A LABORATORY EVALUATION OF RUBBER-ASPHALT PAVING MIXTURES

FINAL REPORT

BY

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Explanation of Column 53

The results of this report are potentially useful. Their implementation is dependent upon the deterioration of this state's present asphalt supplies to a point which is unacceptable for highway use.

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ABSTRACT

The primary objective of this study was to evaluate rubber additive asphalt and its aggregate mixtures in the laboratory with respect to their physical characteristics.

Results obtained on the physical properties of the rubberized asphalt binder were compared to those of the original, untreated asphalt. The data indicate that an acceptable binder can be expected provided the quantity of rubber is closely controlled. Indications of a non-homogeneous composition were apparent for a few of the rubber additives.

Bituminous mixtures were molded in the laboratory using the mechanical Marshall Hammer and also the Gyratory Compactor. The Marshall method of mix design was used in arriving at an optimum asphalt content. The gyratory compaction was intended to simulate traffic conditions and to provide a measure of the performance of the mixes with and without rubber. The results obtained on the physical testing of various compacted mixes indicate that the optimum asphalt content of a mix could be slightly increased when rubber is incorporated into the asphalt cement due to the resulting increased viscosity. With few exceptions, an increase in stability and a decrease in flow values are attained at the same asphalt content when rubberized cement is employed.

INTRODUCTION

The Louisiana Department of Highways presently employs specifications for asphalt cement which have proven acceptable when incorporated into bituminous concrete highway construction. However, the depletion of better crude oils presents a serious threat to the availability of acceptable asphalt cement. Consequently, the intent of this study is to obtain satisfactory high viscosity asphalt binders regardless of the characteristics of the various crude oils available to Louisiana in the near future.

Use of rubber as an additive to asphalt has been known to improve the properties of the material with respect to viscosity, elasticity, or stretchability, and consequently the durability of the resulting paving mixtures. Considerable effort has gone into research studies and experimental construction to indicate the advantages of using rubber in bituminous materials. However, in most cases this effort has been confined to either testing of rubberized asphalt cements or paving mixtures with only a limited number of available rubbers. This has been pointed out in a comprehensive review on the use of rubber in asphalt pavements (1)*.

It was felt that for this study it would be of significant value to perform a laboratory evaluation of paving mixtures utilizing a number of available rubbers.

* Number in parenthesis refers to list of references in the appendix.

PURPOSE OF STUDY

The purpose of this investigation was to ascertain whether or not the introduction of small quantities of rubber to a more readily available asphalt cement from lower quality crudes would improve the characteristics of the resulting rubber modified asphalt-aggregate mixture.

SCOPE

This study was initiated in March 1973 as a Research Project in cooperation with the Federal Highway Administration and consisted of two phases.

Phase I consisted solely of the physical testing of the rubber modified asphalt binder liquid. It was indeed more of a familiarization rather than an evaluation phase. Temperature susceptibility, aging characteristics, and degree of dispersion were of prime interest.

Phase II consisted of the preparation of asphalt-aggregate mixtures using Marshall and Gyratory methods of asphaltic concrete mix design. Mixes with and without rubber were compared in perspective as to the effect of rubberized asphalt versus straight asphalt on the physical properties of the paving mixtures.

It was not the intent of this study to evaluate one manufacturer against another, but rather to evaluate rubberized asphalts against unmodified asphalts.

METHODOLOGY

In July of 1971, the Research and Development Section of the Louisiana Department of Highways made initial contact with various companies in regard to the use of rubber additives in asphalt cements as used for highway construction. From the response of these initial inquiries, the Department decided to take the following direction mainly because of lack of adequate knowledge in the technique of handling and mixing rubber into asphalt cements.

The participating rubber manufacturers were provided with three (3) gallons of each of the following different grades of asphalt cement:

LDH Designation AC-5 (85-100 Penetration)
LDH Designation AC-3 (60-70 Penetration)
LDH Designation AC-40 (45 + Penetration)

The first two of these grades were specially blended at the refinery to yield inferior (low) viscosity asphalts whereas the third one (AC-40) met the Department's specification for its better quality high viscosity asphalt.

The participants were to conduct whatever testing their experience dictated was necessary in order to return to the Department one (1) gallon of each grade of asphalt with the optimum amount of rubber additive. Optimum here was used to imply the phase of the two component system that would improve the quality of the asphalts, compatible with the cost and ease of handling during field use. Table 1 lists the types of rubber submitted and their level of addition.

Upon receipt of the returned rubberized asphalts, the Department's Material Laboratory initiated the first phase of the study; that is, determining the physical properties of the modified cement itself. Properties known to be indicative of asphalt quality were tested for in a manner similar to the testing of the original asphalt. Tables 2, 3, and 4 contain the results of all testing for each grade of asphalt, both the original and the rubber modified. It should be pointed out that this pnase was conducted more for a familiarization with, rather than an evaluation of, rubberized asphalts. As has been noted (2, 3), the significance attached to the results of these standard asphalt tests when applied to rubberized asphalt cement cannot be established until the results are correlated to performance on experimental pavements exposed to the influence of age, weather, and traffic. In total, asphalt cements modified by as many as seven (7) rubber companies were tested in Phase I. This is broken down as follows:

Original Asphalt Grade	Number of Participating Companies	*Number of Modifications
AC-5	6	8
AC-3	7	9
AC-40	5	6

Following the data acquisition of Phase I, a comparison was made between asphaltic concrete whose binder asphalt was admixed with rubber and a control containing the same grade asphalt but no rubber. The composition and proportion of the mix design used is shown in Table 5. The Marshall method of mix design, using 75 blow mechanical hammer compaction, was used to determine the optimum asphalt content for each grade of original straight asphalt. A gyratory compaction machine (4) was then used to prepare specimens using the original and rubber modified asphalts.

Three 1200 gram specimens were molded for each grade of the original asphalt at four asphalt contents from 4.0 percent to 5.5 percent at increments of 0.5 percent; 5.0 percent being the optimum as determined previously by the Marshall method. The compactive effort employed with the Gyratory was 100 psi (7.03 Kg/cm^2) vertical ram pressure, 60 gyratory, and a 1° angle of gyratory. Mixing temperatures were considered to be optimum for each original asphalt grade based on temperature-viscosity data attained in Phase I and presented as curves in Figures 4, 5 and 6.

* Some participating companies submitted two (2) distinct modifications of the original asphalt supplied to them.

These mixing temperatures were: AC-5, 295°F (146.1°C); AC-3, 300°F (148.9°C); AC-40, 325°F (162.8°C). The mix preparation and testing of the rubberized asphalts followed using the same compactive effort of the Gyratory. Mixing temperature for all the rubberized asphalts was 330°F (165.6°C); it was not felt to be practical to mix at the elevated temperatures suggested by the viscosity-temperature curves cited above, nor was it known if the same optimum viscosity range for mixing straight asphalts (85-100 SFS) would apply to rubberized asphalts.

During the molding procedure and before actual testing of the specimens, the gyrograph mechanism of the compactor was monitored for indications of excessive asphalt as detected by widening of the gyrograph, which indicates flushing of the asphalt. These graphs are presented in Figures 11 through 16. Once compacted, both the rubber-modified and control specimens were tested for their resulting physical properties. The data collected is tabulated in Table 6. A stripping test, consisting of a visual observation of aggregate coating following a 10 minute immersion of the mix in boiling water, was performed on all specimens.

In order to evaluate the data collected in both phases, graphs were developed. Figures 8, 9 and 10 show viscosity, penetration, and ductility values before and after aging in a Thin Film Oven Test for both the original and rubberized asphalts. Figures 17, 18 and 19 compare the Marshall stability, flow, and percent voids for the paving mixtures prepared in Phase II.

TEST RESULTS

Phase I

All rubberized asphalts tested increased the softening point (Ring & Ball) of each of the three grades of original asphalt cements. In general, penetration at 77°F (25°C) was decreased by the addition of rubber; the lone exception for each asphalt grade being the admixture using devulcanized rubber powder. This exception has been observed in prior research (5). Low temperature penetration (32°F, 0°C) was increased in all but two cases above the original asphalt value. Low temperature ductility (39.2°F, 4°C) was increased in all but one case. These favorable increases in penetration and ductility substantiate the benefit of the rubberized asphalt in increasing low temperature plasticity (6, 7). A consistent reduction was found in percentage loss of penetration between 77°F (25°C) and 32°F (0°C) for the rubber modified asphalts, which confirms the findings of others claiming reduction in the penetration-temperature susceptibility for asphalt admixed with rubber (8, 9, 10, 11, 12). This decrease in temperature susceptibility is shown graphically as a decrease in slope in Figures 1, 2, and 3. The data representing the results cited above is contained in Tables 2, 3, and 4.

The curves shown in Figures 4, 5, and 6 indicate an increase in viscosity thoughout the temperature span 77°F (25°C) to 350°F (176.7°C) for rubber modified asphalts. A closer examination of the viscosity data presented in Tables 2,3, and 4 confirms the decrease in temperature susceptibility cited above for rubberized asphalt cements. Figure 7 graphically depicts the lower susceptibility (lower slope) for one particular modified ashpalt; namely, AC-3 modified with rubber #6. An important consideration to be noted from this figure is that whereas the rubberized asphalts tested were more viscous at temperatures at or above 77°F (25°C), their reduced temperature-susceptibilities caused them to be less viscous at 32°F (0°C). Although no viscosities were run at this low temperature, this statement is reasonably substantiated by the higher penetrations at 32°C (o°C) as noted both in Tables 2, 3, and 4 and in the penetration-temperature curves previously mentioned. Although the other graphical representations are not included, this same reduction in viscosity-temperature susceptibility is characteristic of each rubber additive tested.

Figures 8, 9, and 10 graphically depict the aging characteristics of the original and modified ashpalt grades following 5 hours at 325°F (162.8°C) in a Thin Film Oven Test. The results are similar to those found in a study on neoprene addition to asphalt (13); that is, a general improvement in the aging characteristics of rubber modified asphalts as demonstrated by a decrease in change of viscosity and penetration following aging. This decrease is numerically presented in Tables 2, 3, and 4 by the viscosity ratio which is simply the ratio of the asphalt's viscosity at 140° (60°C) before aging to its viscosity after aging. It should be pointed out however that the absoulte viscosity value for the aged rubberized asphalts was higher; in some cases as high as 17,000 poises.

The ductilities shown in Figures 8, 9, and 10 are subject to question, especially considering the AC-5 grade asphalt. The low ductility values found for some of the unaged rubberized ashpalts, coupled with the fact that these same modifications increased in ductility upon aging, could be the result of non-homogeneous mixtures.

Any presence of agglomerates, gel structure, or undisperse rubber powder would result in a reduction in extensibility due to the setting up of stress concentrations (14). Improved properties over the original mixtures before aging have been found (15) for those rubberized asphalts which become more rubberized and more elastic as a result of a finer dispersion of the rubber phase with age.

Phase II

Realizing that there exists a difficulty in evaluating rubberized asphalt based solely on standard test procedures presently used for straight asphalt cements (16), a second phase was investigated. Here a laboratory evaluation was performed on pavement mixtures combining asphalt and siliceous gravel aggregate.

The bar graphs presented in Figures 17, 18, and 19 visually represent the numerical data found in Table 6. The intention was to point out the ill effects of an excess asphalt content upon the resulting properties of a paving mix, and to ascertain if rubber as an asphalt additive would have the capability of being used at a binder level equal to and/or in excess of that found optimum for unmodified asphalt.

A decrease in Marshall stability is observed when the control asphalt content is increased 0.5 percent above what had been determined as optimum for those particular mix designs; the largest reduction being for the AC-5 grade whose stability decreased from 1240 lbs. to 1067 lbs. Associated with this loss of stability is an increase in flow values of the resulting mixes when excess unmodified asphalt is introduced; again the largest change occurring for the AC-5 grade where the flow increased from 14 to 19. The mixes prepared with the remaining two grades of original asphalt, AC-3 and AC-40, showed similar trends of lesser magnitude. Densities decreased in each case with the addition of excess asphalt cement.

These same graphs are used to show the results obtained when rubberized asphalts were used as the binder liquid. The same compactive effort was employed; 100 psi, 60 gyrations, and a 1° angle of gyration. The various participating rubber companies are indicated by number across the bottom. These numbers correspond to those found in Tables 2, 3, and 4 where the physical properties of the cement itself are tabulated. It is interesting to note from Figure 17A that for every rubberized AC-5 asphalt tested the Marshall stability increased and the flow decreased when compared to the original asphalt mixes at the same asphalt content, namely 5.5 percent. The same trend is repeated in Figures 18A and 19A for the rubberized AC-3 and AC-40 grade asphalts with few exceptions. No significant change in compaction was observed in any of the mixes when rubberized asphalt was substituted for the original asphalt grades. Void contents fluctuated tightly about the control, the largest variation being 0.7 percent for the AC-40 grade asphalt.

The gyrographs presented in Figures 11 through 16 are intended to indicate excessive asphalt content as shown by a widening of the gyropraph (4). It is visually apparent when looking at Figures 11, 13, and 15 that flusing is definitely present at an asphalt content of 5.5 percent for those mixes using the original asphalt grades. No flushing is present at 4.0 or 4.5 percent; a slight degree of flushing can be observed at a 5.0 percent asphalt content. This basically confirms the choice of 5.0 percent as the optimum asphalt content and substantiates the increased flow values reported previously when the cement content was increased from 5.0 percent to 5.5 percent.

The graphs shown in Figures 17A, 18A, and 19A present a comparison of stability, flow and void content between the original asphalt mixes at 5.0 percent binder content and the rubber modified mixes at 5.5 percent binder content. The results do not lend themselves to a broad statement of improvement in the tested properties. However, they do indicate that certain rubber modified asphalts can maintain or increase the mix stability with no increase in tendency to flow at an asphalt content above that considered optimum for unmodified asphalt. The gyrographs of Figures 12, 14, and 16 show similar findings; that is, some rubber modifications at 5.5 percent asphalt level indicate no greater degree of flushing than does the original asphalt at 5.0 percent.

A visual comparison of aggregate coating following a 10 minute immersion in boiling water was performed on all mixes. No significant stripping was observed for either the control mixes or the rubberized mixes.

CONCLUSIONS

The results from this study warrant the following conclusions with the stipulation that they pertain and are confined to the materials studied herein; namely, Louisiana grade asphalts and asphalt/aggregate mixtures.

(1) The addition of rubber to an asphalt cement resulted in an increase in softening point and a corresponding increase in low temperature ductility.

(2) The viscosity of the asphalts was increased when admixed with rubber for the temperature range considered: 77°F (25°C) through 350°F (176.7°C). Associated with this was a decrease in viscosity-temperature susceptibility.

(3) This decrease in viscosity-temperature susceptibility is further sustantiated at low temperatures (32°F, 4°C and 77°F, 25°C) by an observed decrease in penetration-temperature susceptibility. In all but two cases, this resulted in increased penetrations at 32°F (0°C) for the rubberizing asphalts.

(4) A general improvement in aging characteristics for rubber modified asphalts was demonstrated by a reduction in the magnitude of change in viscosity and penetration following aging.

(5) Inconsistent and misleading ductility values were obtained for those rubberized cements possessing inability to disperse.

(6) For the same binder content, mixes using rubberized asphalt generally had higher Marshall stabilities, equal or lower flow values, and less tendency to bleed or flush.

(7) Certain rubberized mixes showed the capability of being used at a binder level in excess of that found optimum for unmodified ashpalt.

(8) No loss of compaction was noticed for the mixes incorporating rubberized asphalt as the binder.

(9) No loss of adhesion due to stripping was observed for the rubberized asphalt paving mixtures.

RECOMMENDATIONS

Based on the apparent capability of laboratory compacted pavement mixes using rubber modified low quality asphalts to perform satisfactorily, it is suggested that a field evaluation be considered, incorporating those previous participating rubber manufacturers that should so desire. Within the scope of such an evaluation should be an attempt to correlate pertinent laboratory testing to field performance along with an economic analysis based upon new construction costs versus resulting pavement life.

It is advised however that such a field evaluation be contingent upon the reasonable assurance from the participating manufacturer (s) that the desired end results can be achieved with minimum interference with conventional mixing and compacting processes.

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APPENDIX

TABLE 1

RUBBER TYPES AND ADDITION LEVELS*

Rubber Number	Type	Addition Level
1	Gum SBR	AC-5, 0.8%
		AC-3, 0.75%
2	SBR Latex (40-55% solids)	all asphalt, 3-5%
3	SBR Block Copolymer	AC-5, 3.00%
	Hydrogenated SBR	AC-5, 2.00%
	SBR Block Copolymer	AC-3, 1.57%
	Hydrogenated SBR	AC-3, 1.58%
	SBR Block Copolymer	AC-40, 1.00%
	Hydrogenated SBR	AC-40, 1.00%
4	Crumb ethylene-propylene	all asphalt, 4.0%
5	Devulcanized reclaimed rubber powder	all asphalt, 20.0%
6	SBR Latex (60% solids)	all asphalt, 22.0%
7	Neoprene Latex (39% solids)	AC-5, 2.5%
		AC-5, 5.0%
		AC-3, 1.5%
		AC-3, 3.0%
		AC-40, 1.0%

*Solid rubber content as weight % of asphalt.

TABLE 2

PHYSICAL PROPERTIES OF ORIGINAL AND RUBBER MODIFIED AC-5

	Original	Rubber 1	Rubber 3A	Rubber 3B	Rubber 4	Rubber 5	Rubber 6	Rubber 7A	Rubber 7B
Specific Gravity, 77°F	1.030	1.033	1.027	1.028	1.036	1.067	1.027	1.031	1.041
Softening Point, R&B	112	123	121	122	124	121	124	115	124
Flash Point, C.O.C.°F	570	620	585	570	--	--	580	565	560
Viscosity									
Saybolt Furol Sec. @350°F	30.2	49.3	55.6	45.9	75.7	142	110	66.5	164
Saybolt Furol Sec. @275°F	152	277	303	251	418	634	543	323	858
Absolute @140°F, Poises	1407	3962	3066	2797	4458	3319	3619	2034	4255
Absolute @77°F, Poises (Shear rate = 0.05 $Sec.^{-1}$)	1.05×10^6	--	2.39×10^6	2.25×10^6	3.14×10^6	--	2.24×10^6	1.44×10^6	1.65×10^6
Penetration @77°F, 100g, 5 sec.	96	54	65	69	69	118	78	92	85
Penetration @32°F, 200g, 60 sec.	20	13	16	21	23	37	20	23	24
Ductility @77°F, 5cm/min.	150+	150+	55	150+	52	35	150+	150+	150+
Ductility @39.2°F, 5cm/min.	0.0	15.5	20.0	35.5	8.0	24.0	150+	59.0	71.0
Thin Film Oven Test,									
Loss % @325°F, 5 hrs.	0.20	0.15	0.04	0.04	0.29	0.71	0.23	0.20	0.17
Penetration of Residue @77°F	64	40	50	50	52	78	56	63	61
Absolute Viscosity @140°F, Poises	2621	6612	5695	5192	7225	7333	4691	4077	7950
Viscosity Ratio @140°F	1.9	1.7	1.9	1.9	1.6	2.2	1.3	2.0	1.9
Ductility of Residue @77°F	150+	150+	131	150+	79	71	150+	150+	150+
Solubility in CS_2	99.99	99.98	99.98	99.78	98.69	--	99.93	99.59	--
Homogeneity Test	Neg.	Neg.	Neg.	Neg.	Neg.	Pos.	Neg.	Pos.	Pos.

TABLE 3

PHYSICAL PROPERTIES OF ORIGINAL AND RUBBER MODIFIED AC-3

	Original	Rubber 1	Rubber 2	Rubber 3A	Rubber 3B	Rubber 4	Rubber 5	Rubber 6	Rubber 7A	Rubber 7B
Specific Gravity, 77°F	1.038	1.041	1.036	1.036	1.039	1.046	1.078	1.038	1.041	1.046
Softening Point, R&B	121	124	130	126	126	137	131	135	125	128
Flash Point, C.O.C.°F	590	615	540	550	560	--	505	545	565	--
Viscosity										
Saybolt Furol Sec. @350°F	32.2	41.7	129.3	44.3	44.7	93.3	--	136.0	51.4	83.6
Saybolt Furol Sec. @275°F	172	233	714	263	266	580	940	758	313	479
Absolute @140°F, Poises	2567	3520	6943	4166	4516	10823	6383	8434	3755	4961
Absolute @77°F, Poises (Shear rate = 0.05 $Sec.^{-1}$)	2.7×10^6	--	4.5×10^6	5.4×10^6	4.3×10^6	1.2×10^7	--	4.1×10^6	4.6×10^6	4.8×10^6
Penetration @77°F, 100g, 5 sec.	60	52	52	48	46	43	85	52	57	62
Penetration @32°F, 200g, 60 sec.	11	12	16	18	12	18	30	15	14	16
Ductility @77°F, 5cm/min.	150+	150+	150+	150+	150+	109	34	150+	150+	150+
Ductility @39.2°F, 5cm/min.	6.25	13.0	62.0	11.0	13.0	1.0	17.0	150+	20.5	40.0
Thin Film Oven Test,										
Loss % @325°F, 5 hrs.	0.18	0.12	0.16	0.08	0.04	0.15	0.52	0.18	0.17	0.13
Penetration of Residue @77°F	41	40	44	36	35	35	54	39	41	45
Absolute Viscosity @140°F, Poises	4923	6067	8128	8026	8281	17199	16817	8903	6657	7816
Viscosity Ratio @140°F	1.9	1.7	1.2	1.9	1.8	1.6	2.6	1.1	1.8	1.6
Ductility of Residue @77°F	150+	150+	150+	150+	150+	69	31	150+	150+	150+
Solubility in CS_2	99.98	99.94	--	99.81	99.91	99.38	--	99.89	99.70	--
Homogeneity Test	Neg.	Neg.	Neg.	Neg.	Neg.	Neg.	Pos.	Neg.	Pos.	Pos.

TABLE 4

PHYSICAL PROPERTIES OF ORIGINAL AND RUBBER MODIFIED AC-40

	Original	Rubber 3A	Rubber 3B	Rubber 4	Rubber 5	Rubber 6	Rubber 7
Specific Gravity, 77°F	1.027	1.028	1.026	1.036	1.063	1.027	1.033
Softening Point, R&B	124	125	129	134	125	132	125
Flash Point, C.O.C.°F	675	665	660	--	540	655	640
Viscosity							
Saybolt Furol Sec. @350°F	53.8	59.8	60.8	97.5	153	92.0	63.2
Saybolt Furol Sec. @275°F	297	365	381	583	788	529	374
Absolute @140°F, Poises	4051	5313	5491	9457	5950	7123	4727
Absolute @77°F, Poises (Shear rate = 0.05 $Sec.^{-1}$)	3.95×10^6	5.85×10^6	5.25×10^6	8.00×10^6	--	6.80×10^6	5.30×10^6
Penetration @77°F, 100g, 5 sec.	51	45	44	43	79	45	48
Penetration @32°F, 200g, 60 sec.	6	12	12	14	25	13	13
Ductility @77°F, 5cm/min.	150+	150+	150+	107	31	122	150+
Ductility @39.2°F, 5cm/min.	0.25	5.25	7.00	1.00	16.00	6.00	6.00
Thin Film Oven Test,							
Loss % @325°F, 5 hrs.	0.00	0.00	0.00	0.16	0.49	0.00	0.00
Penetration of Residue @77°F	38	35	35	35	54	32	36
Absolute Viscosity @140°F, Poises	7453	9135	10201	16256	13103	10201	7881
Viscosity Ratio @140°F	1.8	1.7	1.9	1.7	2.2	1.4	1.7
Ductility of Residue @77°F	150+	150+	150+	99	33	148	150+
Solubility in CS_2	99.98	99.96	99.95	98.80	90.31	99.89	--
Homogeneity Test	Neg.	Neg.	Neg.	Neg.	Pos.	Neg.	Neg.

TABLE 5

COMPOSITION AND PROPORTION OF MIX DESIGN

Bin Number	Specific Gravity	Proportions-%
1	2.650	43
2	2.620	37
3	2.620	15
Mineral Fillers (Limestone)	2.700	5
Binder (Varied)	1.030	Varied

GRADATION

Percent Passing

U. S. Sieve	Bin 1	Bin 2	Bin 3	Filler	Composite
3/4"			100		100
1/2"		100	60		94
No. 4		27	11		60
No. 10	87	7	1		45
No. 40	53	1		100	28
No. 80	15			96	11
No. 200	8			85	8

TABLE 6

AVERAGE RESULTS OF LABORATORY TESTING ON COMPACTED MIXES*

Binder	Percent	Specific Gravity	% Theoretical Gravity	Voids %	V.F.A. %	Density lbs/cu.ft.	Marshall Stability	Flow
Original AC-5	5.0	2.356	96.3	3.7	75.5	147.0	1240	14
Original AC-5	5.5	2.347	96.7	3.3	79.1	146.4	1067	19
Rubber Modified 2	5.5	2.350	96.8	3.2	79.7	146.6	1159	15
3A	5.5	2.341	96.4	3.6	77.6	146.1	1301	14
3B	5.5	2.348	96.7	3.3	79.2	146.5	1224	14
4	5.5	2.357	97.1	2.9	81.3	147.1	1381	17
5	5.5	2.333	96.1	3.9	76.2	145.6	1342	14
6	5.5	2.341	96.4	3.6	77.6	146.1	1202	13
7A	5.5	2.347	96.7	3.3	79.2	146.5	1366	13
7B	5.5	2.354	97.0	3.0	80.7	146.9	1607	17
Original AC-3	5.0	2.361	96.5	3.5	76.7	147.3	1300	13
Original AC-3	5.5	2.344	96.5	3.5	78.1	146.3	1180	17
Rubber Modified 2	5.5	2.345	96.6	3.4	78.6	146.3	1419	14
3A	5.5	2.347	96.7	3.3	79.2	146.5	1263	17
3B	5.5	2.347	96.7	3.3	79.2	146.5	1197	15
4	5.5	2.353	96.9	3.1	80.2	146.8	1490	18
5	5.5	2.339	96.3	3.7	77.1	146.0	1647	14
6	5.5	2.343	96.5	3.5	78.1	146.2	1390	12
7A	5.5	2.341	96.4	3.6	77.6	146.1	1422	16
7B	5.5	2.340	96.4	3.6	77.6	146.0	1423	18
Original AC-40	5.0	2.354	96.2	3.8	75.0	146.9	1321	15
Original AC-40	5.5	2.339	96.3	3.7	77.2	146.0	1219	17
Rubber Modified 3A	5.5	2.351	96.8	3.2	79.7	146.7	1249	10
3B	5.5	2.348	96.7	3.3	79.2	146.5	1176	12
4	5.5	2.354	97.0	3.0	80.7	146.9	1533	18
5	5.5	2.333	96.1	3.9	76.2	145.6	1496	14
6	5.5	2.338	96.3	3.7	77.1	145.9	1263	14
7	5.5	2.345	96.6	3.4	78.6	146.3	1314	18

* Gyratory Compacted at 100 PSI, 60 Gyrations, and 1° angle of gyration
Mixing Temperature: Rubber Modified = 330°F
Original AC-5 = Optimum, 295°F
Original AC-3 = Optimum, 300°F
Original AC-40 = Optimum, 325°F

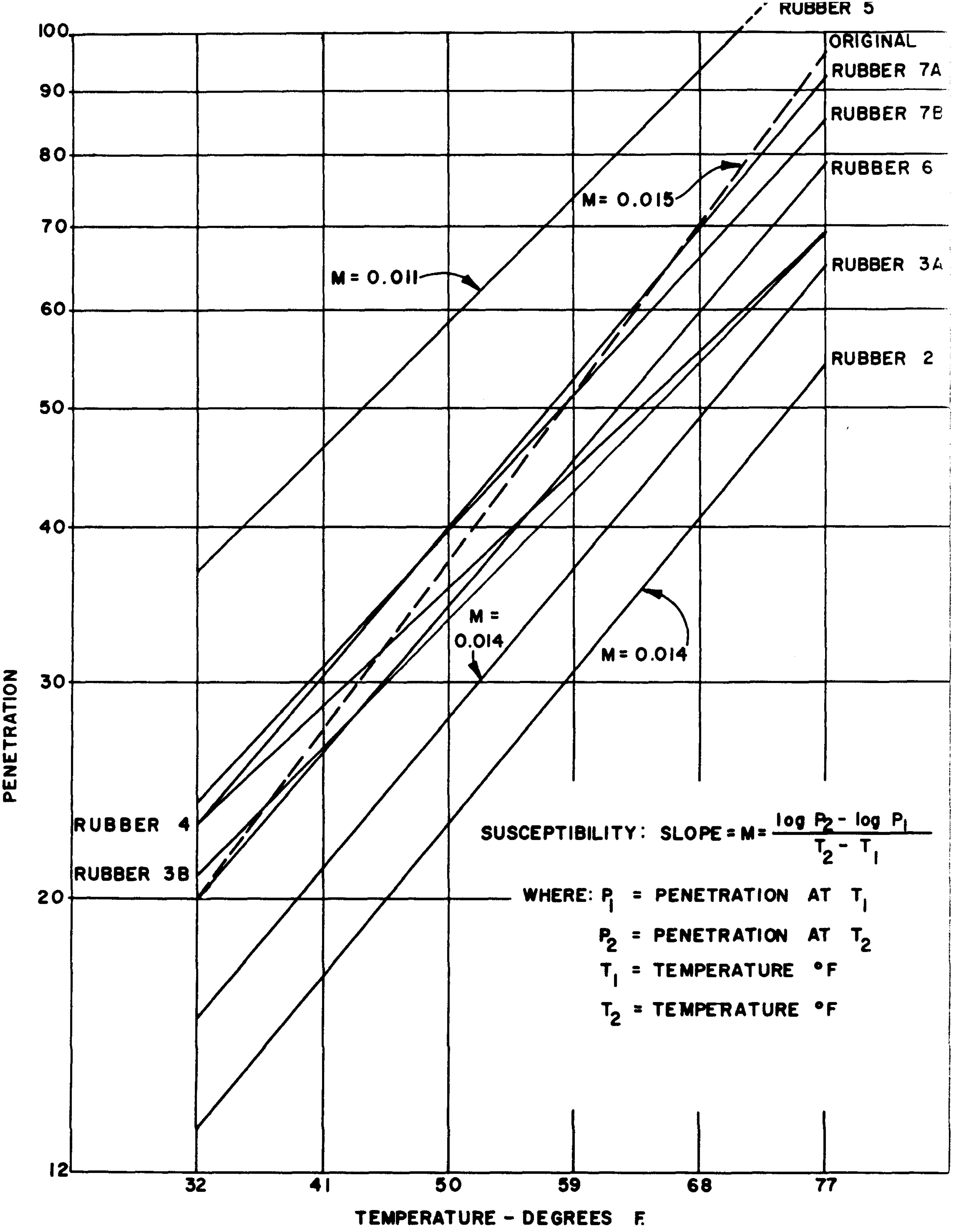


FIGURE 1 - PENETRATION-TEMPERATURE CURVES: AC-5 CEMENT

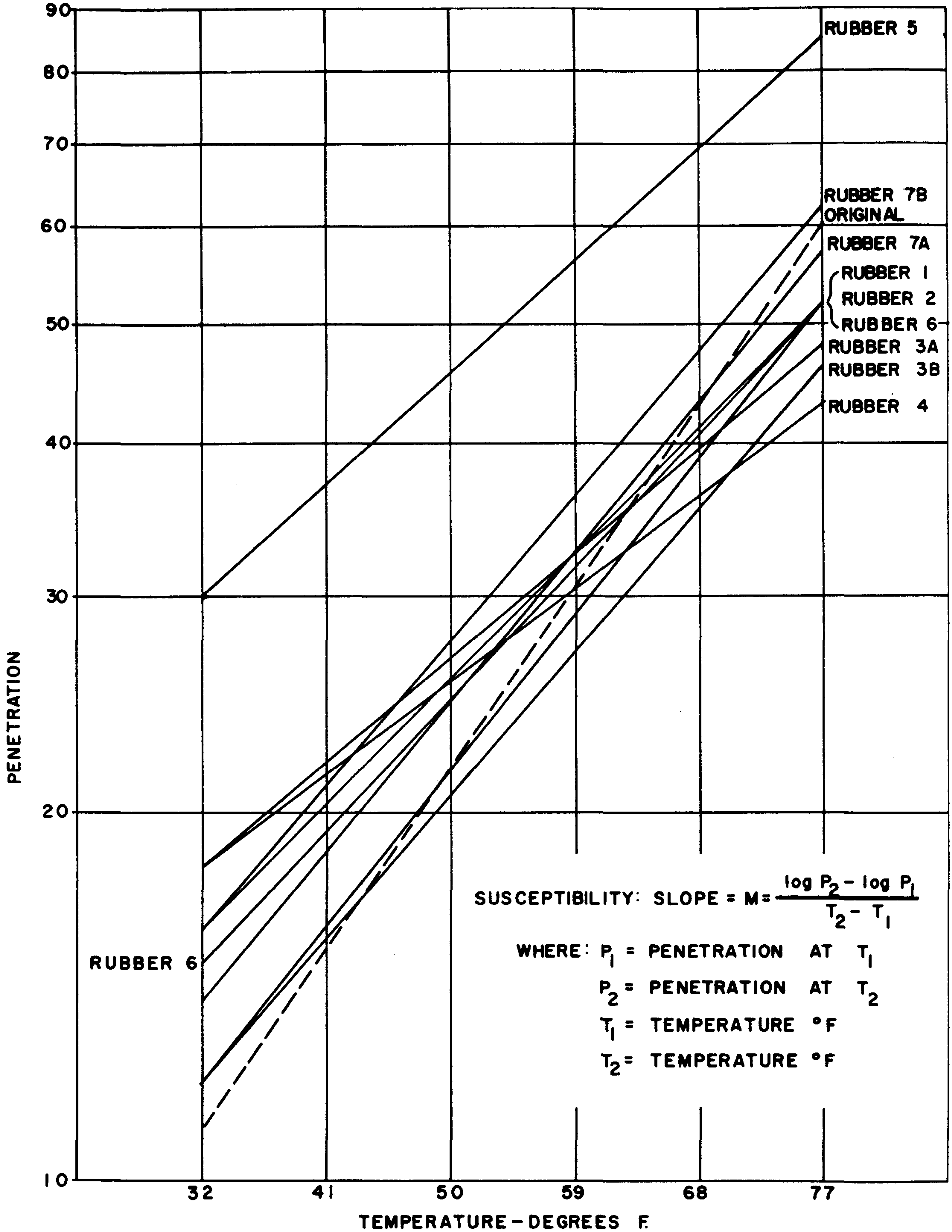


FIGURE 2 - PENETRATION-TEMPERATURE CURVES: AC-3 CEMENT

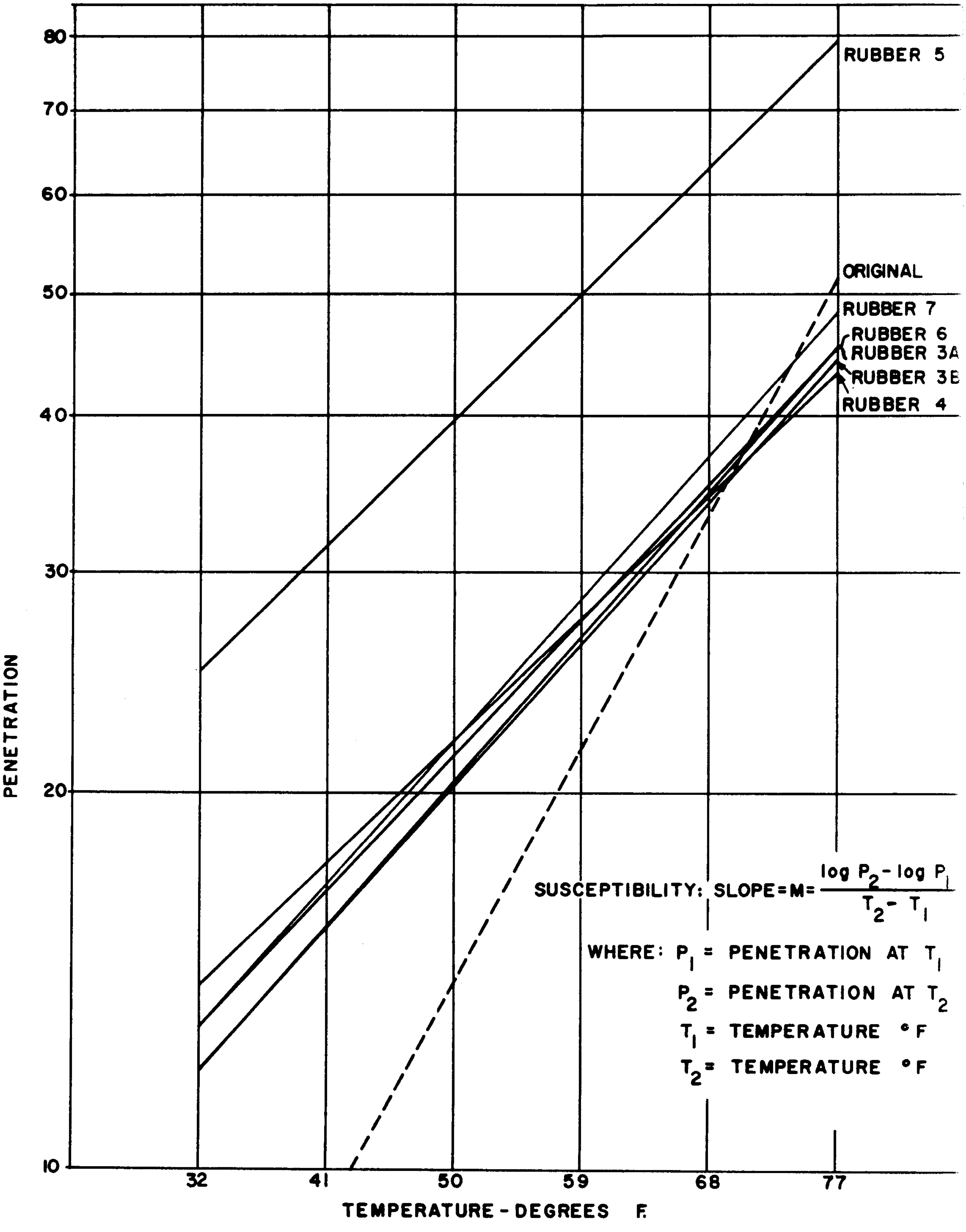
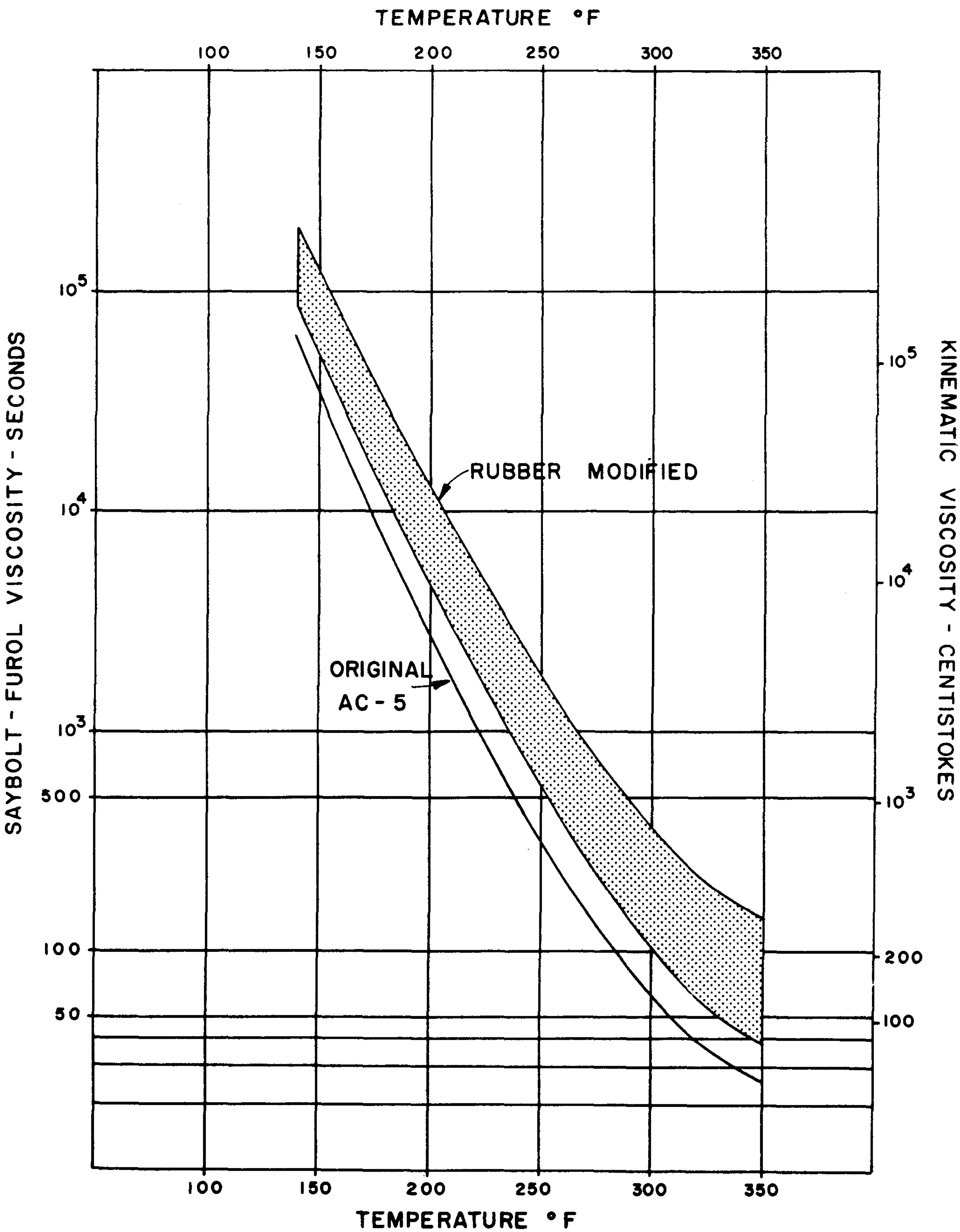


FIGURE 3 - PENETRATION-TEMPERATURE CURVES: AC-40 CEMENT



TEMPERATURE °F
100
150
200
250
300
350
SAYBOLT - FUROL VISCOSITY - SECONDS
10^5
10^4
10^3
500
100
50
KINEMATIC VISCOSITY - CENTISTOKES
10^5
10^4
10^3
200
100
RUBBER MODIFIED
ORIGINAL AC - 5

FIGURE 4

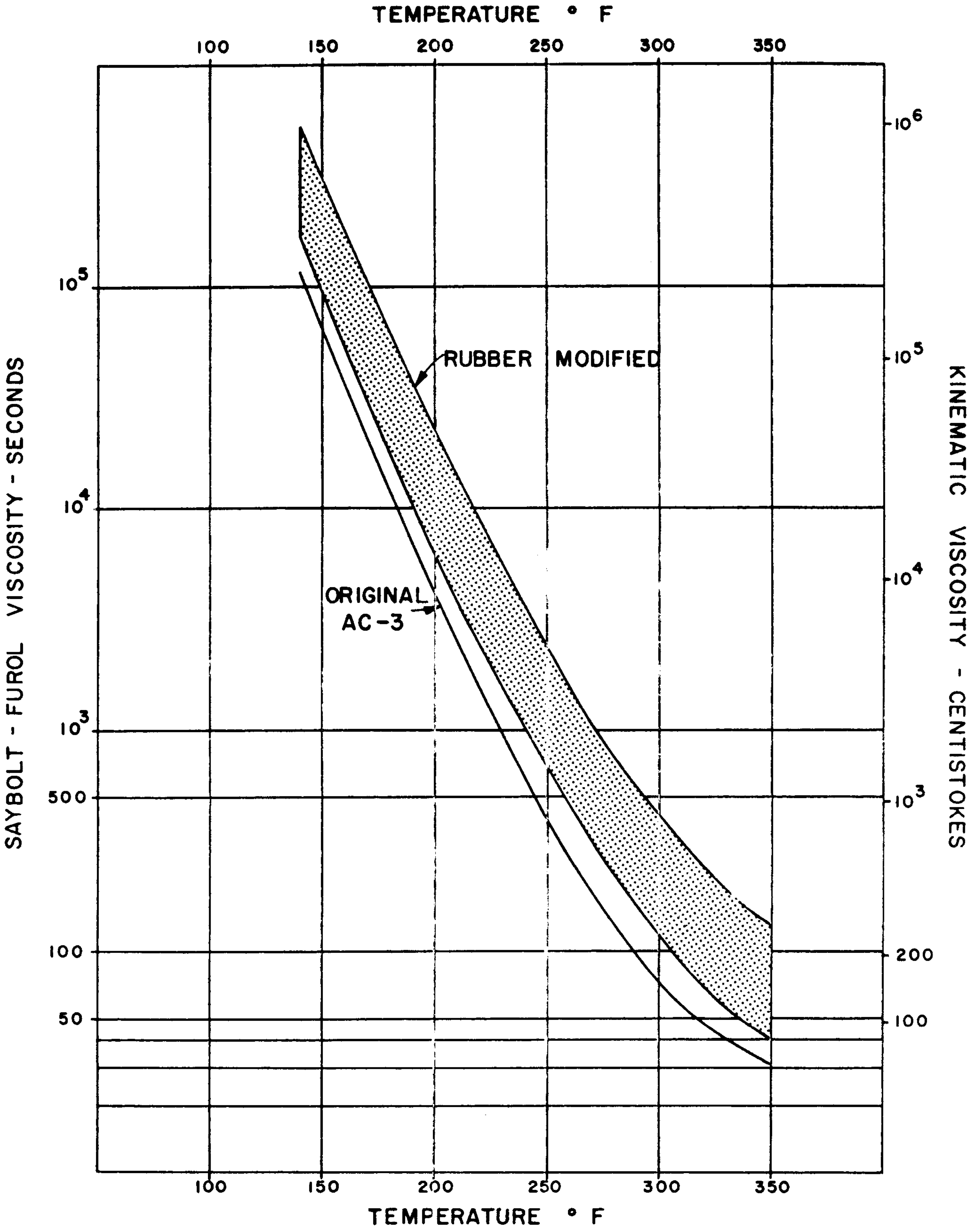

TEMPERATURE ° F
100
150
200
250
300
350
SAYBOLT - FUROL VISCOSITY - SECONDS
10^5
10^4
10^3
500
100
50
KINEMATIC VISCOSITY - CENTISTOKES
10^6
10^5
10^4
10^3
200
100
RUBBER MODIFIED
ORIGINAL AC-3

FIGURE 5

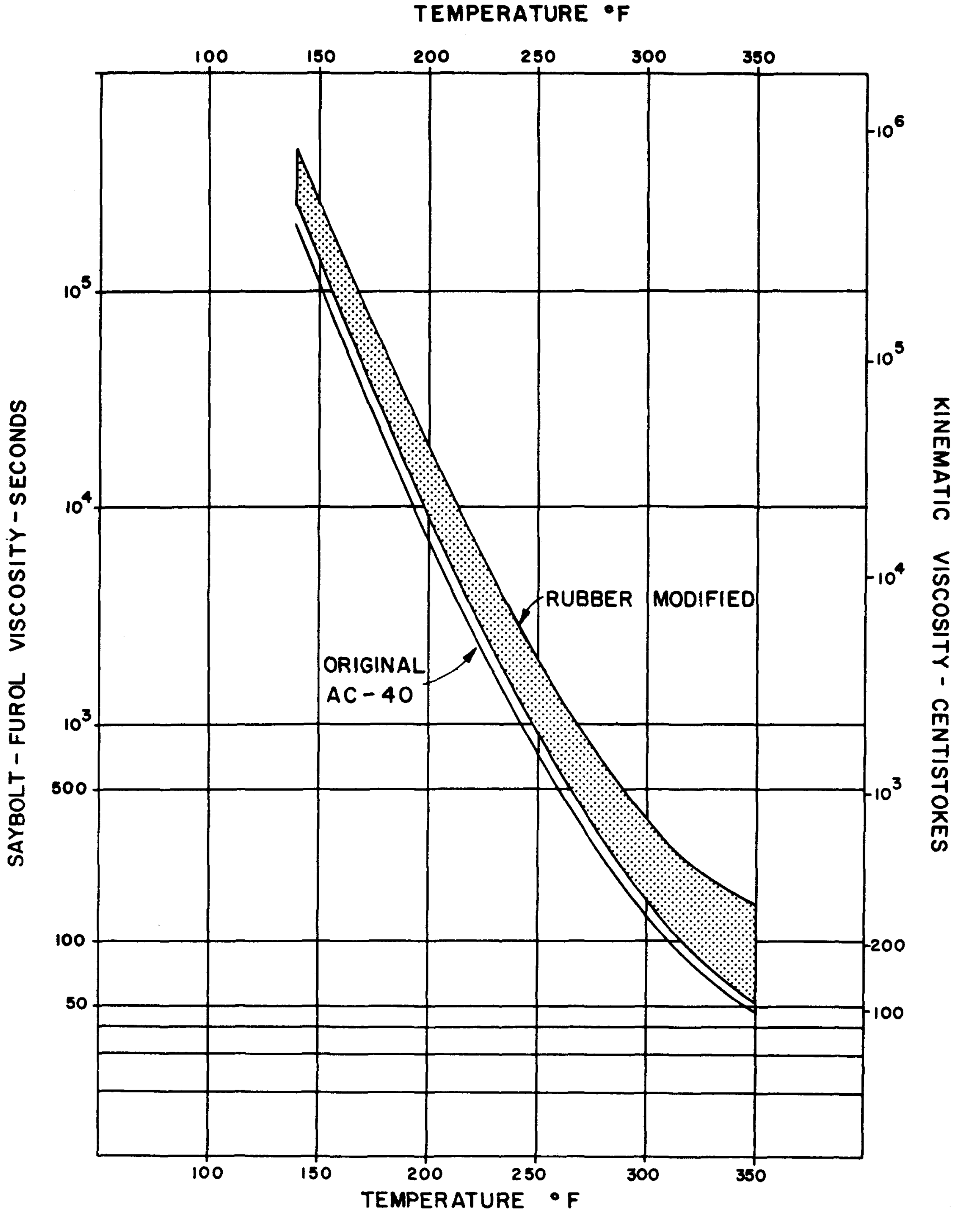

TEMPERATURE °F
100
150
200
250
300
350
SAYBOLT - FUROL VISCOSITY - SECONDS
10^5
10^4
10^3
500
100
50
KINEMATIC VISCOSITY - CENTISTOKES
10^6
10^5
10^4
10^3
200
100
RUBBER MODIFIED
ORIGINAL
AC - 40
TEMPERATURE °F

FIGURE 6

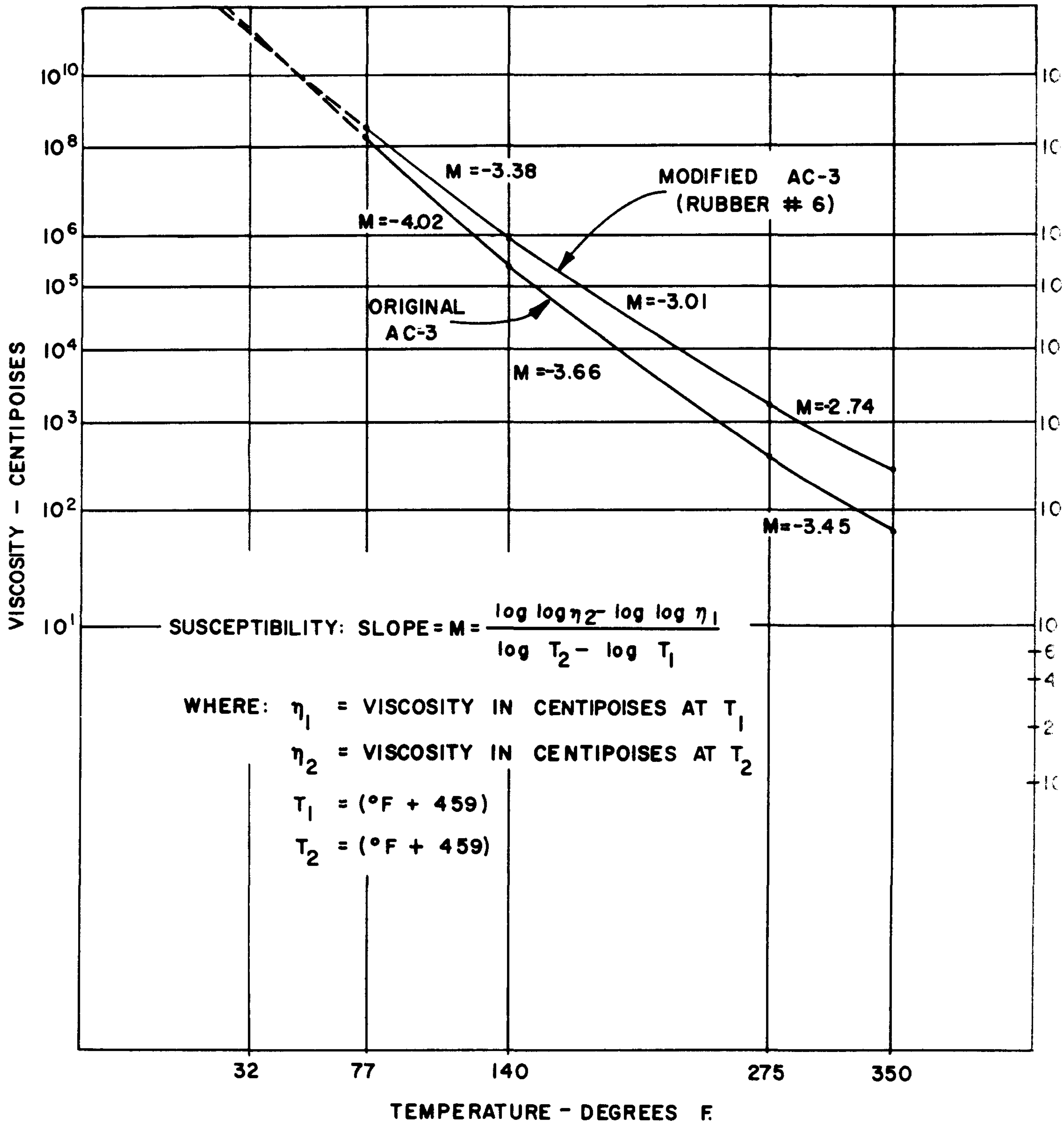
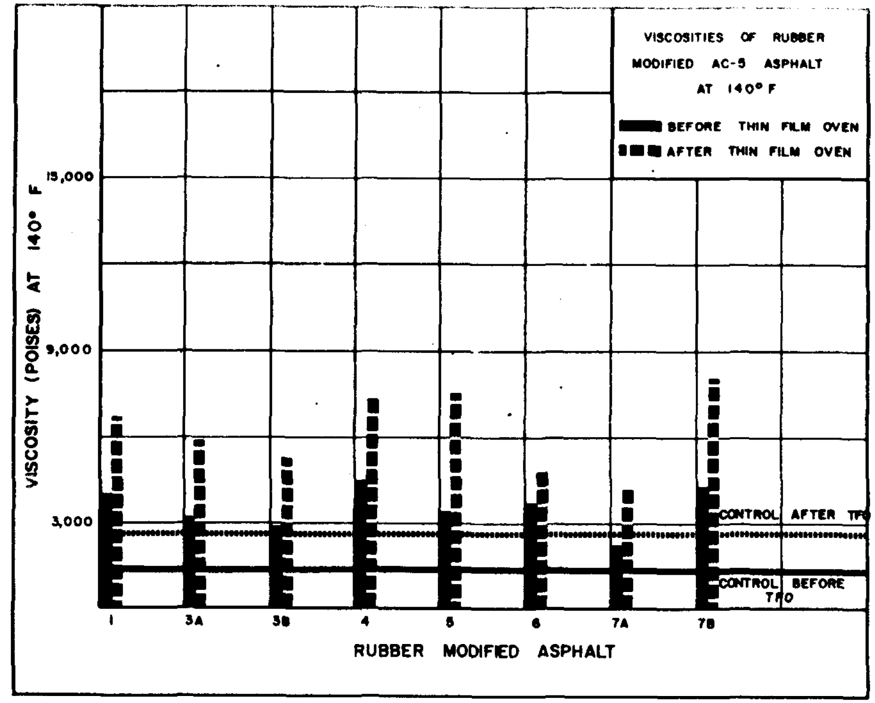
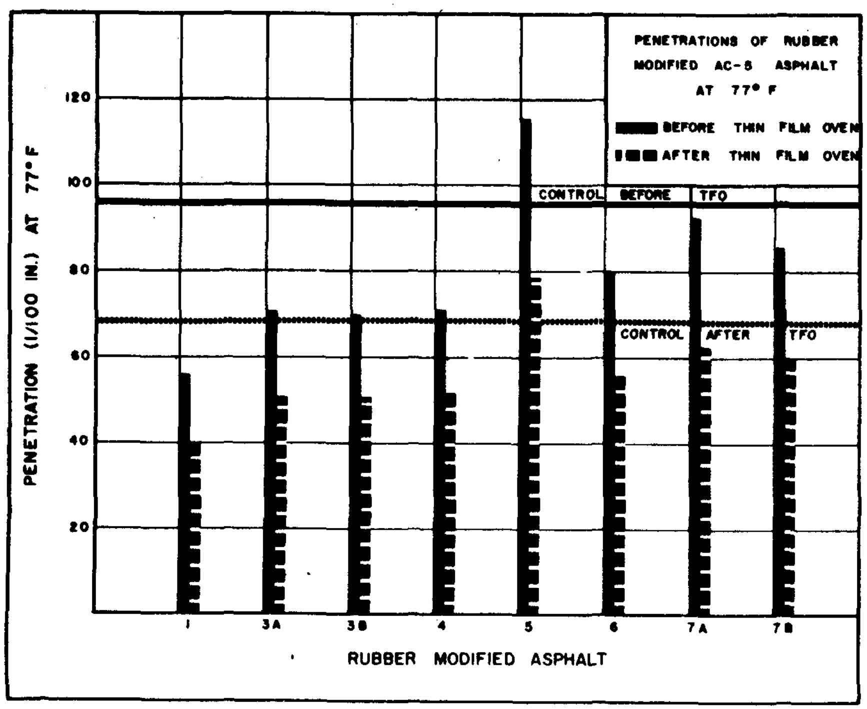


FIGURE 7 - VISCOSITY-TEMPERATURE SUSCEPTIBILITY

FIGURE 8

HEAT AGING CHARACTERISTICS
OF ORIGINAL AND RUBBER MODIFIED
AC-5 CEMENT





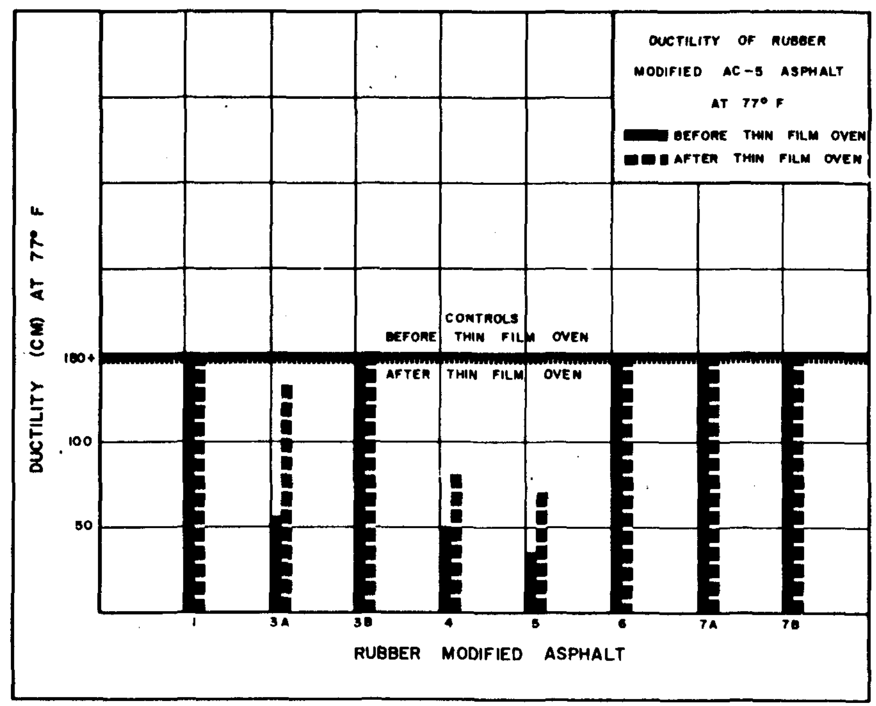
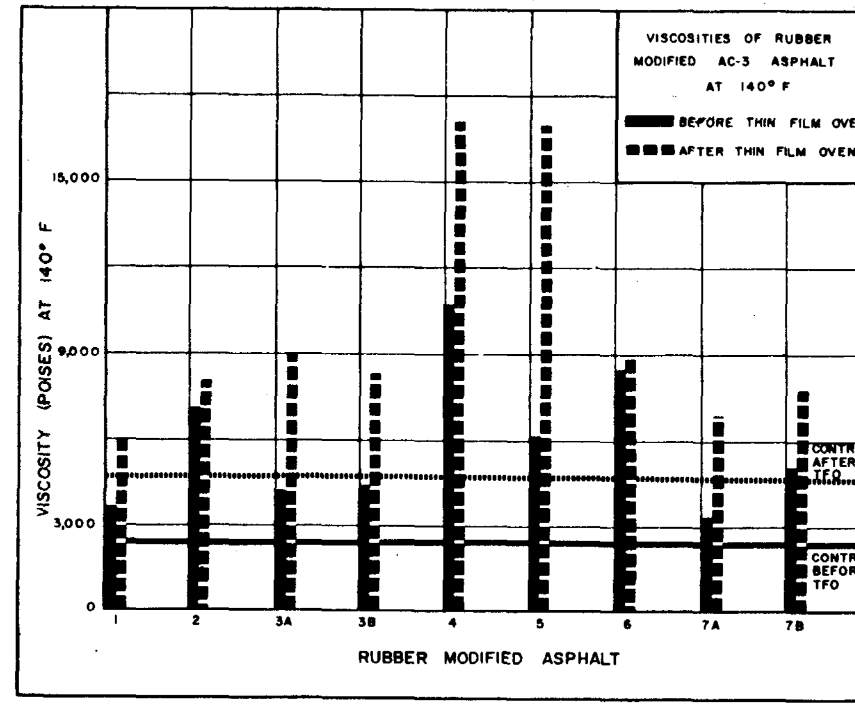


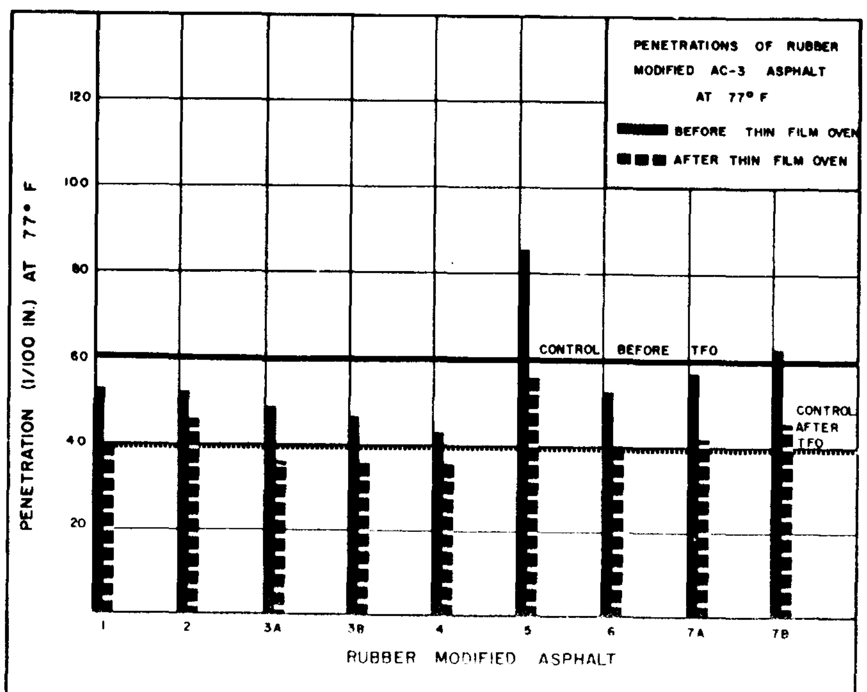
Figure 9

HEAT AGING CHARACTERISTICS

OF ORIGINAL AND RUBBER MODIFIED

AC-3 CEMENT





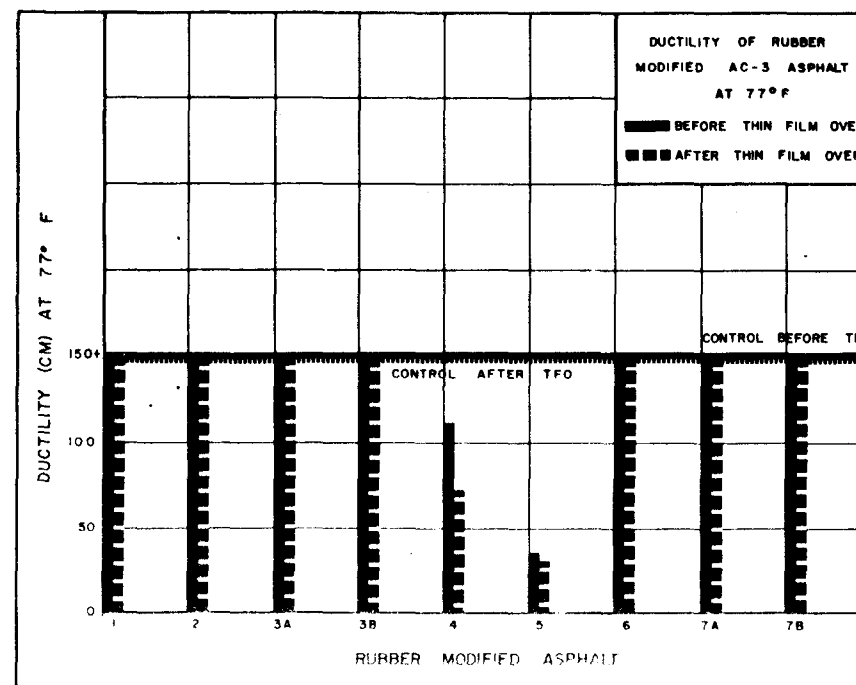
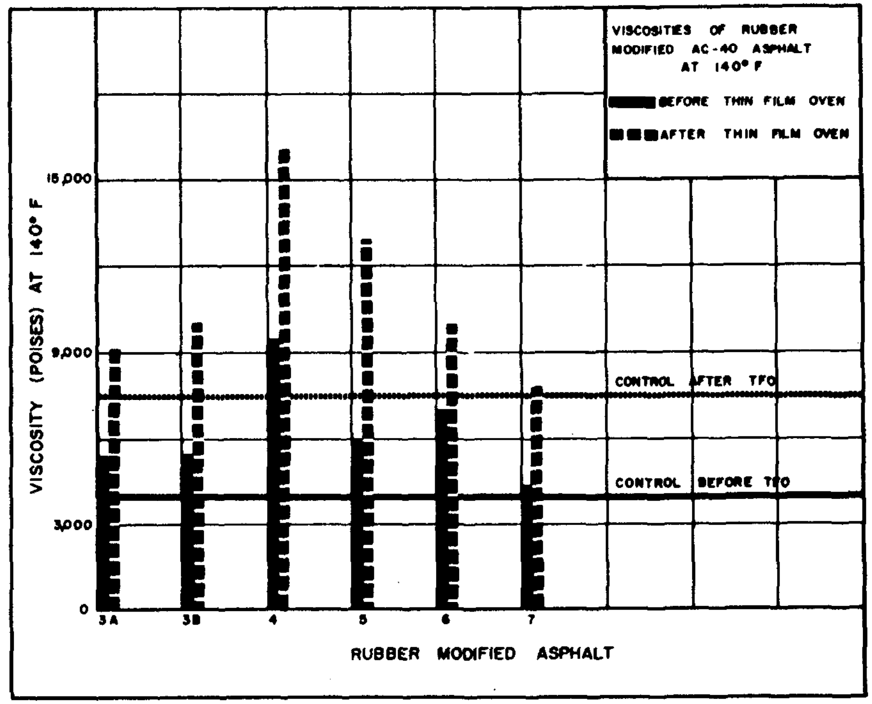


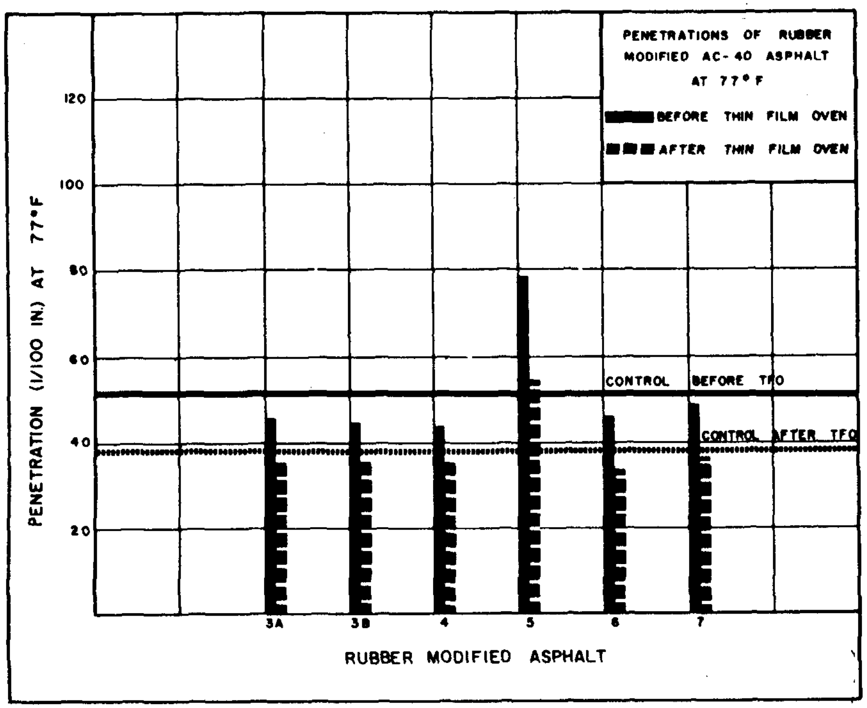
FIGURE 10

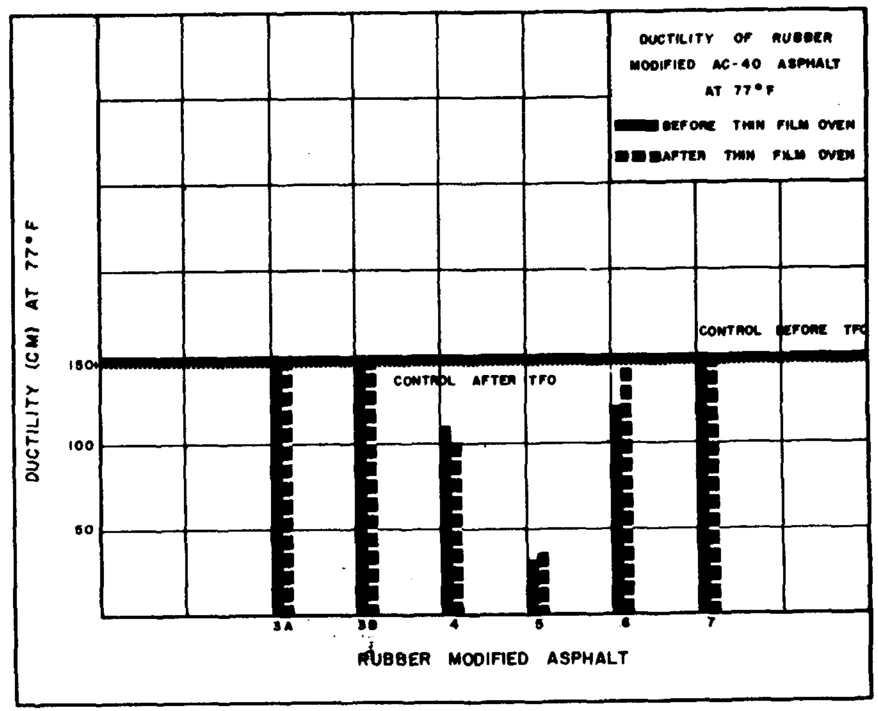
HEAT AGING CHARACTERISTIC

OF ORIGINAL AND RUBBER MODIFIED

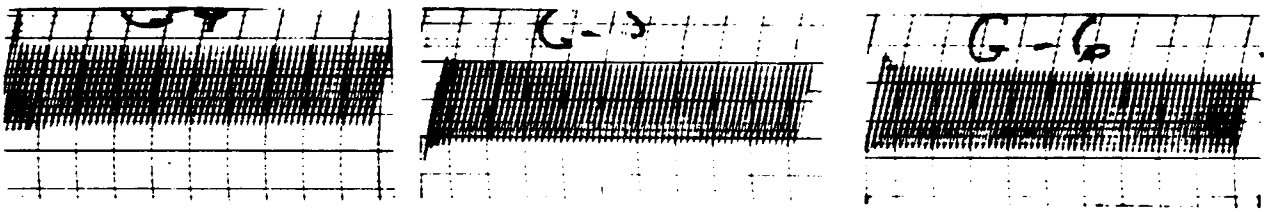
AC-40 CEMENT



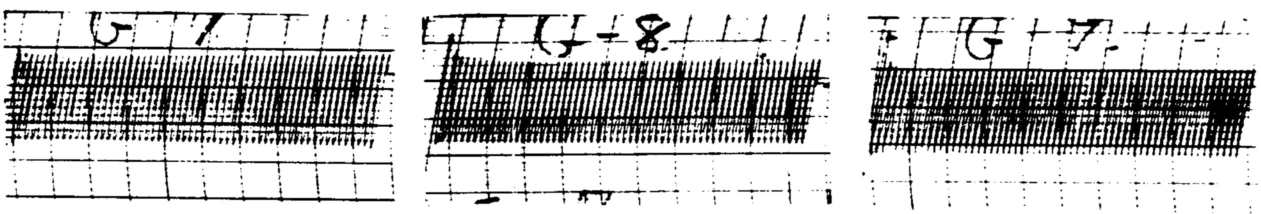




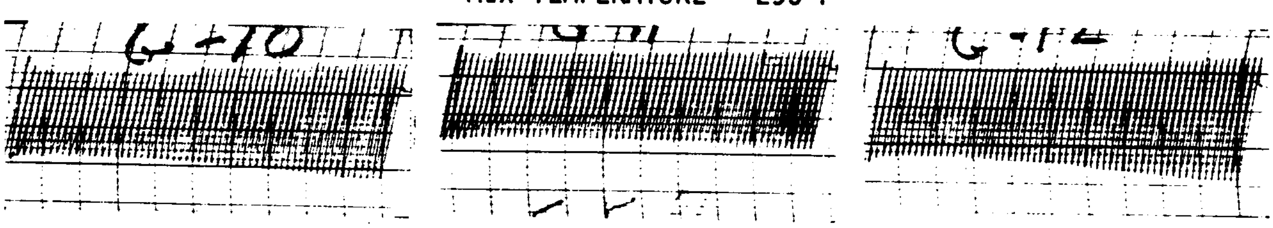
ASPHALT CONTENT = 4.0%
MIX TEMPERATURE = 295°F



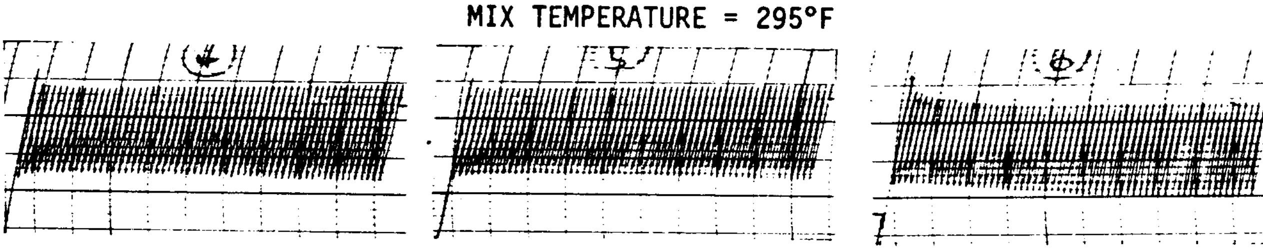
ASPHALT CONTENT = 4.5%
MIX TEMPERATURE = 295°F



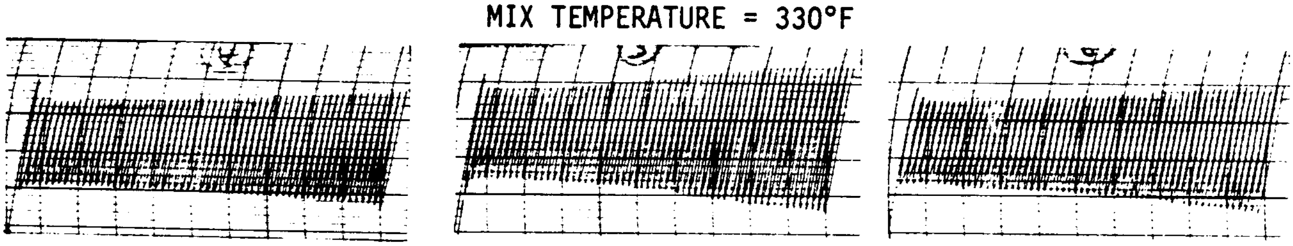
ASPHALT CONTENT = 5.0%
MIX TEMPERATURE = 295°F



ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 295°F



ASPHALT CONTENT = 5.0%
MIX TEMPERATURE = 330°F

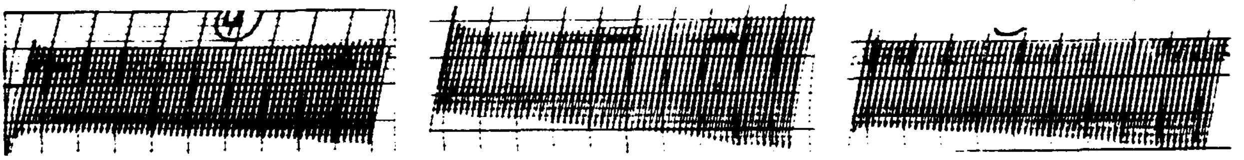


ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F

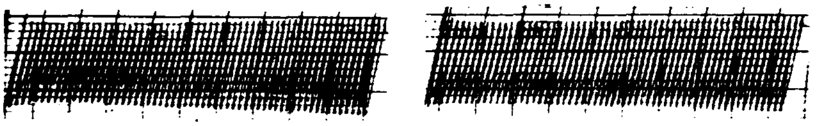
GYROGRAPH CURVES OF ORIGINAL AC-5

100 PSI, 60 GYRATIONS, 1° ANGLE OF GYRATION

FIGURE 11



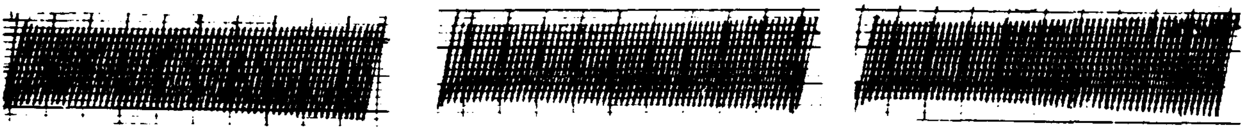
RUBBER 2, ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F



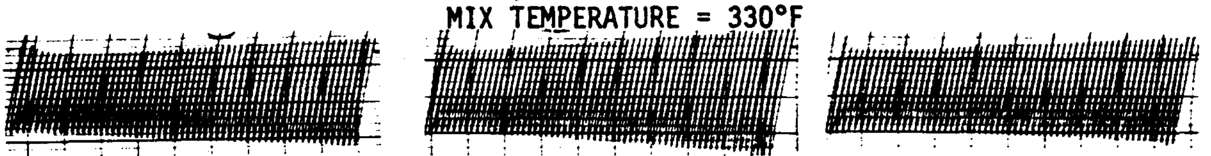
BAD SAMPLE

NO DATA

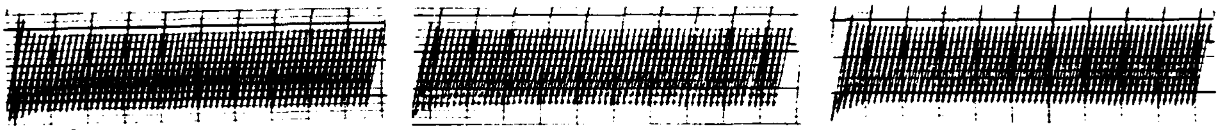
RUBBER 3A, ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F



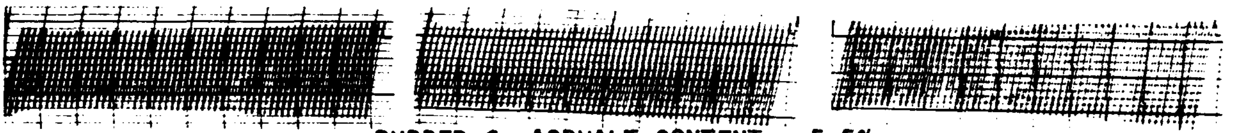
RUBBER 3B, ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F



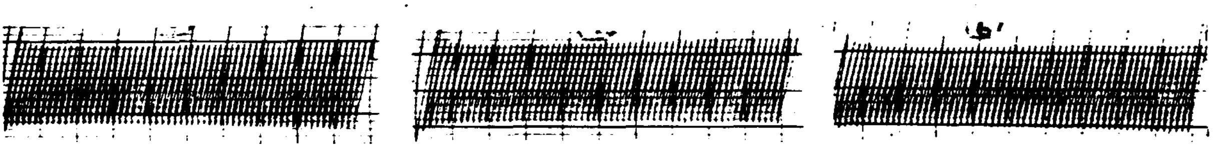
RUBBER 4, ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F



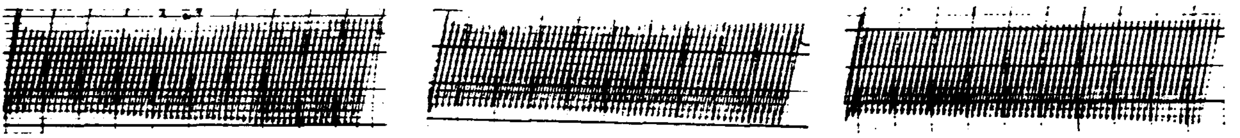
RUBBER 5, ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F



RUBBER 6, ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F



RUBBER 7A, ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F

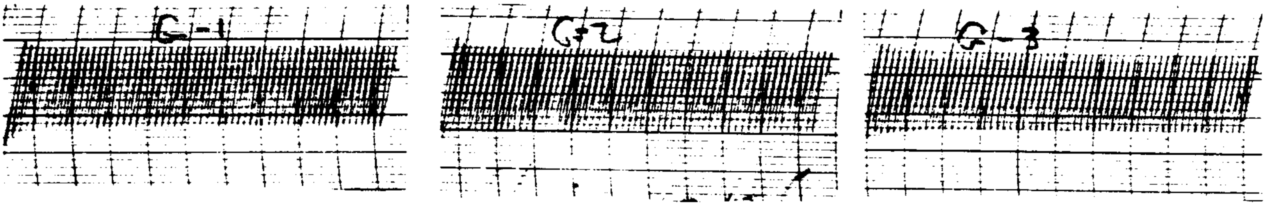


RUBBER 7B, ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F

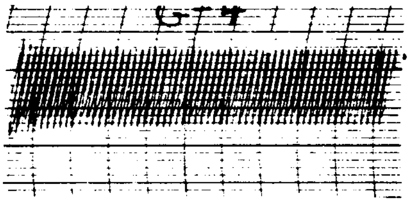
GYROGRAPH CURVES OF RUBBER MODIFIED AC-5

100 PSI, 60 GYRATIONS, 1 ANGLE OF GYRATION

FIGURE 12



ASPHALT CONTENT = 4.0%
MIX TEMPERATURE = 300°F



BAD SAMPLE

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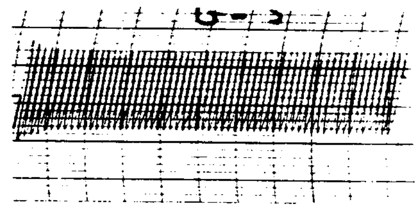
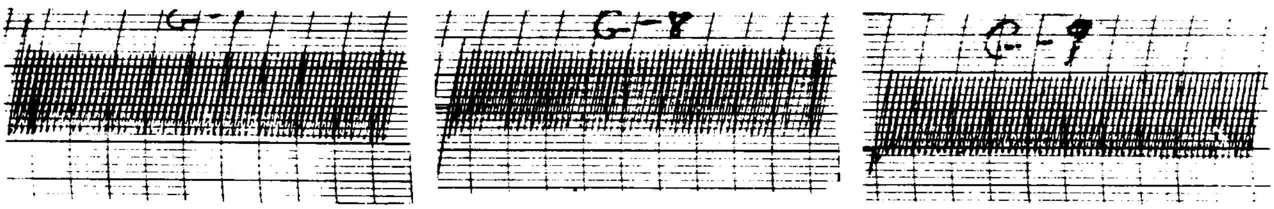
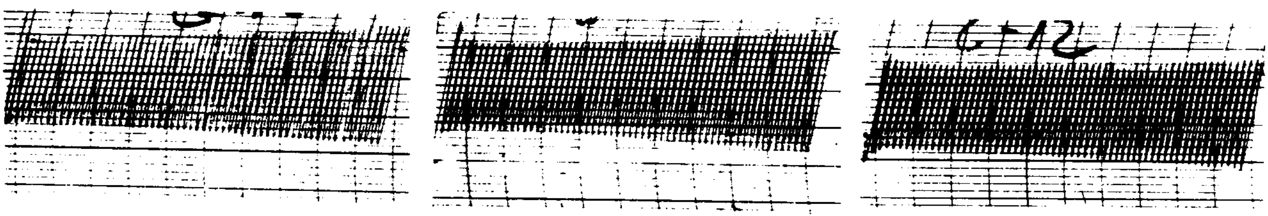


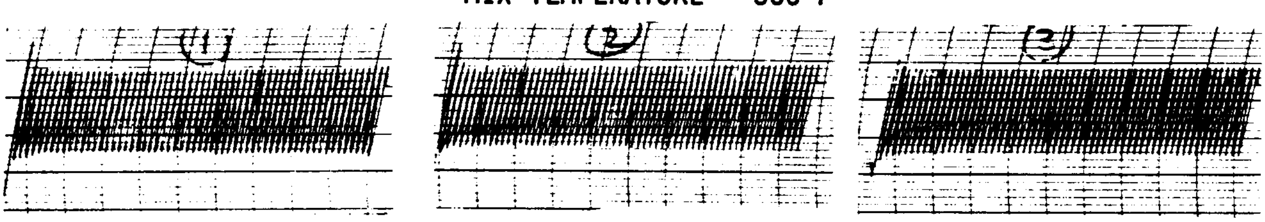
ASPHALT CONTENT = 4.5%
MIX TEMPERATURE = 300°F



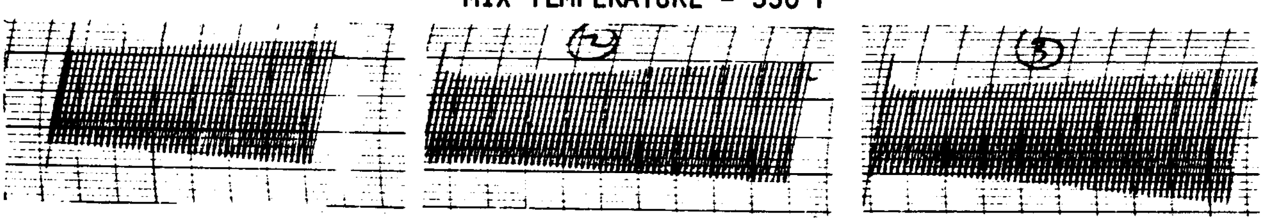
ASPHALT CONTENT = 5.0%
MIX TEMPERATURE = 300°F



ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 300°F



ASPHALT CONTENT = 5.0%
MIX TEMPERATURE = 330°F



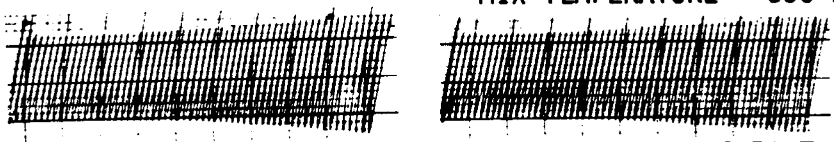
ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F

GYROGRAPH CURVES OF ORIGINAL AC-3

100 PSI, 60 GYRATIONS, 1° ANGLE OF GYRATION

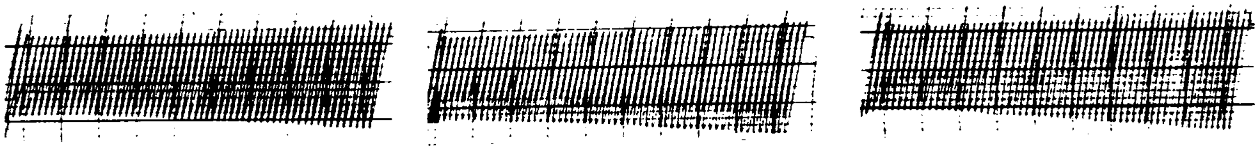
FIGURE 13

RUBBER 2, ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F

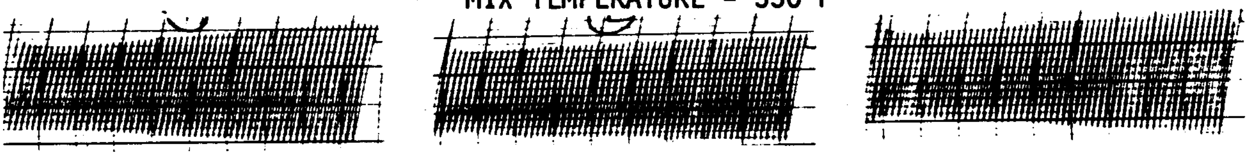


BAD SAMPLE
NO DATA

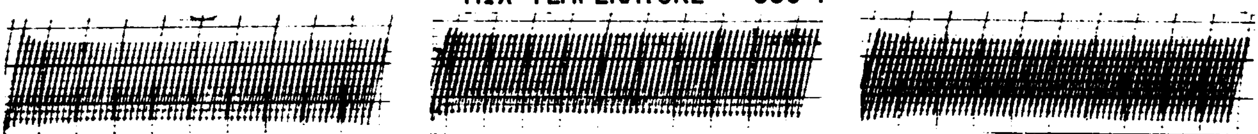
RUBBER 3A, ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F



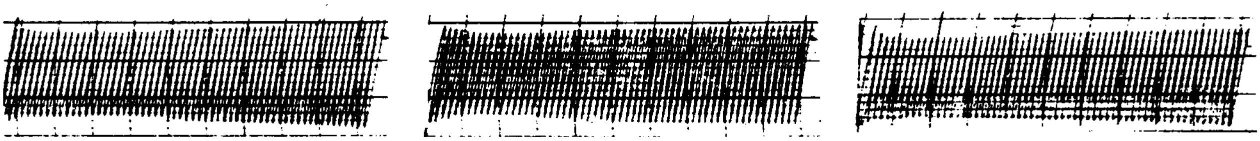
RUBBER 3B, ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F



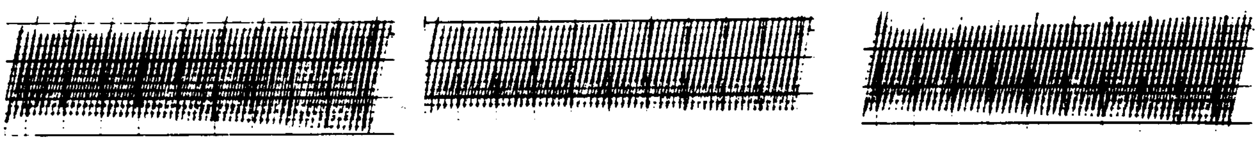
RUBBER 4, ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F



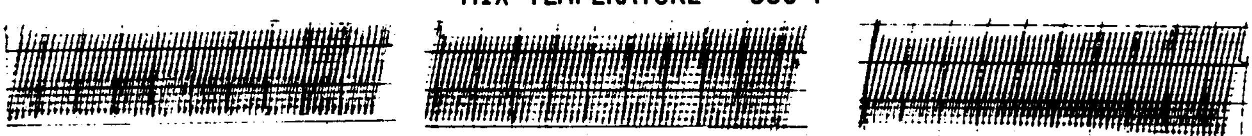
RUBBER 5, ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F



RUBBER 6, ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F



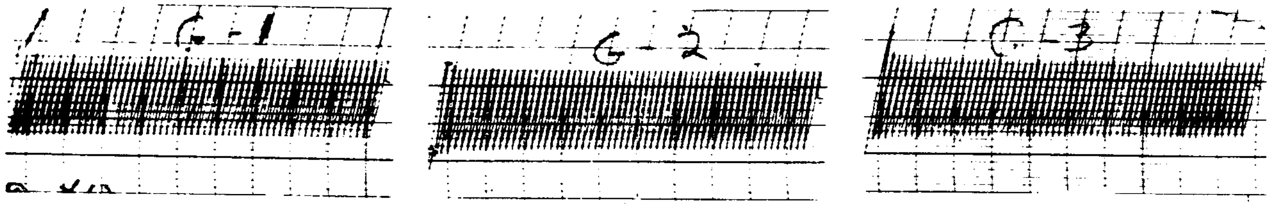
RUBBER 7A, ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F



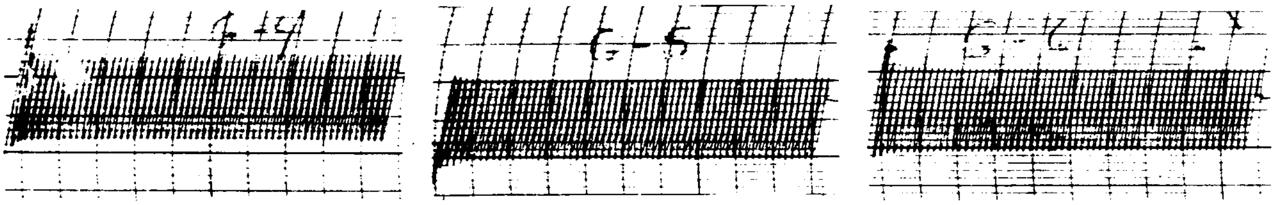
RUBBER 7B, ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F

GYROGRAPH CURVES OF RUBBER MODIFIED AC-3
100 PSI, 60 GYRATIONS, 1° ANGLE OF GYRATION

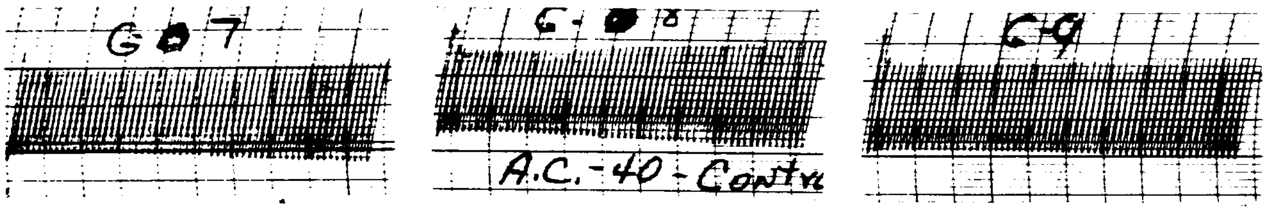
FIGURE 14



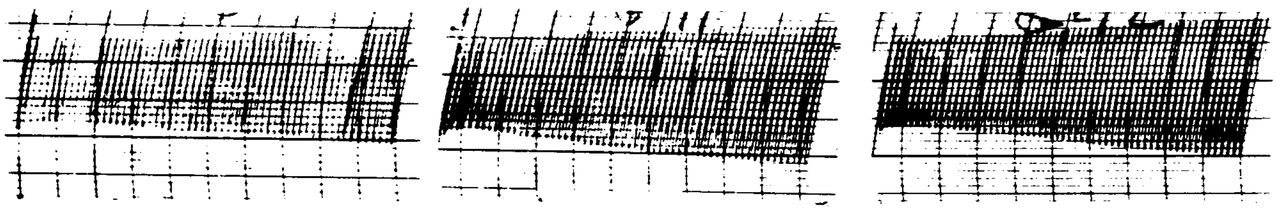
ASPHALT CONTENT = 4.0%
MIX TEMPERATURE = 325°F



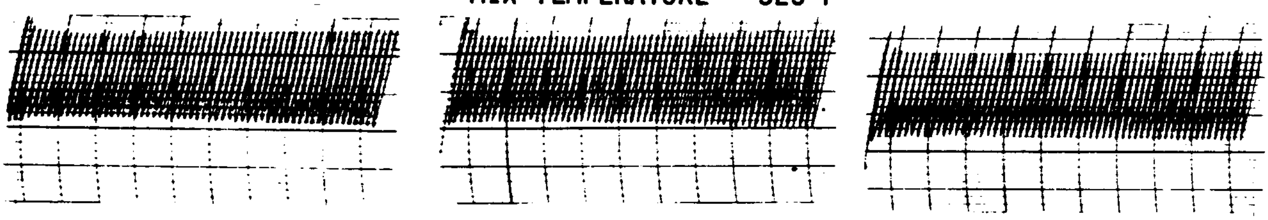
ASPHALT CONTENT = 4.5%
MIX TEMPERATURE = 325°F



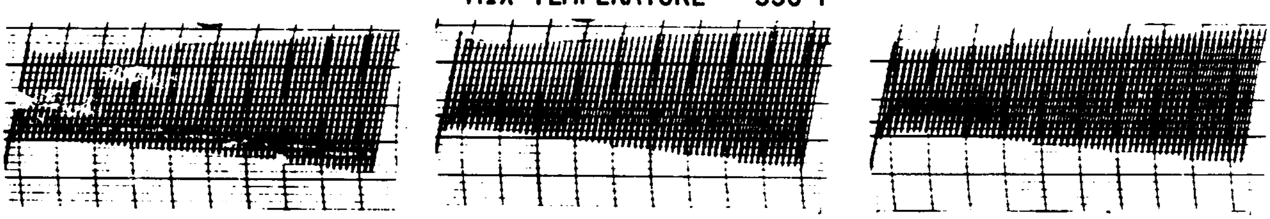
ASPHALT CONTENT = 5.0%
MIX TEMPERATURE = 325°F



ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 325°F



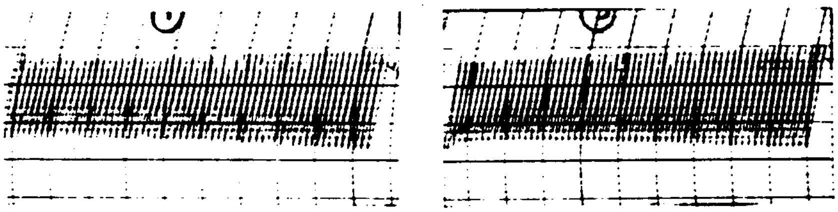
ASPHALT CONTENT = 5.0%
MIX TEMPERATURE = 330°F



ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F

GYROGRAPH CURVES OF ORIGINAL AC-40
100 PSI, 60 GYRATIONS, 1° ANGLE OF GYRATION

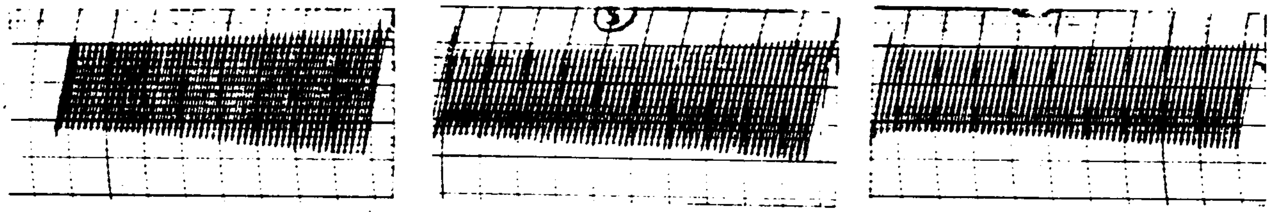
FIGURE 15



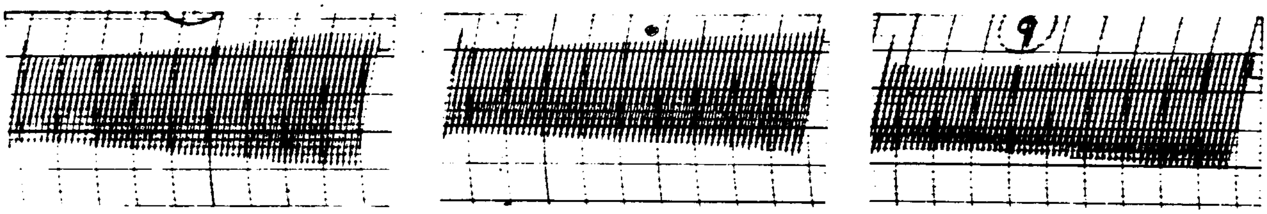
BAD SAMPLE

NO DATA

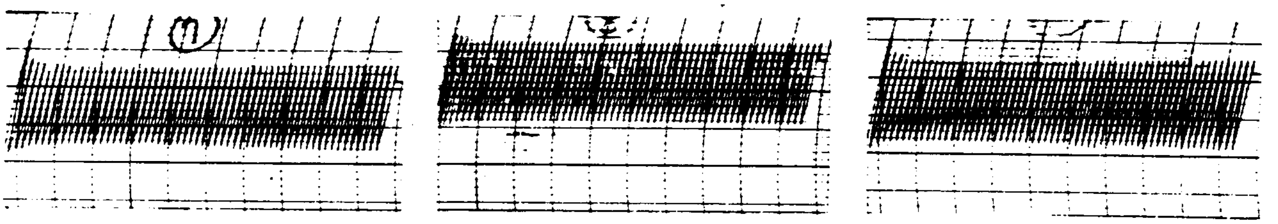
RUBBER 3A, ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F



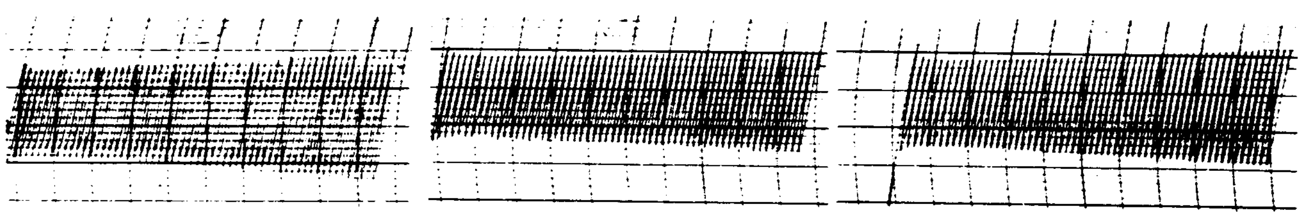
RUBBER 3B, ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F



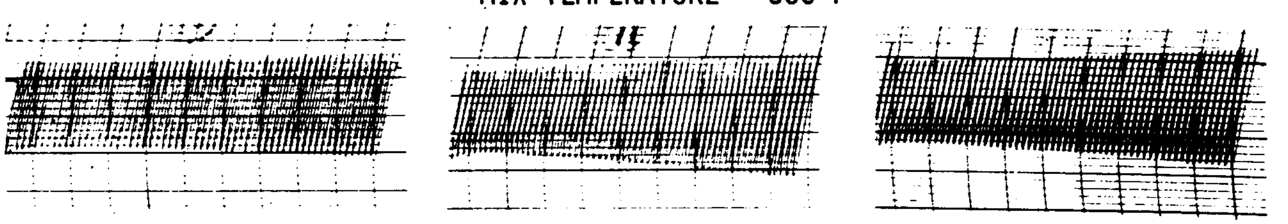
RUBBER 4, ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F



RUBBER 5, ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F



RUBBER 6, ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F



RUBBER 7, ASPHALT CONTENT = 5.5%
MIX TEMPERATURE = 330°F

GYROGRAPH CURVES OF RUBBER MODIFIED AC-40

100 PSI, 60 GYRATIONS, 1° ANGLE OF GYRATION

FIGURE 16

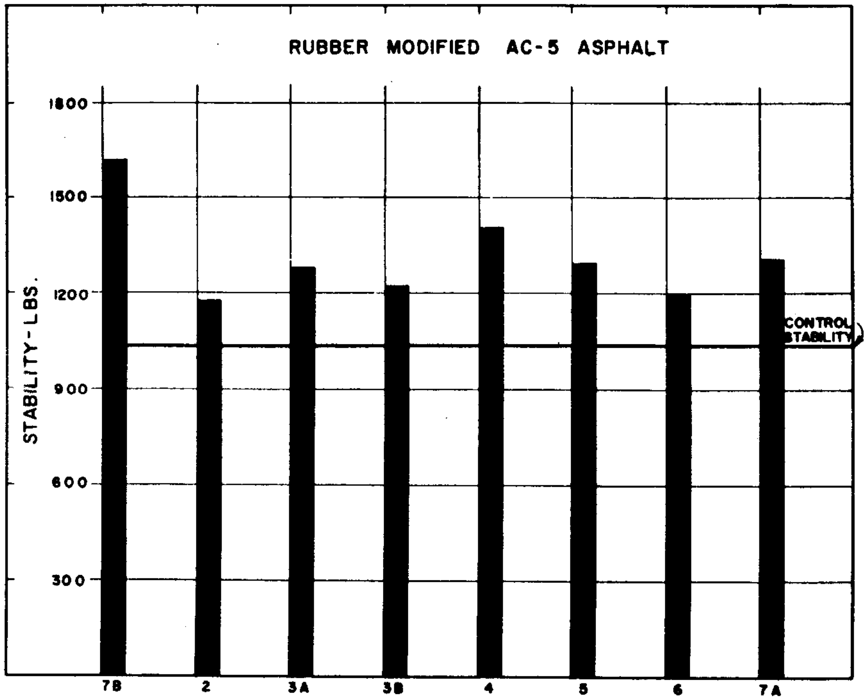
FIGURE 17A

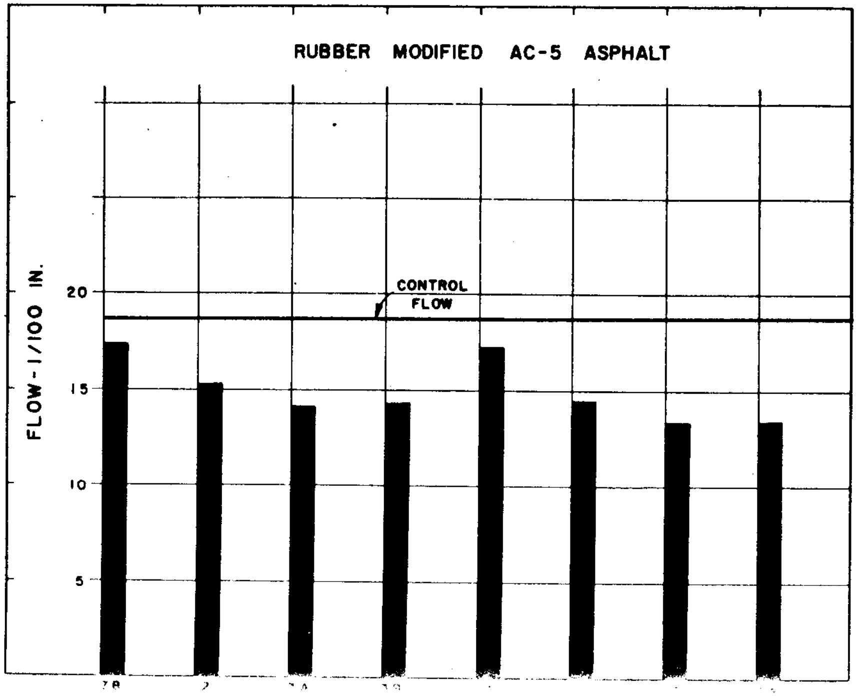
AVERAGE RESULTANT MIX PROPERTIES WITH AC-5 AS BINDER

ORIGINAL CEMENT LEVEL OF 5.5%

VERSUS

RUBBER MODIFIED CEMENT LEVEL OF 5.5%





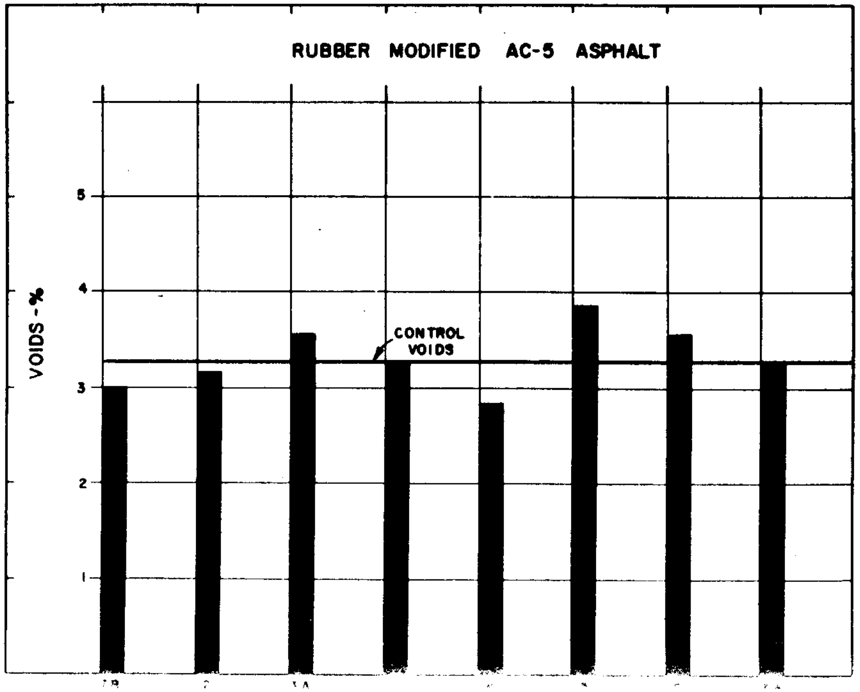
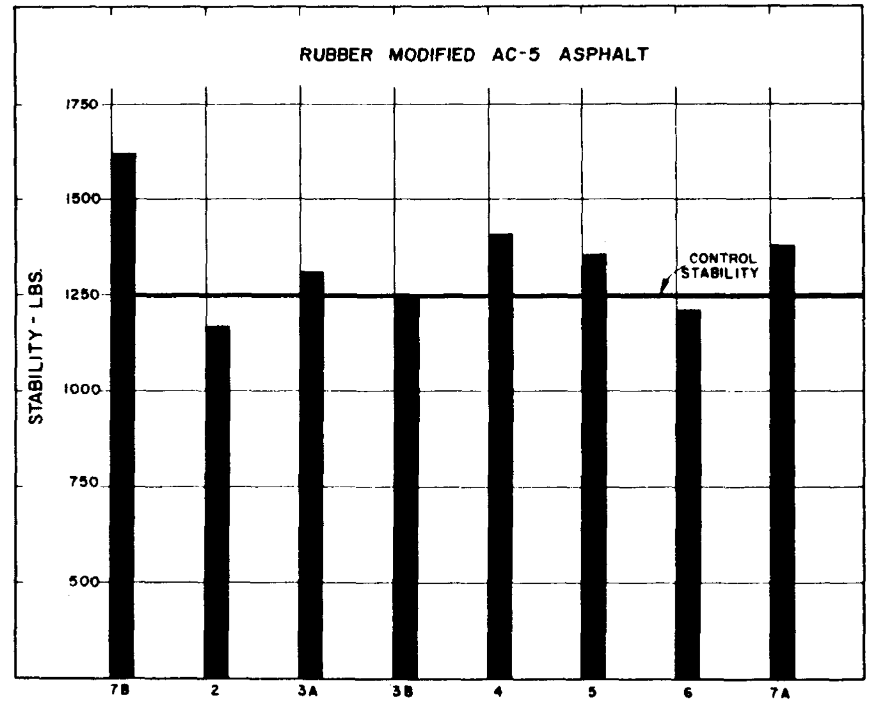
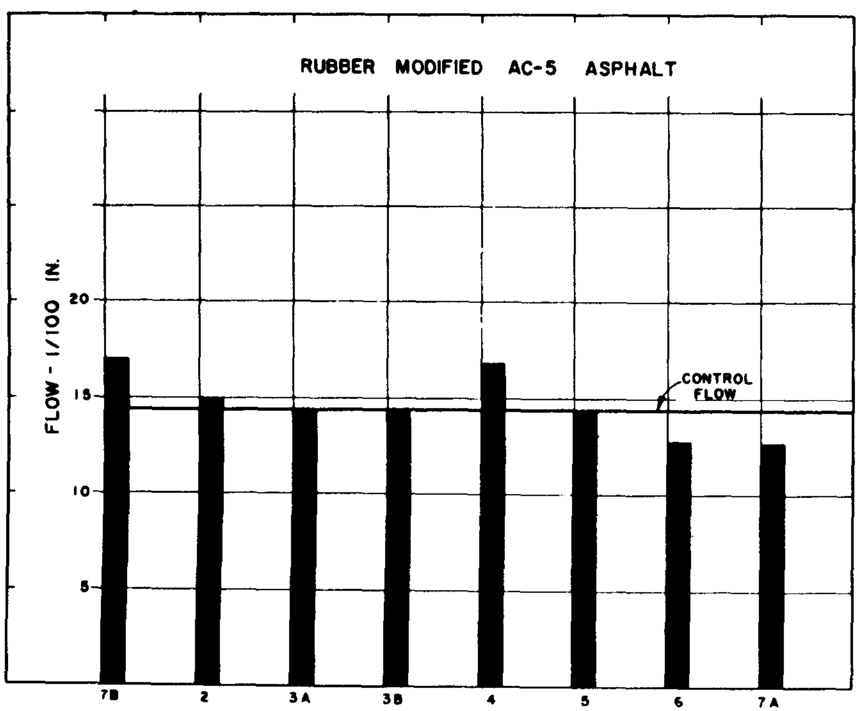


FIGURE 17B
AVERAGE RESULTANT MIX PROPERTIES WITH AC-5 AS BINDER
ORIGINAL CEMENT LEVEL OF 5.0%
VERSUS
RUBBER MODIFIED CEMENT LEVEL 5.5%





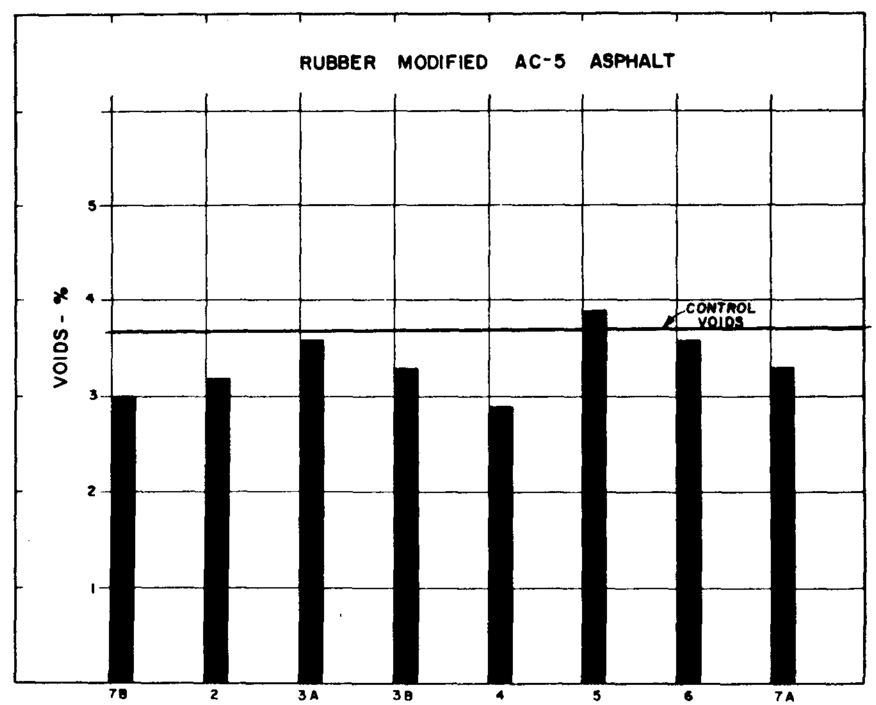


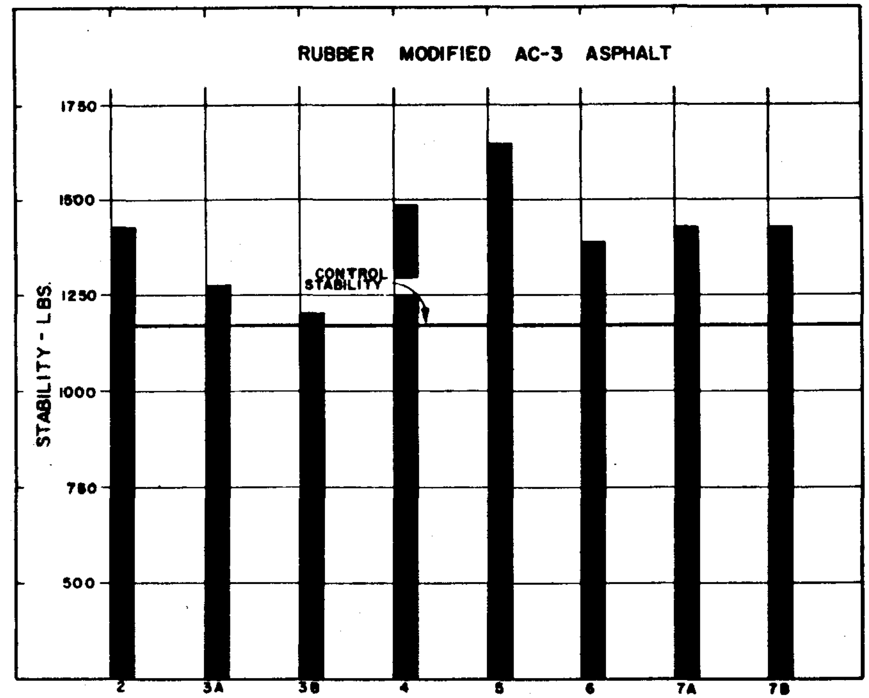
FIGURE 18A

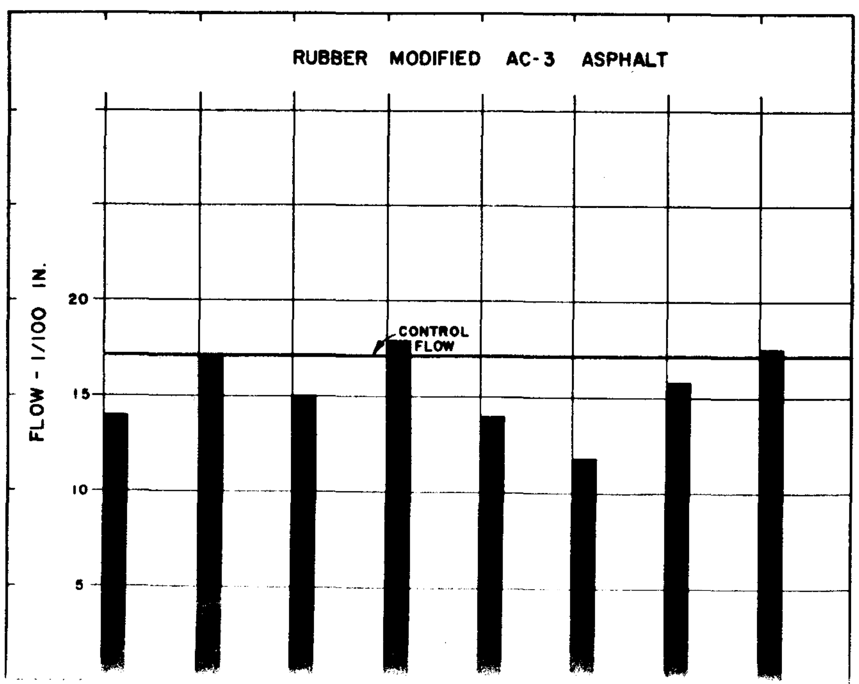
AVERAGE RESULTANT MIX PROPERTIES WITH AC-3 AS BINDER

ORIGINAL CEMENT LEVEL OF 5.5%

VERSUS

RUBBER MODIFIED CEMENT LEVEL OF 5.5%





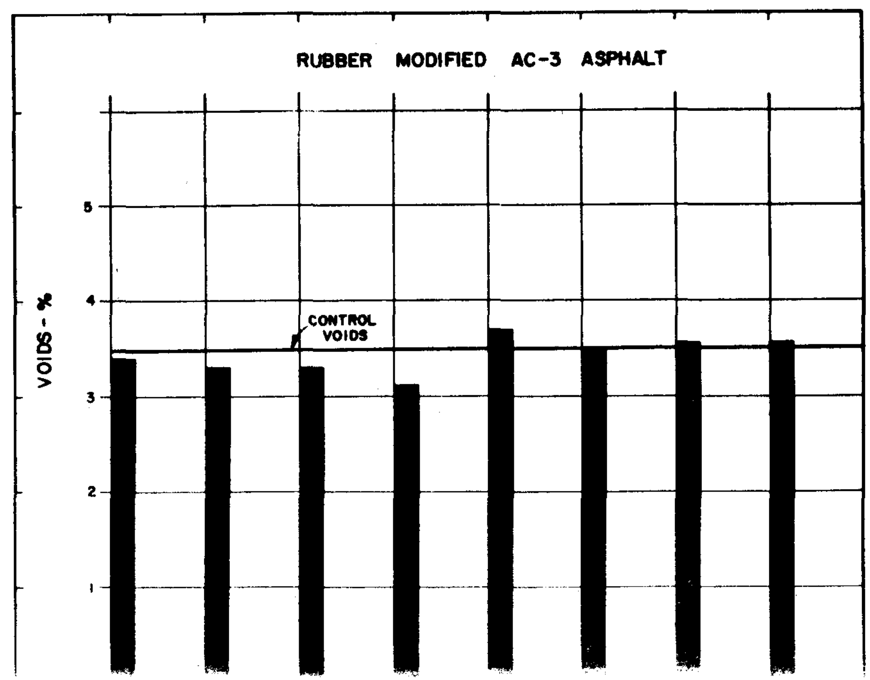
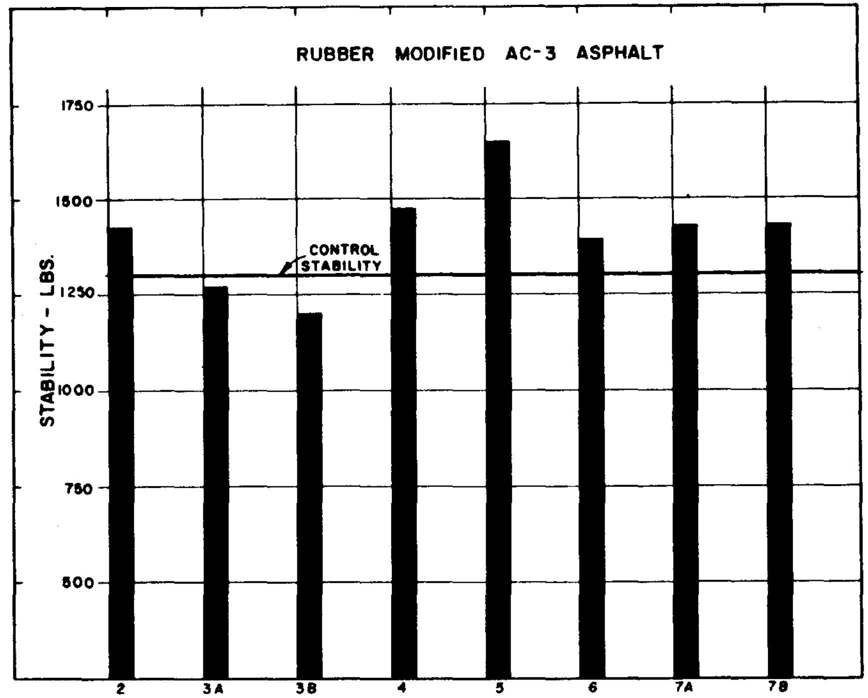
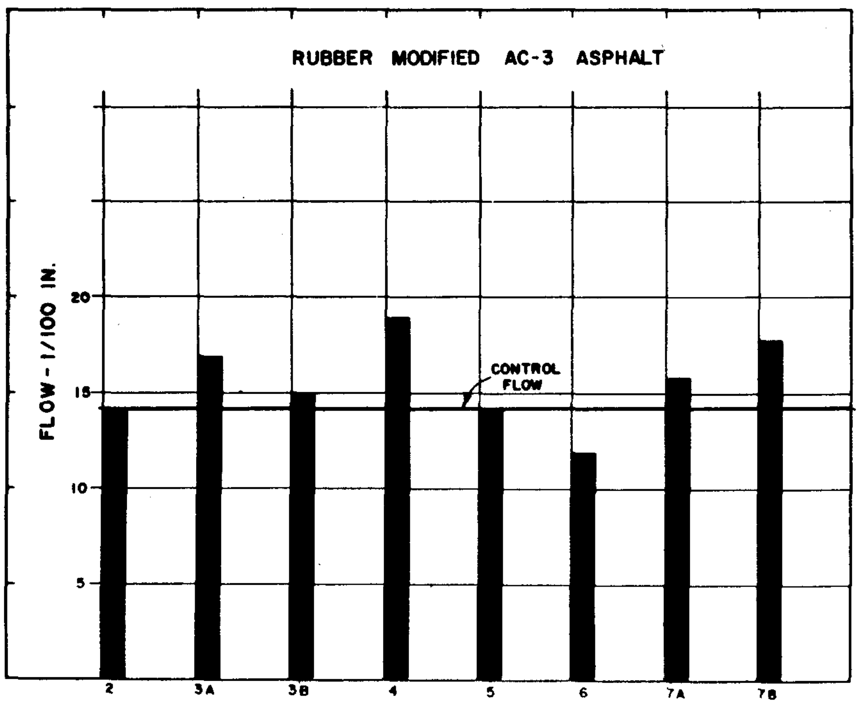


FIGURE 18B
AVERAGE RESULTANT MIX PROPERTIES WITH AC-3 BINDER
ORIGINAL CEMENT LEVEL OF 5.0%
VERSUS
RUBBER MODIFIED CEMENT LEVEL OF 5.5%





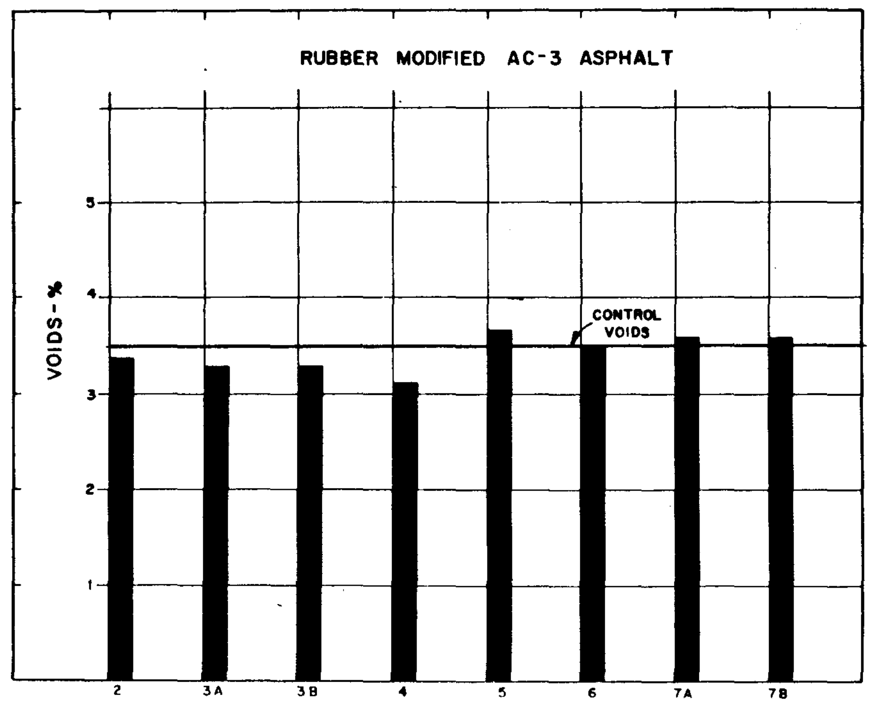


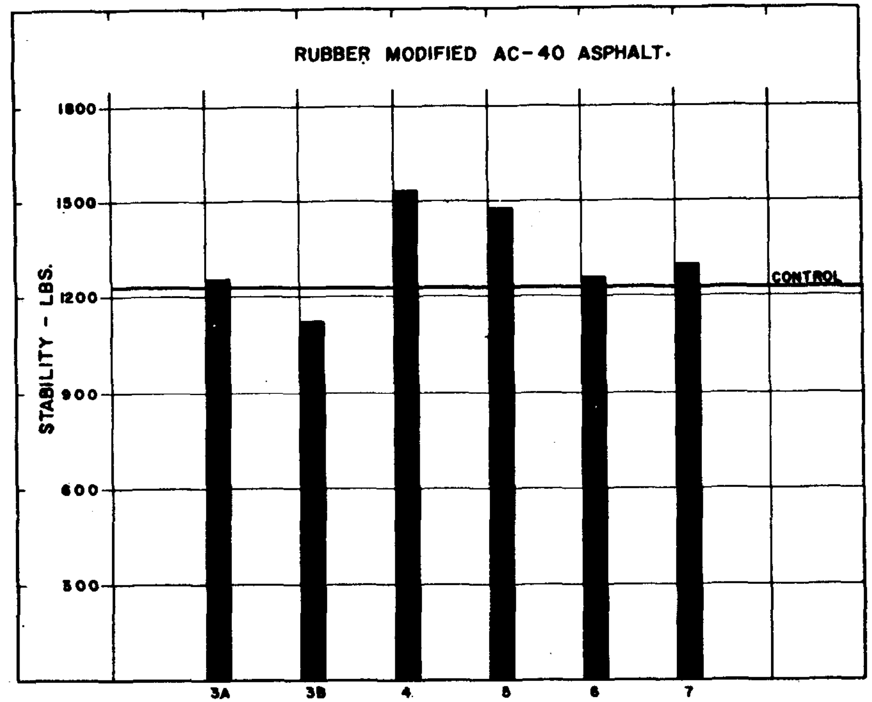
FIGURE 19A

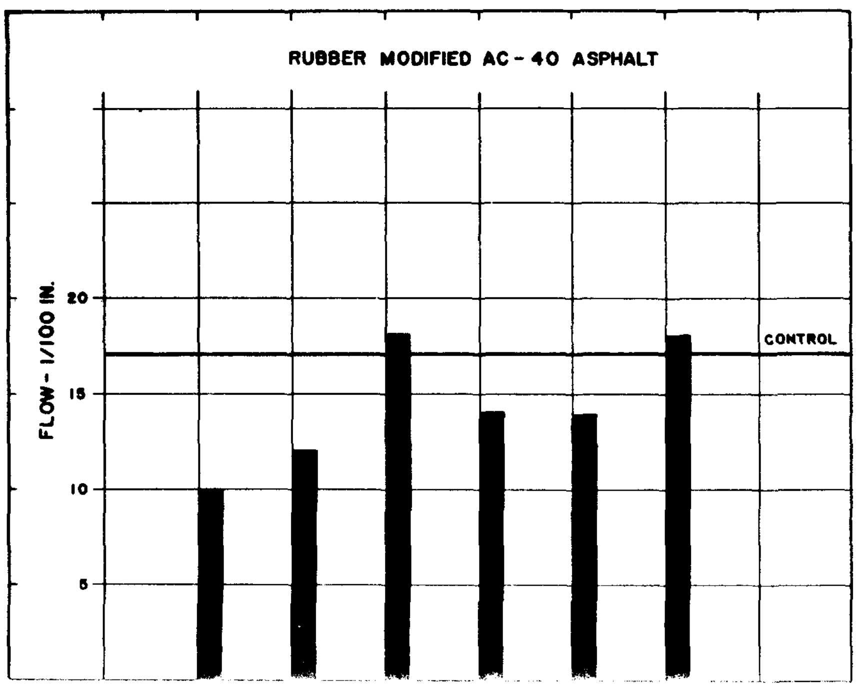
AVERAGE RESULTANT MIX PROPERTIES WITH AC-40 AS BINDER

ORIGINAL CEMENT LEVEL OF 5.5%

VERSUS

RUBBER MODIFIED CEMENT LEVEL OF 5.5%





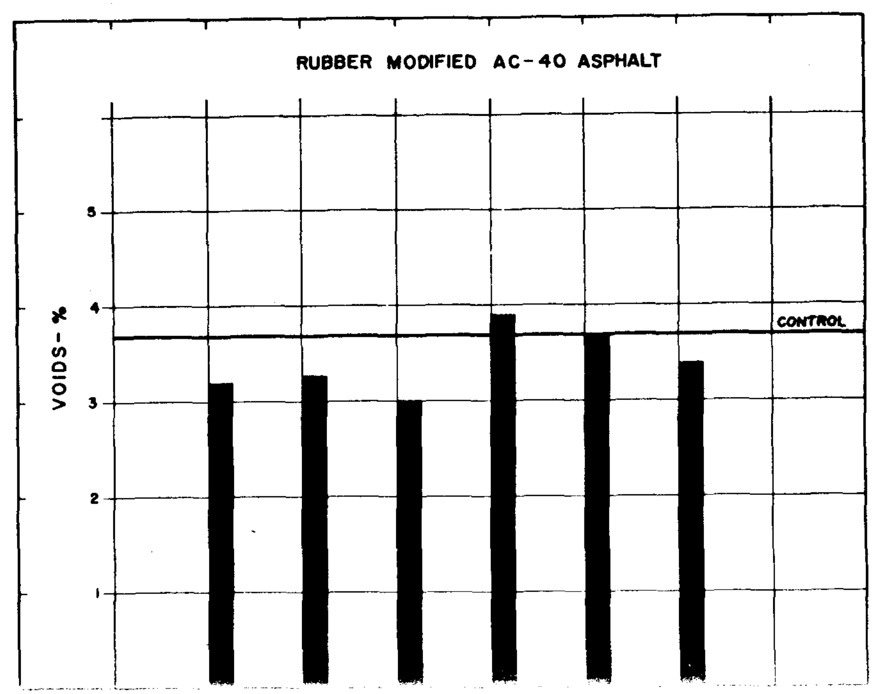


FIGURE 19B

AVERAGE RESULTANT MIX PROPERTIES WITH AC-40 AS BINDER

ORIGINAL CEMENT LEVEL OF 5.0%

VERSUS

RUBBER MODIFIED CEMENT LEVEL OF 5.5%