00	1.48	13.10	32.90	480.00
K-10	0.02	0.11	0.87	3.88	0.44	0.79	7.22	15.80
J-10	0.02	0.04	0.56	1.21	0.37	0.50	4.89	7.92
C-12	0.03	0.18	1.10	13.40	0.53	1.75	9.61	59.50
LL-12	0.13	2.80	5.54	324.00	1.55	22.00	36.60	1070.00
S-12	0.15	3.80	6.31	582.00	1.55	33.40	40.90	1900.00
K-12	0.02	0.11	0.70	5.56	0.40	1.07	6.31	30.00
J-12	0.02	0.13	0.94	6.08	0.47	1.08	8.31	25.00

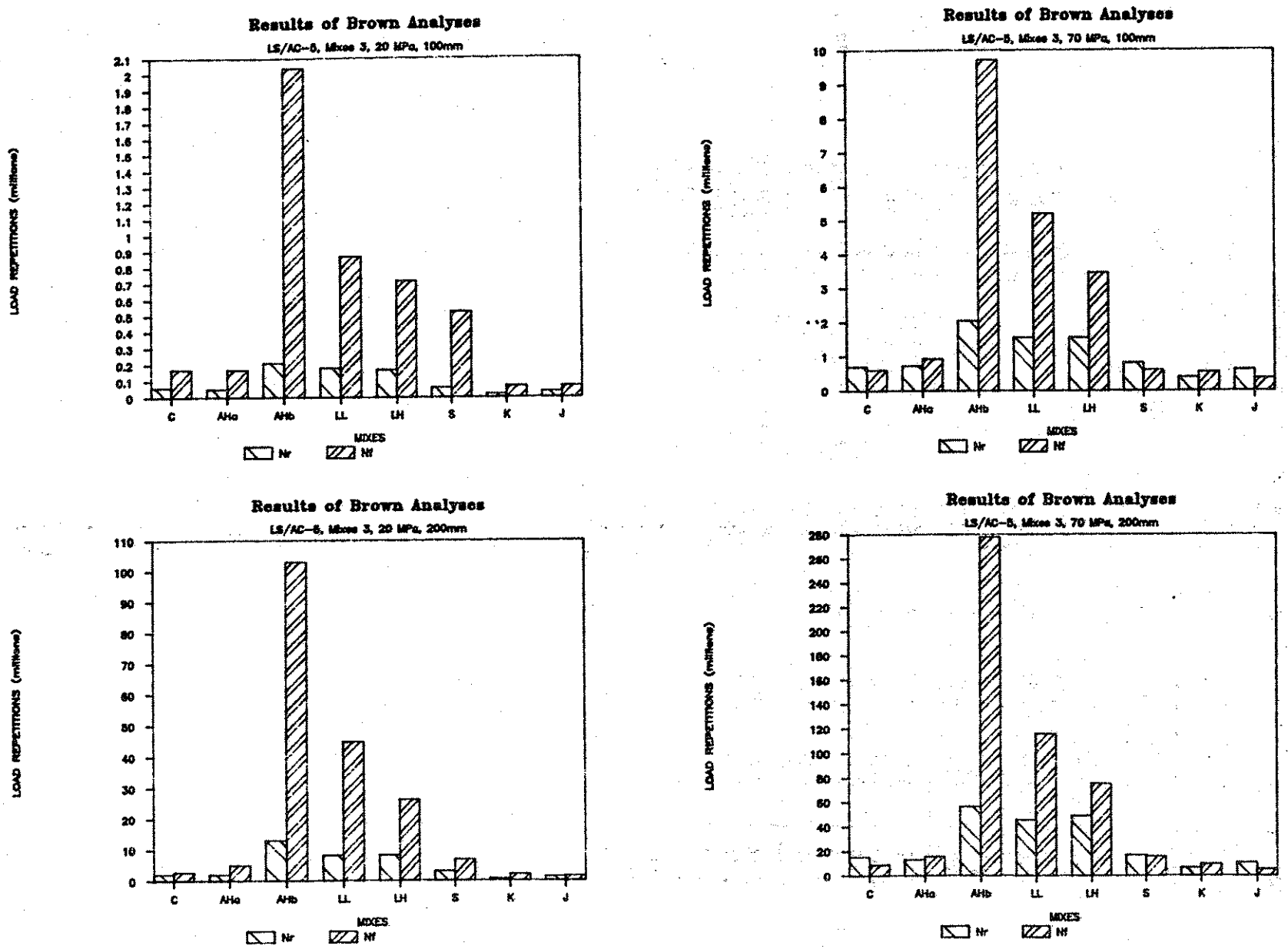


Fig. 45a. Structural analyses by Brown procedure, LS/AC-5.

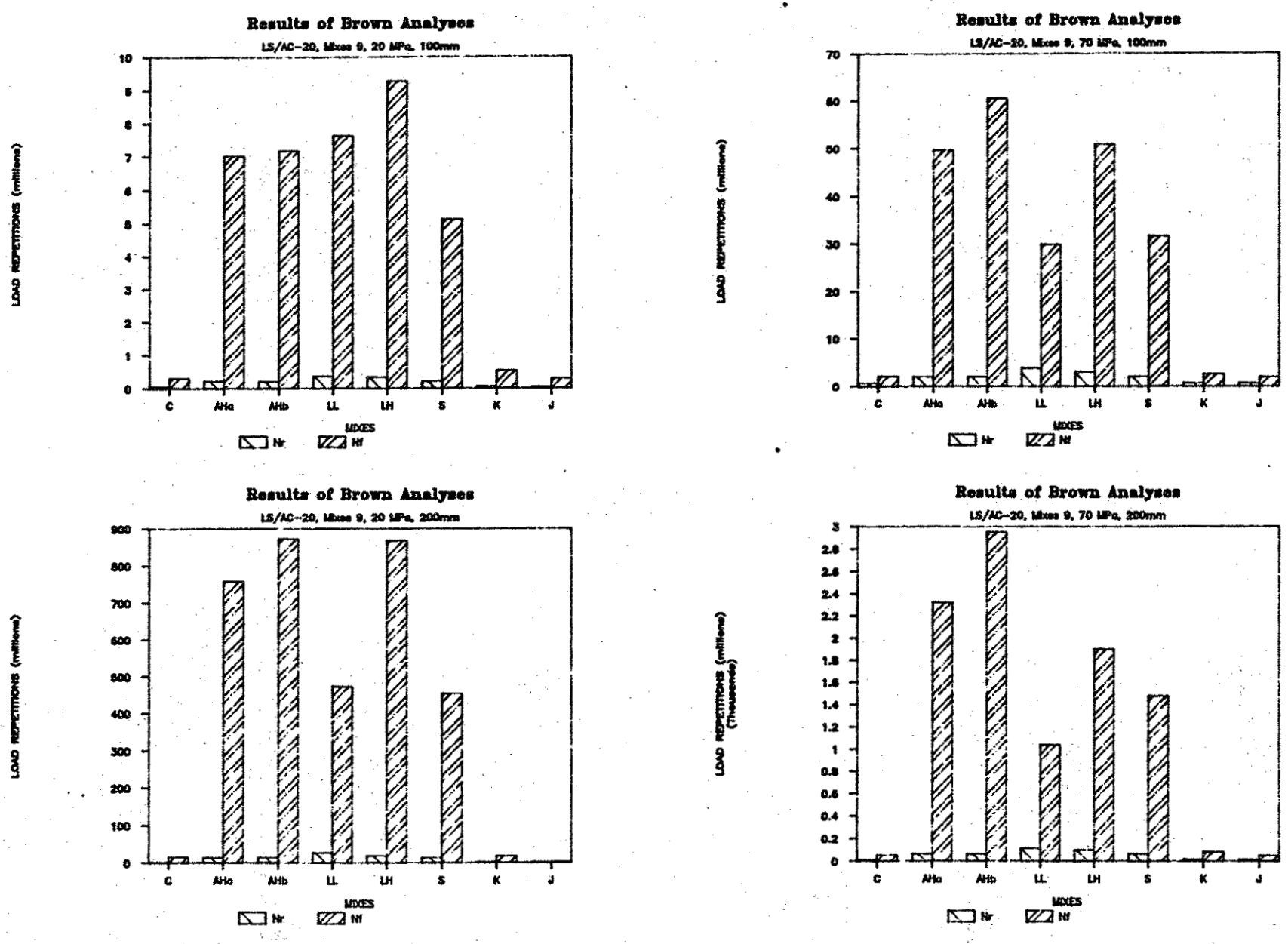


Fig. 45b. Structural analyses by Brown procedure, LS/AC-20.

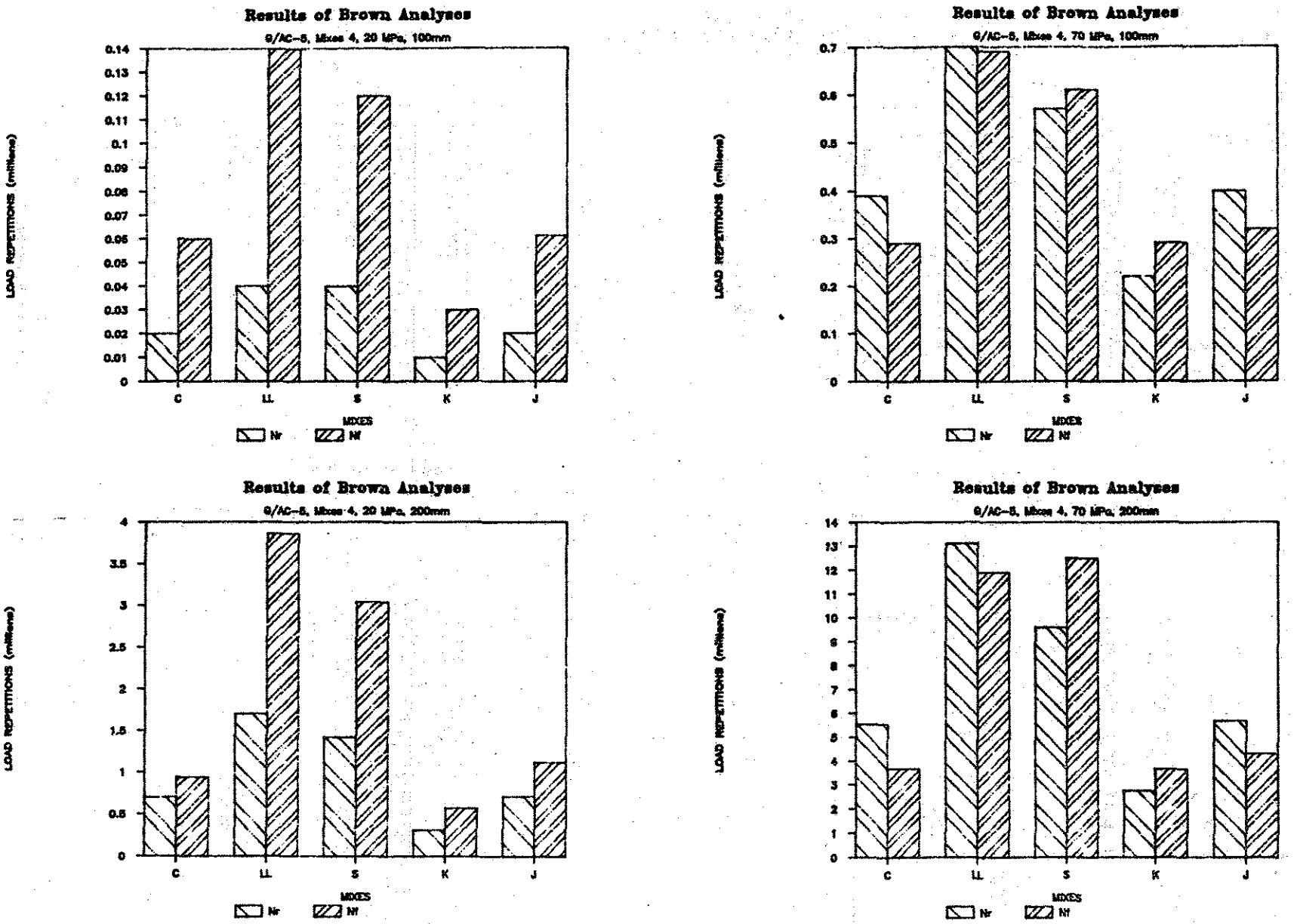


Fig. 45c. Structural analyses by Brown procedure, G/AC-5.

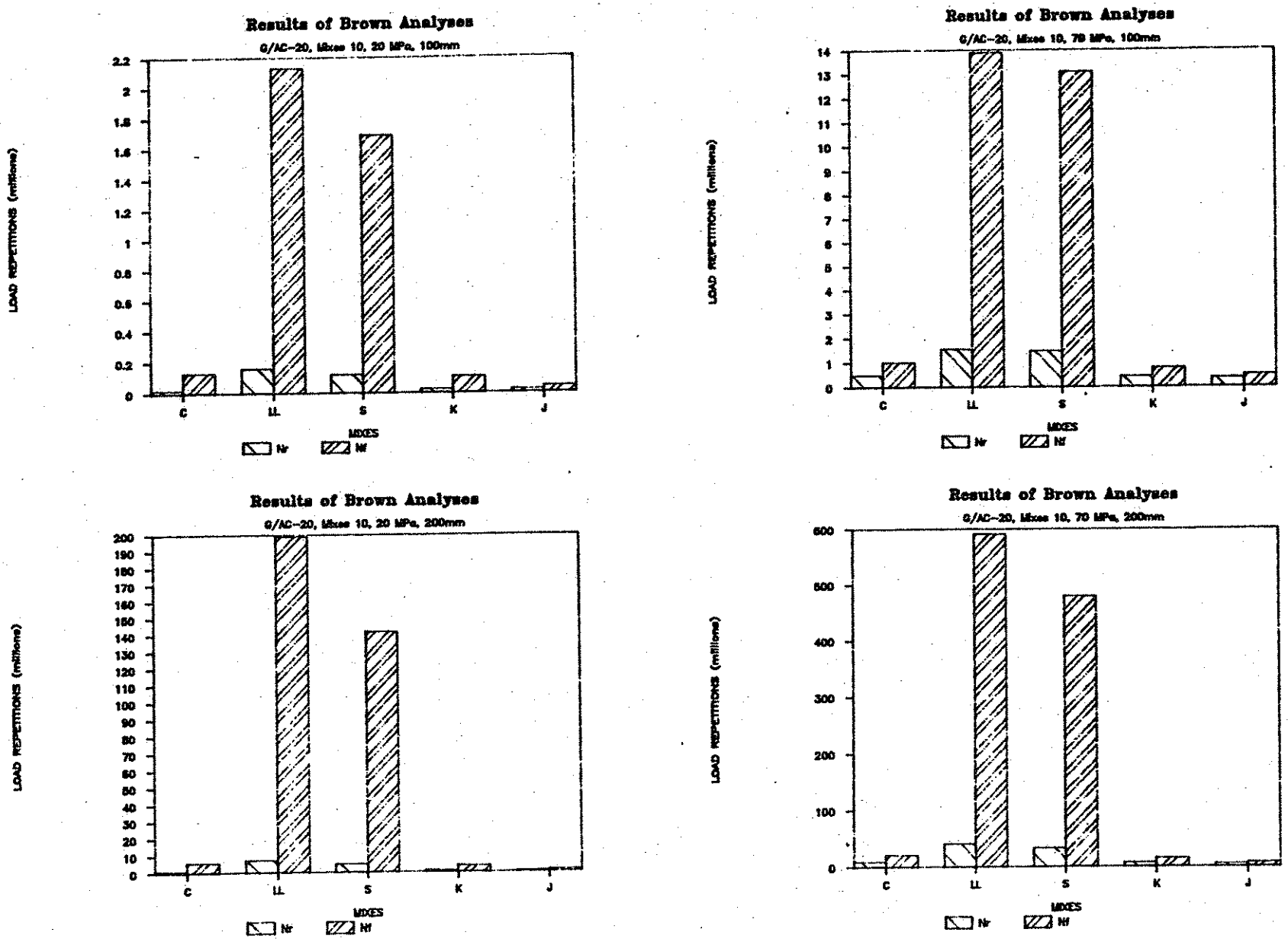


Fig. 45d. Structural analyses by Brown procedure, G/AC-20.

6. SUMMARY AND CONCLUSIONS

The effects of three additives (Asphadur, SBS, and hydrated lime) on two grades of asphalt cements were evaluated in Phase I of the study. Thirteen physical and chemical tests were performed on a total of 16 binder blends, both before and after thin film oven tests. From these tests, six additional index properties were calculated.

In Phase II the effects of five additives (Asphadur, hydrated lime, SBS, neoprene, and SBR) on mixture properties were evaluated in conjunction with the two asphalt cements studied in Phase I and with two aggregates (limestone and gravel). Eight engineering tests were performed on more than 1300 specimens from a total of 72 mixtures.

Data from Phases I and II were used to perform 384 structural analyses for eight hypothetical pavement sections by using the DAMA computer program and the Brown (Nottingham) procedures.

Data analysis and interpretation were difficult because an enormous amount of data were obtained, and because the effects derived from one test on one binder or mixture sometimes contradicted those derived from another test. To help show the meaning of the data, we prepared Tables 13 and 14, somewhat subjectively, to summarize the effects of additives on the important binder properties and mixture properties, respectively. Changes due to additives that led to better stability, strength, rutting resistance, fatigue resistance, durability, low-temperature cracking resistance, resistance to moisture-induced damages and structural capacity in a pavement system were considered improvements.

Table 13. Summary of effects of additives on binder properties.

Property	AC Grade	AL	AH	LL	S
Retained Penetration		-	-	-	-
Viscosity at 60 C		++	++	+	+
Vicosity Ratio, 25 C	AC-5	-	--	--	--
	AC-20	++	++	-	-
PI	AC-5	+	+	+	+
	AC-20	+	-	-	-
VTS	AC-5	0	0	-	+
	AC-20	-	+	0	+
PVN	AC-5	+	+	0	+
	AC-20	+	+	+	+
Tensile Strength, O		0	0	0	++
R		0	+	+	+
Toughness, O		0	0	0	++
R	AC-5	+	+	+	+
	AC-20	-	-	-	+
Tenacity, O		0	0	0	++
R	AC-5	-	-	-	-
	AC-20	0	0	0	-
Force Ductility, O		+	+	0	-
R		+	+	-	+
Elastic Recovery, O		-	-	-	++
R		0	0	0	0
Dropping Ball (t2/t1), O		-	-	-	++
R		-	0	0	+
HPLC, %LMS, O		0	0	0	0
R		-	-	-	-
Cracking Temperature	AC-5	0	+	-	+
	AC-20	+	+	+	+
Temp. Equiv. Stiffness	AC-5	0	+	0	+
	AC-20	-	-	0	0

++	improves significantly	AL	Asphadur, 4%
+	improves slightly	AH	Asphadur, 6%
0	no effects	LL	hydrated lime, 5%
-	worsens slightly	S	SBS
--	worsens significantly	O	original
		R	TFOT residue

Table 14. Summary of effects of additives on mixture properties.

Property	AC	AGG	Additive					
			AH	LL	LH	S	K	J
Marshall Stability	5	G		0		0	0	0
	5	LS	++	0	+	+	0	0
	20	G		+		+	+	0
	20	LS	++	++	+	+	0	0
Tensile Strength	5	G		+		+	+	-
	5	LS	++	+	+	+	0	-
	20	G		+		++	0	-
	20	LS	++	-	0	0	-	--
Moisture Resistance								
Marshall immersion	5	G		+		+	++	++
	5	LS	+	0	0	0	+	+
	20	G		+		0	0	+
	20	LS	++	-	0	0	0	0
Tensile strength* (vac-sat/Lottman)	5	G		0/0		+/-	+/0	-/0
	5	LS	-/0	-/+	0/0	0/+	0/0	-/+
	20	G		0/0		+/+	+/+	0/+
	20	LS	0/+	0/++	+/++	+/0	0/+	+/+
Resilient modulus (vac-sat/Lottman)	5	G		-/0		0/0	+/0	-/0
	5	LS	-/0	0/+	-/+	-/+	0/0	0/0
	20	G		-/-		-/-	-/-	-/0
	20	LS	0/0	0/+	0/+	++/0	0/+	+/0
B/C ratio	5	G		0		0	0	0
	5	LS	-	0	0	+	0	0
	20	G		-		-	+	+
	20	LS	+	++	++	0	+	++
Fatigue Resistance								
Shell-strain	5		+	0	0	0	+	0
Shell-stress	5		+	0	0	0	+	0
Maupin	5		+	0	0	0	0	-
Brown	5		+	0	0	0	+	0
Shell-strain	20		-	-	-	-	0	0
Shell-stress	20		-	-	-	-	0	0
Maupin	20		0	0	0	0	0	0
Brown	20		0	0	0	0	0	0
Rutting Resistance	5	LS	+	+	+	0	0	0
	5	G		0		0	0	0
	20	LS	++	0	+	0	0	0
	20	G		+		0	0	0
DAMA Analysis	5	LS	++	0	0	0	-	-
	5	G		+		0	0	-
	20	LS	++	0	0	-	-	-
	20	G		++		+	+	-
Brown (Nottingham) Analysis								
Rutting (Nr)	5	LS	+	+	+	+	-	-
	5	G		++		+	-	0
	20	LS	+	+	+	+	0	-
	20	G		+		+	-	-
Fatigue (Nf)	5	LS	++	+	+	+	-	-
	5	G		++		+	-	0
	20	LS	++	++	++	++	+	-
	20	G		++		++	-	-

++	improves significantly	AH	Asphalt, 6%
+	improves slightly	LL	hydrated lime, 1%
0	no effects	LH	hydrated lime, 2%
-	worsens slightly	S	SBS
--	worsens significantly	K	neoprene
		J	SBR

The following conclusions, first with respect to binder properties and then with respect to mixture properties and finally with respect to overall evaluation, were drawn from examining the data and these two tables. It must be emphasized that the conclusions on the beneficial effects are applicable only to the materials and material combinations tested. Because of the enormous variety of polymers available and the fact that each may behave differently in a different asphalt, no claim will be made that these conclusions will be applicable to other additives or the same additives in combination with different asphalts and aggregates.

Additive Effects on Binder Properties

ASPHADUR

Although adding Asphadur (3 min. at 400° F) and hydrated lime at high concentrations (10%) were more appropriate for conditions in the field with aggregates, they resulted in nonhomogeneous, partially dissolved/dispersed asphalt binders when they were added to asphalts. Therefore, data on these samples (Samples 2a, 3a, 5, 8a, 9a and 11) were often erroneous and misleading. Their beneficial effects can only be evaluated in Phase II when asphalt concrete mixes with aggregates are examined. Based on tests of nearly homogeneous modified binders, the following conclusions are drawn.

- Asphadur significantly increased the viscosity of asphalt at high temperatures. This leads to the expectation of improved resistance to rutting.

- Asphadur increased penetration at 5° C somewhat but decreased penetration at 25° C. This is reflected by the decreased (improved) temperature susceptibility as measured by VTS, PI, and PVN.
- Asphadur seemed to have improved the low-temperature cracking resistance of asphalts as measured by the calculated cracking temperatures and critical stiffnesses at low temperature and long loading time.
- Asphadur dissolves better in AC-5 than in AC-10.
- Asphadur, added to asphalts, did not result in significant improvements in toughness, tenacity, and tensile properties.
- Large increases in percent LMS based on HPLC data on TFOT residues may suggest increased susceptibility to cracking.
- The optimum beneficial effects of adding Asphadur are expected when Asphadur is used in conjunction with softer grade asphalts.

HYDRATED LIME

Although it has been suggested that hydrated lime reduces the hardening rate of asphalt and thereby increases durability or useful life of pavements (39), the major beneficial effect of hydrated lime is in improving the moisture susceptibility of asphalt mixes by serving as an antistripping agent (37,49). This effect can be verified only when aggregate is introduced in the asphalt concrete mixes. The relative benefits of adding aggregate as compared with other additives will be discussed later. The effect of lime on asphalt binder without aggregate will be based on low-concentration blends (5% lime) because of the lack of homogeneity in high-concentration blends (10% lime).

- Increases in viscosity at high temperatures (60° C to 135° C) because of lime suggest improved resistance to rutting.
- Temperature susceptiblity, low-temperature cracking resistance, toughness, tenacity, tensile and elastic properties of asphalt are not signficantly affected by lime.
- Although there was little increase in percent LMS based on HPLC data on original asphalts, there were significant increases in percent LMS in TFOT residues. If current correlations between percent LMS and pavement cracking hold for asphalts with additives are assumed, these increases may signal increased susceptibility to cracking.

STYRELF (SBS)

- Styrelf appears to be a uniform, homogeneous, polymerized asphalt formulation rather than a dispersion.
- Styrelf increased viscosity of base asphalt at high temperatures (60° C and 135° C); thus it is expected to increase rutting resistance of asphalt pavement.
- By most measures, Styrelf reduced the temperature susceptibility of base asphalts. However, its effect on cracking temperature was inconclusive.
- Although there were improvements in the elastic properties of asphalt because of Styrelf modification, not all of the benefits were retained when exposed to thin film oven aging.

- There were significant improvements on toughness, tenacity and tensile properties because of Styrelf modification. However, some of these improvements were drastically reduced due to thin film oven aging.
- The increase in percent LMS based on HPLC because of Styrelf was small. However, additional increases in percent LMS after thin film oven aging were significant.
- Resistance to heating and aging of asphalts containing Styrelf should be carefully examined.

Additive Effects on Mixture Properties

ASPHADUR

- Asphadur significantly increased the Marshall stability, Marshall stiffness, and tensile strength values of all mixes.
- The effects of Asphadur on moisture resistance were mixed and not significant.
- Asphadur increased the fatigue resistance of AC-5 mixes but showed no improvements on the fatigue behavior of AC-20 mixtures.
- Asphadur improved the rutting resistance of the mixes on the basis of results of creep tests. This is consistent with the observation of increased PVN, high-temperature viscosity, and increased Marshall stiffness.
- Asphadur improved the structural capacities of mixtures compared to the control mixes.

HYDRATED LIME

- Lime treatments increased the moisture resistance of most mixes as determined by the Lottman procedure. The effects on moisture resistance measured by warm water immersion and vacuum-saturation treatments were not as clear. Lime treatments improved the benefit-to-cost ratios for AC-20/limestone mixes.
- Lime treatments improved the Marshall stability for limestone mixes and tensile strength for AC-5 mixes.
- Lime used at low levels had little effect on fatigue and rutting resistance; there were some improvements in rutting resistance when lime was used at high levels.
- Lime treatments resulted in improved structural capacities, especially for gravel mixes and by Brown analyses.

SBS (Styrelf)

- SBS improved Marshall stability, Marshall stiffness, and tensile strength of most mixes.
- SBS had little effect on mixture resistance to moisture, fatigue, and rutting.
- SBS-modified asphalts improved structural capacity of mixtures, especially when they were based on the Brown (Nottingham) method.

NEOPRENE (K)

- There were little differences between neoprene-modified asphalts and control mixes in terms of stability and tensile strength.

- In the majority of the mixes, neoprene improved the moisture resistance and the associated benefit-to-cost ratios.
- Neoprene improved the fatigue resistance of soft grade AC-5 mixes.
- Neoprene had mixed effects on structural capacity.

SBR (J)

- SBR-modified asphalts had little effect on stabilities of mixes but reduced the tensile strengths.
- SBR improved the moisture resistance, especially measured by Marshall immersion, the tensile strength ratio and the benefit-to-cost ratio.
- Compared to the control mixes, there were little other beneficial effects.

OVERALL CONCLUSIONS

1. Each additive showed some degree of improvement in at least one of the desired properties. However, no additive tested showed consistent improvement in every binder as well as mixture property.

2. Improvements in binder properties may or may not be reflected in mixture or structural performance.

3. Soft grade AC-5 seemed to have benefitted more from additives than AC-20.

4. Heat stability of the polymer modifications may be a concern as reflected in penetration retention, viscosity ratio, and large increases in percent LMS by HPLC analyses.

5. It is difficult and perhaps inappropriate to compare or rank the additives tested because many polymers are asphalt specific. Although Asphadur and SBS were added to AC-5 and AC-20 grade asphalts and made the modified asphalts at least one grade more viscous, SBR- and neoprene-modified asphalts were supplied in the AC-5 and AC-20 viscosity ranges with different base asphalts.

7. RECOMMENDATIONS

1. There is sufficient evidence, both from this study and studies conducted elsewhere (especially in Japan and Europe), to indicate that polymer additives have enormous potential in improving some aspects of asphalt properties. It is recommended that research on asphalt additives be continued, including laboratory evaluation of new additives and field tests of promising additives.

2. Structural, distress, and performance analysis should be an integral part of mix design and additive or new material evaluation. The approach taken in this research or similar methodology presented by Monismith et al. (29) is recommended.

3. Softer asphalt AC-5 seemed to have benefitted most from the additives studied. Modified softer asphalts can combine the normally expected better low-temperature cracking resistance and thus the improved temperature susceptibility with increased stability and rutting resistance for high temperature and traffic conditions for improved overall performance. Field trials of polymer-modified soft grade asphalts are recommended.

4. It is recommended that the PVN (penetration-viscosity number) be considered in studying or specifying modified asphalts to assure low-temperature cracking resistance and that Marshall stiffness be considered (in lieu of more time-consuming creep tests) in evaluating mixes containing additives to assure resistance to rutting.

5. Because none of the additives studied showed consistent improvements in every aspect of binder and mix properties, one must first decide what specific improvement is desired before choosing an additive.

6. Specifications for polymer-modified asphalts must be performance based. To ensure the enhanced performance properties of these new materials, additional tests for heat stability, tensile, and elastic properties should be considered. However, to encourage the development of competing materials, the specifications should be generic and not based on one particular product.

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APPENDIX A: TENSILE STRENGTH TEST

The tensile strength tests conducted were modifications on ASTM standard test methods for rubber properties in tension D412-80.

Apparatus--Instron table model universal testing instrument.

Temperature Cabinet--High temperature cabinet including temperature controller, probe and attachment for liquid carbon dioxide or liquid nitrogen coolant.

Load Cell--Metric 5 kg capacity, 0.500 g. lowest range.

Chart Recorder--Strip chart recorder standard with instrument.

Sample Size--3 cm x 0.3 cm x 0.3 cm samples are cast in rubber molds.

Testing Conditions--Specimen is stretched to 800% elongation at +20° C at rates of 500 mm/min. The temperature should be specified, depending upon the end use of the material.

EXAMPLES:

MATERIAL	TEMPERATURE	LOAD RANGE
Asphalt Cement	20° C	5
Emulsion Residue (Seal Coat)	4° C	10 - 20
Emulsion Residue (Mixing Grade)	-10° C	0.5
PAC-20	20° C	5
PAC-30	20° C	5

APPENDIX B: ELASTIC RECOVERY BY MEANS OF DUCTILOMETER

PROCEDURE—The brass plate, mold, and briquet specimen are prepared in accordance to the ASTM Test Method for Ductility of Bituminous Materials, D113-79. After the ductilometer and specimen are conditioned at 10° C (50° F) for 85 to 95 minutes, the specimen is elongated to 20 cm at a rate of pull of 5 cm/min. After elongation, the ductilometer is stopped and the sample is held in the stretched position for 5 minutes. At this time, the sample is cut in half with a pair of scissors or other suitable cutting device. The sample is left undisturbed for one hour, when the half sample specimen is retracted until the two broken ends touch. The new pointer reading is recorded in cm.

INTERPRETATION OF RESULTS - The percent elongation recovery is calculated as follows:

$$\% \text{ Recovery} = \frac{20 - L}{20} \times 100$$

where L = Final reading in cm.

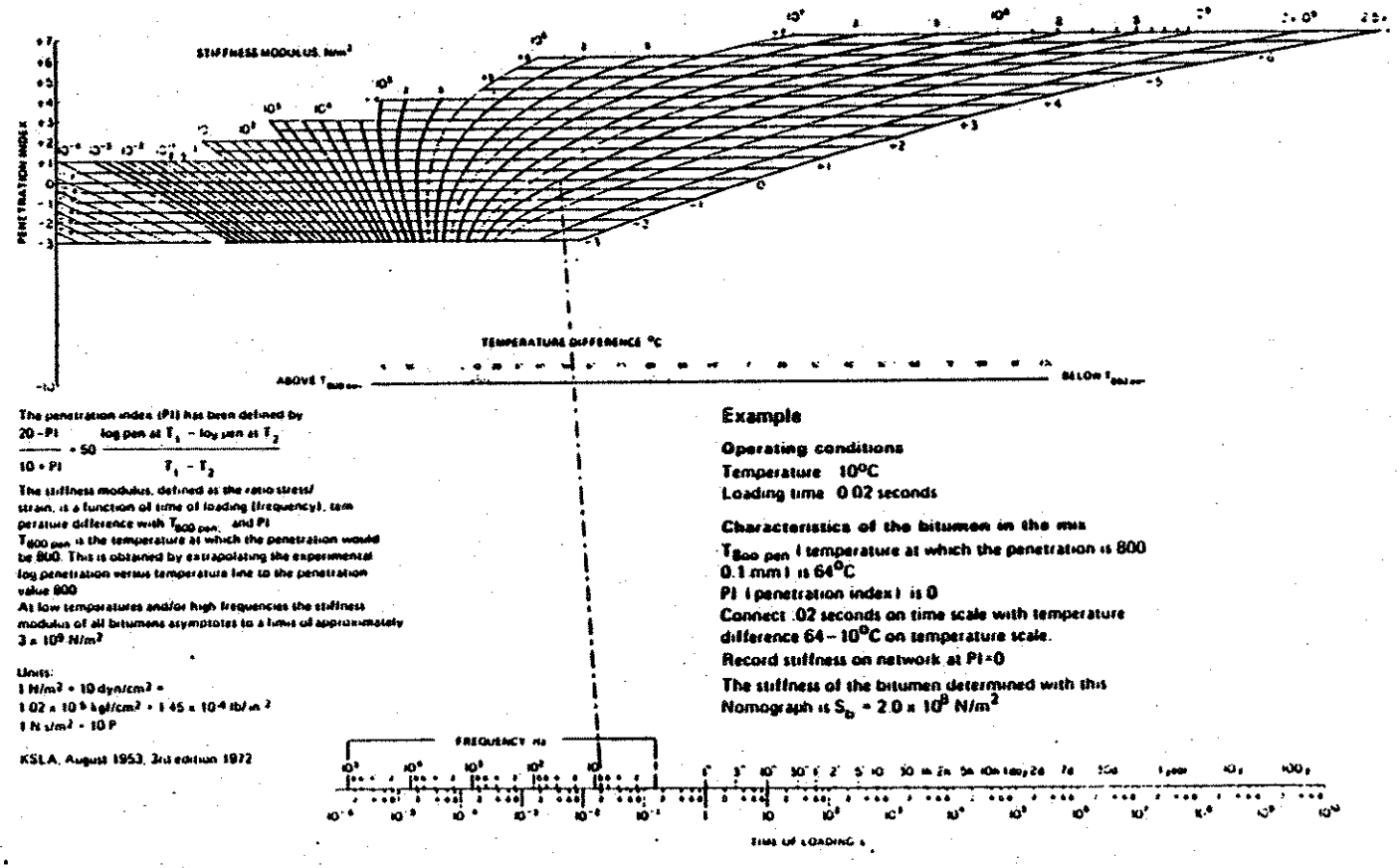
APPENDIX C: DROPPING BALL TEST PROCEDURE

PROCEDURE—The sample to be tested is heated slowly, with frequent stirring, to approximately 149° C (300° F). Approximately 8.0 + 0.1 g. of the sample is poured into the dropping ball container, avoiding inclusion of air bubbles. The container is covered with the ball centering guide and the ball is placed on the guide. The assembly is cooled for 30 minutes at ambient room temperature.

After 30 minutes, the timer is started as the assembly is placed upside down on its support, a ring stand with a flat notched plate 30 cm above the base. (The plate is notched to hold the assembly while allowing the ball to drop freely.) When the top of the ball is tangent to the edge of the centering guide, the time is recorded at T1. When the ball hits the base of the support, the total time, T, is recorded.

INTERPRETATION OF RESULTS—T2 is obtained by subtracting T1, the initial time, from T, the total time. (T1 is the time from start to tangent, T2 is the time from that point to when the ball strikes the base and T is the total time.) Since T1 is primarily dependent upon the viscosity of the material and T2 is a measure of the material's tensile strength after being stretched the ratio of T2/T1 is a measure of the elasticity of the sample. A large ratio, therefore, indicates more elastomeric character.

APPENDIX D: NOMOGRAPH FOR PREDICTING ASPHALT STIFFNESS AFTER VAN DER POEL (52).



The penetration index (PI) has been defined by

$$\frac{20 - PI}{10 + PI} = 50 \frac{\log \text{pen at } T_1 - \log \text{pen at } T_2}{T_1 - T_2}$$

The stiffness modulus, defined as the ratio stress/strain, is a function of time of loading (frequency), temperature difference with $T_{800\,pen}$ and PI

$T_{800\,pen}$ is the temperature at which the penetration would be 800. This is obtained by extrapolating the experimental log penetration versus temperature line to the penetration value 800

At low temperatures and/or high frequencies the stiffness modulus of all bitumens asymptotes to a limit of approximately 3×10^9 N/m²

Units:
1 N/m² = 10 dyn/cm² =
1.02×10^{-5} kgf/cm² = 1.45×10^{-4} lb/in²
1 N s/m² = 10 P

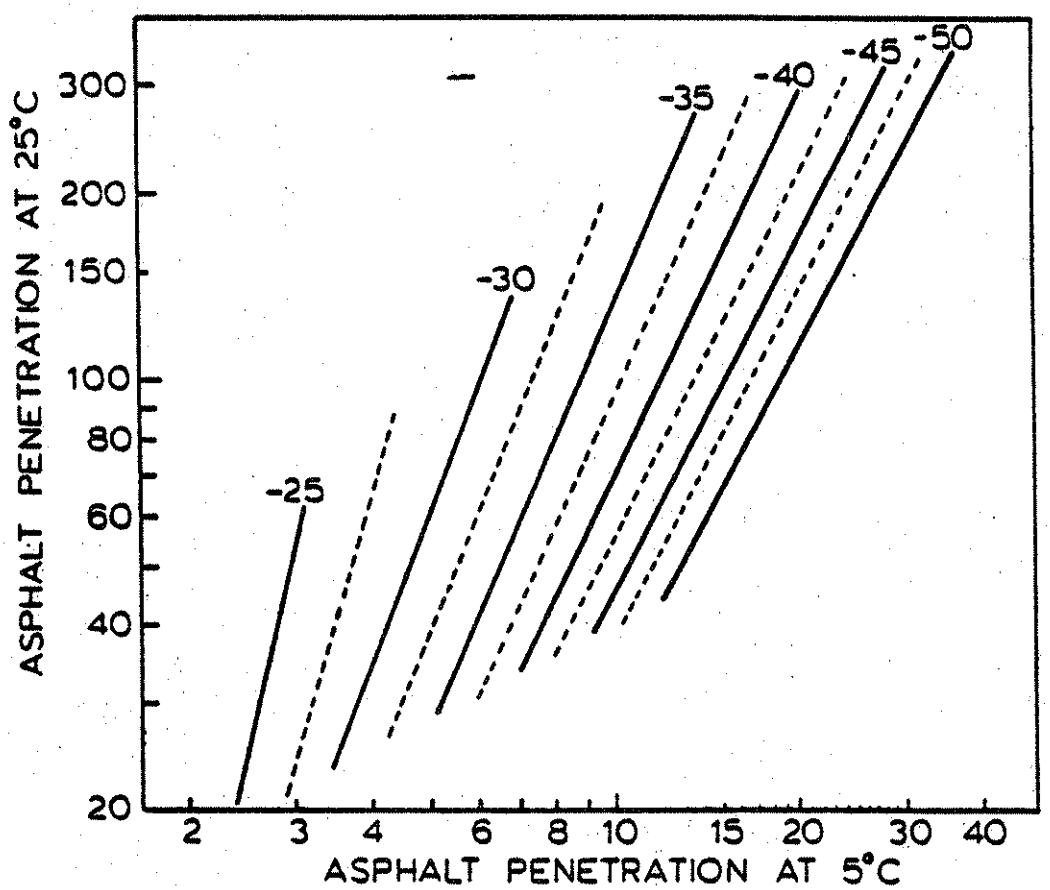
KSLA, August 1953, 3rd edition 1972

Example

Operating conditions
Temperature 10°C
Loading time 0.02 seconds

Characteristics of the bitumen in the mix
$T_{800\,pen}$ (temperature at which the penetration is 800 0.1 mm) is 64°C
PI (penetration index) is 0
Connect .02 seconds on time scale with temperature difference 64 – 10°C on temperature scale.
Record stiffness on network at PI=0
The stiffness of the bitumen determined with this Nomograph is $S_b = 2.0 \times 10^8$ N/m²

APPENDIX E: NOMOGRAPH FOR PREDICTING CRACKING TEMPERATURE AFTER HILLS (18).



APPENDIX F: SAMPLE COMPUTER PRINTOUT FROM DAMA

```
DDDDDDDD          AAAAA        MMM     MMM        AAAAA          222222
DDDDDDDDD        AAAAAAA       MMMM   MMMM       AAAAAAA        22222222
DD      DDD     AAA   AAA      MMMMM MMMMM      AAA   AAA      222    222
DD       DDD   AAA     AAA     MM MMMMM MM     AAA     AAA             22
DD        DD   AAA     AAA     MM  MMM  MM     AA       AA            222
DD        DD   AA       AA     MM       MM     AA       AA          2222
DD        DD   AAAAAAAAAAA     MM       MM     AAAAAAAAAAA        2222
DD        DD   AAAAAAAAAAA     MM       MM     AAAAAAAAAAA       2222
DD       DDD   AA       AA     MM       MM     AA       AA      22
DDDDDDDDD      AA       AA     MM       MM     AA       AA      2222222222
DDDDDDDD       AA       AA     MM       MM     AA       AA      2222222222
```

THIS PROGRAM HAS BEEN DEVELOPED SOLELY FOR

THE ASPHALT INSTITUTE
COLLEGE PARK, MARYLAND

BY PROF. M. W. WITCZAK AND DAEKYOO HWANG.

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

S3 H1=4 in. S.G.E=4500 psi

SECTION AND MATERIAL PROPERTIES

LAYER NUMBER	MATERIAL	POISSON'S RATIO	THICKNESS (IN)
1	A. C.	0.35	4.00
2	SUBGR	0.45	

CURING CONDITIONS

LAYER NUMBER	MATERIAL	CURE TIME (MONTHS)	MONTH OPENED TO TRAFFIC	MONTHS CURED BEFORE OPENING
1	A. C.	0.0	JULY	0

TRAFFIC CONDITION

NUMBER OF REPETITIONS PER MONTH 1000

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

JAN.	FEB.	MARCH	APRIL	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.
45.0	38.0	43.0	45.0	56.0	70.0	78.0	81.0	78.0	73.0	58.0	54.0

LOAD CONFIGURATION AND COMPUTATIONAL POINTS

LOAD PER TIRE = 4500. LBS
TIRE PRESSURE = 70. PSI
RADIUS OF LOAD = 4.52 IN
LOAD SPACING = 13.5 IN

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

MODULI CONDITIONS

ASPHALT STABILIZED LAYERS

LAYER NUMBER	MATERIAL
1	A. C.

TEMPERATURE/MODULUS (DEG. F/ PSI)

POINT	1	2	3	4	5	6	7	8	9	10	11	12
TEMPERATURE	40.	50.	55.	60.	65.	70.	75.	80.	85.	90.	95.	99.
MODULUS EI	873200.	660800.	554600.	448400.	377600.	306800.	236000.	188800.	155760.	122720.	101480.	77880.

SUBGRADE LAYER

SUBGRADE MODULUS BY MONTH(PSI)

LAYER NUMBER	MATERIAL	JAN.	FEB.	MARCH	APRIL	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.
2	SUBGR	4500.	11625.	18750.	2700.	3150.	3600.	4050.	4500.	4500.	4500.	4500.	4500.

DAMAGE MODELS

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

WHERE

NF IS LOAD REPETITIONS TO FAILURE
FO IS DISTRESS TO PERFORMANCE FACTOR
10**M IS MIX FACTOR (M= F4*(VB/(VB+VV)-F5)
VV IS VOLUME OF VOID IN ASPHALT (PERCENT)
VB IS VOLUME OF BITUMEN IN ASPHALT (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

FO =.1840E 02	F1 =.4325E-02	F2 =.3291E 01	F3 =.8540E 00
F4 =.4840E 01	F5 =.6900E 00	VB = 15.2	VV = 3.6

***** FINAL FATIGUE EQUATION NF =.2953E 00*(ET)**(-.3291E 01)*MOD**(-.8540E 00)

RUTTING DAMAGE NF = DO * EV**(-D1)

WHERE

NF IS LOAD REPETITIONS TO FAILURE
DO AND D1 ARE COEFFICIENTS OF RUTTING MODEL
EC IS VERTICAL COMPRESSIVE STRAIN

DO =.1365E-08 D1 =.4477E 01

***** MONTHLY STRUCTURAL RESPONSE AND DAMAGE *****

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)

MON	L	PVT. TEMP	MODULUS (PSI)	RESP TYPE	STRUCTURAL RESPONSES H -	H -	H -	MONTHLY DAMAGES H -	H -	H -
1	1	92	112661.	DZ	0.732E-01	0.751E-01	0.744E-01			
1	1	92	112661.	ET	0.123E-02	0.122E-02	0.119E-02	0.01855	0.01819	0.01648
1	2		4050.	EC	0.282E-02	0.226E-02	0.198E-02	2.83665	1.05083	0.57541
2	1	95	96168.	DZ	0.695E-01	0.709E-01	0.699E-01			
2	1	95	96168.	ET	0.129E-02	0.127E-02	0.123E-02	0.01880	0.01791	0.01599
2	2		4500.	EC	0.291E-02	0.224E-02	0.191E-02	3.26531	1.00205	0.49095
3	1	92	112661.	DZ	0.673E-01	0.689E-01	0.681E-01			
3	1	92	112661.	ET	0.118E-02	0.117E-02	0.113E-02	0.01603	0.01555	0.01401
3	2		4500.	EC	0.269E-02	0.212E-02	0.183E-02	2.26603	0.78088	0.41001
4	1	86	146311.	DZ	0.637E-01	0.656E-01	0.651E-01			
4	1	86	146311.	ET	0.101E-02	0.101E-02	0.981E-03	0.01209	0.01204	0.01098
4	2		4500.	EC	0.234E-02	0.192E-02	0.170E-02	1.22115	0.50011	0.28946
5	1	68	326519.	DZ	0.533E-01	0.553E-01	0.552E-01			
5	1	68	326519.	ET	0.607E-03	0.616E-03	0.604E-03	0.00448	0.00472	0.00442
5	2		4500.	EC	0.150E-02	0.134E-02	0.124E-02	0.16607	0.10098	0.07153
6	1	63	394175.	DZ	0.510E-01	0.529E-01	0.529E-01			
6	1	63	394175.	ET	0.534E-03	0.544E-03	0.534E-03	0.00347	0.00368	0.00346
6	2		4500.	EC	0.134E-02	0.122E-02	0.114E-02	0.10203	0.06641	0.04854
7	1	53	593559.	DZ	0.461E-01	0.478E-01	0.479E-01			
7	1	53	593559.	ET	0.403E-03	0.411E-03	0.404E-03	0.00193	0.00208	0.00196
7	2		4500.	EC	0.106E-02	0.986E-03	0.930E-03	0.03466	0.02544	0.01964
8	1	44	764922.	DZ	0.211E-01	0.219E-01	0.218E-01			
8	1	44	764922.	ET	0.251E-03	0.254E-03	0.249E-03	0.00051	0.00053	0.00049
8	2		11625.	EC	0.613E-03	0.544E-03	0.502E-03	0.00304	0.00178	0.00124
9	1	50	645071.	DZ	0.151E-01	0.156E-01	0.155E-01			
9	1	50	645071.	ET	0.234E-03	0.234E-03	0.228E-03	0.00035	0.00035	0.00032
9	2		18750.	EC	0.545E-03	0.450E-03	0.400E-03	0.00179	0.00076	0.00045
10	1	53	593559.	DZ	0.673E-01	0.695E-01	0.699E-01			
10	1	53	593559.	ET	0.464E-03	0.476E-03	0.468E-03	0.00309	0.00335	0.00319
10	2		2700.	EC	0.129E-02	0.123E-02	0.118E-02	0.08462	0.06911	0.05674
11	1	66	360364.	DZ	0.683E-01	0.708E-01	0.708E-01			
11	1	66	360364.	ET	0.635E-03	0.649E-03	0.637E-03	0.00567	0.00608	0.00573
11	2		3150.	EC	0.164E-02	0.152E-02	0.143E-02	0.24995	0.17664	0.13401
12	1	82	169845.	DZ	0.735E-01	0.761E-01	0.757E-01			
12	1	82	169845.	ET	0.100E-02	0.101E-02	0.988E-03	0.01343	0.01378	0.01276
12	2		3600.	EC	0.239E-02	0.205E-02	0.186E-02	1.33686	0.67339	0.43490

***** DAMAGE SUM FOR 12 MONTHS

LAYER 1	0.098402	0.098254	0.089604
LAYER 2	11.668159	4.448379	2.532855

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

LAYER	DAMAGE TYPE	CUMULATIVE DAMAGE	CRITICAL POSITION	DESIGN LIFE(YEARS)	DESIGN REPETITIONS
1	FATIGUE	1.000	1	10.2	0.1219E 06
2	RUTTING	2.837	1	0.1	0.1000E 04

**********LAYER 2 CONTROLS DESIGN LIFE

ANALYSIS 1 ... MS-1 FAILURE REPETITION ANALYSIS

LAYER	MAT'L	THICK	SR	TAE(I)
1	A. C.	4.00	1.00	4.00

TOTAL TAE = 4.00

DESIGN REPETITIONS BY MS-1

.12943E 04

REPETITION RATIO (DAMA)
(NF RUTTING/NF FATIGUE)

LAYER 1 0.008

REPETITION RATIO (MS-1)
(NF DAMA CRITICAL/NF BY MS-1)

0.773

ANALYSIS 2 ... MS-1 THICKNESS ANALYSIS(INCH)

REQUIRED TA(MS-1)	ACTUAL TAE(DAMA)	DIFFERENCE (TA-TAE)
3.71	4.00	-0.29