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STATE DEPARTMENT
OF HIGHWAYS AND
PUBLIC TRANSPORTATION

COOPERATIVE
RESEARCH

ASPHALT-RUBBER BINDER LABORATORY PERFORMANCE

in cooperation with the
Department of Transportation
Federal Highway Administration

RESEARCH REPORT 347-1F
STUDY 2-9-83-347
ASPHALT-RUBBER BINDERS

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16. Abstract

Three experimental test roads containing asphalt-rubber interlayers were constructed. Test pavements were designed as statistical experiments such that future performance analysis could be obtained. Precondition surveys were conducted prior to rehabilitation to provide documentation for future condition surveys.

Samples of asphalt-rubber were obtained during field mixing of asphalt and rubber for laboratory characterization. Samples of asphalt and rubber were obtained for mixing in the laboratory. A comparison was made between laboratory test results of field and laboratory prepared asphalt-rubber.

Three new laboratory tests were used to evaluate asphalt-rubber engineering properties. These included force ductility, double ball softening point, and torque fork viscosity.

Results of these laboratory tests indicate engineering properties of field prepared asphalt-rubber can be duplicated by laboratory prepared mixtures. This means future mixtures of asphalt-rubber can be designed in the laboratory prior to construction.

Procedures are described which would allow prediction of rubber content from rotational viscosity data. Prediction of rubber content could be possible in the field by highway department personnel responsible for quality assurance.

17. Key Words
Asphalt-rubber, stress absorbing membrane interlayers, seal coats factorial design, Latin square design

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Asphalt-Rubber Binder Laboratory Performance

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State Department of
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with the
United States Department of Transportation
Federal Highway Administration

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August, 1985

OBJECTIVES

This project was intended to design and supervise construction of three experimental test roads containing asphalt-rubber as interlayer binders. Control sections were included. Asphalt-rubber was obtained from each test road as prepared in the field. Asphalt-rubber was also fabricated in the laboratory. Properties of asphalt-rubber prepared under both conditions were determined by force ductility, double ball softening point, and rotational viscosity.

Future correlation of laboratory properties and field performance should be possible due to extensive precondition surveys conducted at each test road.

DISCLAIMER

ABSTRACT

Three experimental test roads containing asphalt-rubber interlayers were constructed. Test pavements were designed as statistical experiments such that future performance analysis could be obtained. Precondition surveys were conducted prior to rehabilitation to provide documentation for future condition surveys.

Samples of asphalt-rubber were obtained during field mixing of asphalt and rubber for laboratory characterization. Samples of asphalt and rubber were obtained for mixing in the laboratory. A comparison was made between laboratory test results of field and laboratory prepared asphalt-rubber.

Three new laboratory tests were used to evaluate asphalt-rubber engineering properties. These included force ductility, double ball softening point, and torque fork viscosity.

Results of these laboratory tests indicate engineering properties of field prepared asphalt-rubber can be duplicated by laboratory prepared mixtures. This means future mixtures of asphalt-rubber can be designed in the laboratory prior to construction.

Procedures are described which would allow prediction of rubber content from rotational viscosity data. Prediction of rubber content could be possible in the field by highway department personnel responsible for quality assurance.

Keywords: asphalt-rubber, stress absorbing membrane interlayers, seal coats, force ductility, Latin Square design, factorial design.

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SUMMARY

Test roads were constructed near El Paso, Buffalo and Brownsville. All test roads were designed as statistical experiments such that future analysis of effects due to asphalt-rubber formulation could be determined. Asphalt-rubber was formulated using various rubber concentrations, rubber types, digestion conditions, and interlayers were applied at various binder application rates. In addition, aggregate grade was varied at Brownsville, and single and double binder applications were studied.

Laboratory evaluation of binder properties provides a basis for future correlation between laboratory and field performance.

IMPLEMENTATION STATEMENT

Laboratory test results obtained in this study by four new or modified test procedures should provide information necessary to develop a state specification for asphalt-rubber based on performance. However, until field performance is established, it will be difficult to establish specification requirements based on laboratory test results.

However, observations and tests made in the field during construction of the three test roads, along with experience gained on previous and concurrent asphalt-rubber research, allowed preparation of a modified seal coat design procedure recommended for construction of asphalt-rubber seal coats and interlayers. Also, an updated specification is included which is recommended for future asphalt-rubber construction.

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CHAPTER I

INTRODUCTION

History

Ground tire rubber has been used as an additive in various types of asphalt pavement construction in recent years. The use of rubber is an attempt to input additional elasticity to paving materials.

A blend of paving asphalt cement and ground tire rubber is called "asphalt-rubber". Rubber content of this blend is 18 to 26 percent by total weight of the blend (1). The blend is formulated at elevated temperature to promote chemical and physical bonding of the two components. Various petroleum distillates are sometimes added to the blend to reduce viscosity and promote workability.

Asphalt-rubber binders have been used in a number of Civil Engineering applications, including chip seals, interlayers and asphalt concrete. An asphalt-rubber seal coat sandwiched between an existing cracked asphalt concrete pavement and new asphalt concrete overlay is called an asphalt-rubber "interlayer" (2). Observations of field installations of over two hundred separate pavement sections containing asphalt-rubber have indicated that asphalt-rubber bound materials reduce the occurrence of reflection cracking when used as interlayers in certain applications (1).

Asphalt-rubber has been used in pavement rehabilitation systems where reduction of reflection cracks is desired. However, much of the asphalt-rubber use is in seal coat construction (1,4). This is due to the ability of asphalt-rubber to retain aggregate chips under relatively high traffic compared with conventional binders. The good chip retention is due to higher allowable initial embedment of aggregate chips. Higher initial embedment is possible because of the relatively high viscosity of asphalt-rubber binders compared with conventional binders. These high embedment depths and corresponding high binder application rates also aid in waterproofing substrate pavement layers which also aides in prolonging pavement service life.

Historically, the design and construction of asphalt-rubber seal coats and interlayers has been identical, although recent research suggests modifications of old techniques are justified (3).

Past construction techniques for seal coats and interlayers specified the quantity of asphalt-rubber binder with little regard for materials properties of the mineral aggregates to be used. Field surveys conducted throughout the United States (1), and in Texas (4), indicate performance of asphalt-rubber seal coats and interlayers could be improved by following an engineering design procedure. The design procedure is an adaptation of an existing procedure developed for conventional seal coats (26) with provision for higher initial aggregate embedment. These studies (1,4) show that although reflection cracking is reduced in some pavements, it may be at the expense of increased flushing that this desirable cracking performance is achieved. These researchers believe engineering design of these systems will help balance performance between flushing and cracking. Many types of asphalt-rubber formulations are possible due to a wide assortment of constituents available. Evidence suggests certain asphalt-rubber blends may produce undesirable results in the laboratory (5). Although some data are available regarding performance of asphalt-rubber in the laboratory (5,6,7,8,9) a correlation between laboratory data and field performance has not been developed.

Scope

The purpose of this research was to design and construct three field test pavements containing asphalt-rubber interlayers. Pavement condition surveys conducted prior to interlayer construction provide data regarding initial pavement condition. These data establish a datum which will allow future comparison of field performance for the various types of interlayer blends placed at each test road.

Laboratory tests were performed on blends of asphalt-rubber prepared in the field as well as blends prepared in the laboratory. These data form the basis for future correlations between laboratory properties and field performance.

Three field test pavements were constructed as part of this research. One test pavement was constructed in the east and westbound travel lanes on Interstate Highway 10 east of El Paso, Texas for approximately nine miles between FM 34 and the McNary interchange. This pavement will be referred to as the "El Paso Test Road".

The second test pavement was constructed in the northbound travel lane of Interstate Highway 45 from the Leon-Freestone County Line north to the U.S. 84 overpass, a distance of approximately eighteen miles. This pavement will be referred to as the "Buffalo Test Road".

Test road number three was constructed in the north and southbound lanes of State Highway 4 from the International Bridge north approximately two miles. This pavement will be referred to as the "Brownsville Test Road".

CHAPTER II

MATERIALS

El Paso Test Road

Asphalt cements used in the preparation of asphalt-rubber binders and asphalt concrete was obtained from the Chevron refinery in El Paso, Texas. These asphalts meet the Texas State Department of Highways and Public Transportation (SDHPT) specification (12) requirements for AC-10 and AC-20 viscosity graded materials as shown in Table 1.

Three sources of rubber were used to produce asphalt-rubber binders investigated at the El Paso Road. These rubber materials were obtained from the suppliers shown in Table 2. Sieve analysis of rubber was accomplished following a modified ASTM C136 procedure (10). The procedure was changed by lightly rubbing the rubber particles by hand on each sieve to prevent rebound from the sieve surface. Undue force was not applied using this procedure to avoid pushing particles through the sieve.

It was desired to estimate the precision of the modified sieve analysis procedure. Therefore, ten random sieve analyses were performed by the same operator on each of the three rubber types. The percent rubber passing each sieve was measured and confidence intervals have been established for gradation of each rubber type based on average and standard deiration for percent passing each sieve size. Gradations with 95 percent confidence limits appear in Table 3. Average gradation for each rubber type is plotted in Figure 1. Further characterization of each rubber type following ASTM procedure D297 (11) provides data relating to physical and chemical properties as shown in Table 4.

Dolomite mineral aggregates used for construction of interlayer and asphalt concrete were obtained from the Esperanza Pit, Esperanza, Texas. Interlayer aggregates were precoated with approximately one percent Chevron AC-20 and stockpiled prior to application.

Table 1. Asphalt Cement Properties.

Properties	AC-10					AC-20				
	Asphalt			Spec		Asphalt			Spec	
	El Paso	Buffalo	Brownsville	Min.	Max.	El Paso	Buffalo	Brownsville	Min.	Max.
Viscosity, 140F poises	1048	868	930	1000±200		1860	1755	1792	2000±400	
Viscosity, 275F stokes	2.9	2.8	2.9	1.9	-	3.8	3.5	3.7	2.5	-
Penetration, 77F, 100g, 5 sec	92	150	136	85	-	69	70	88	55	-
Flash Point C.O.C., F	600+	N/A	530	450	-	600+	595	582	450	-
Specific Gravity, 77F	1.010	1.017	1.022	N/A		1.012	1.013	1.024	N/A	
Tests on residues from thin film oven test:										
Viscosity, 140F poises	2257	2445	2228	-	3000	4146	4485	3431	-	6000
Ductility, 77F, 5 cms per min., cms	141+	141+	141+	70	-	141+	141+	141+	50	-

Table 2. Rubber Types.

Rubber	Source	Source Designation	Manufacturers Designation
El Paso Test Road			
A	Genstar Conservation Chandler, Arizona	C104	Whole Tire, Vulcanized, Ambient Grind
B	Atlos Manufacturing Los Angeles, CA	TPO 44	Tread Tire, Vulcanized, Ambient Grind
C	Midwest Elastomers Wapokonetta, Ohio	N/A	Whole Tire, Vulcanized, Cryogenic Grind
Buffalo/Brownsville Test Roads			
D	Genstar Conservation, Chandler, Arizona	C106	Whole Tire, Vulcanized Ambient Grind
E	Baker Rubber, South Bend, Indiana	1MAT-20	High Natural Rubber Content, Vulcanized, Ambient Grind

Table 3. El Paso Rubber Gradations.

	Percent Passing		
Sieve	Rubber A	Rubber B	Rubber C
No. 8	100	100	100
No. 10	100	100	99 ± 0.5
No. 16	65 ± 5.6	38 ± 2.1	67 ± 3.9
No. 30	2 ± 0.3	8 ± 0.6	8 ± 1.1
No. 40	0.5 ± 0.4	4 ± 0.4	3 ± 0.9
No. 50	0	3 ± 0.4	1 ± 0.6
No. 100		0.4 ± 0.5	0.2 ± 0.4
No. 200		0	0

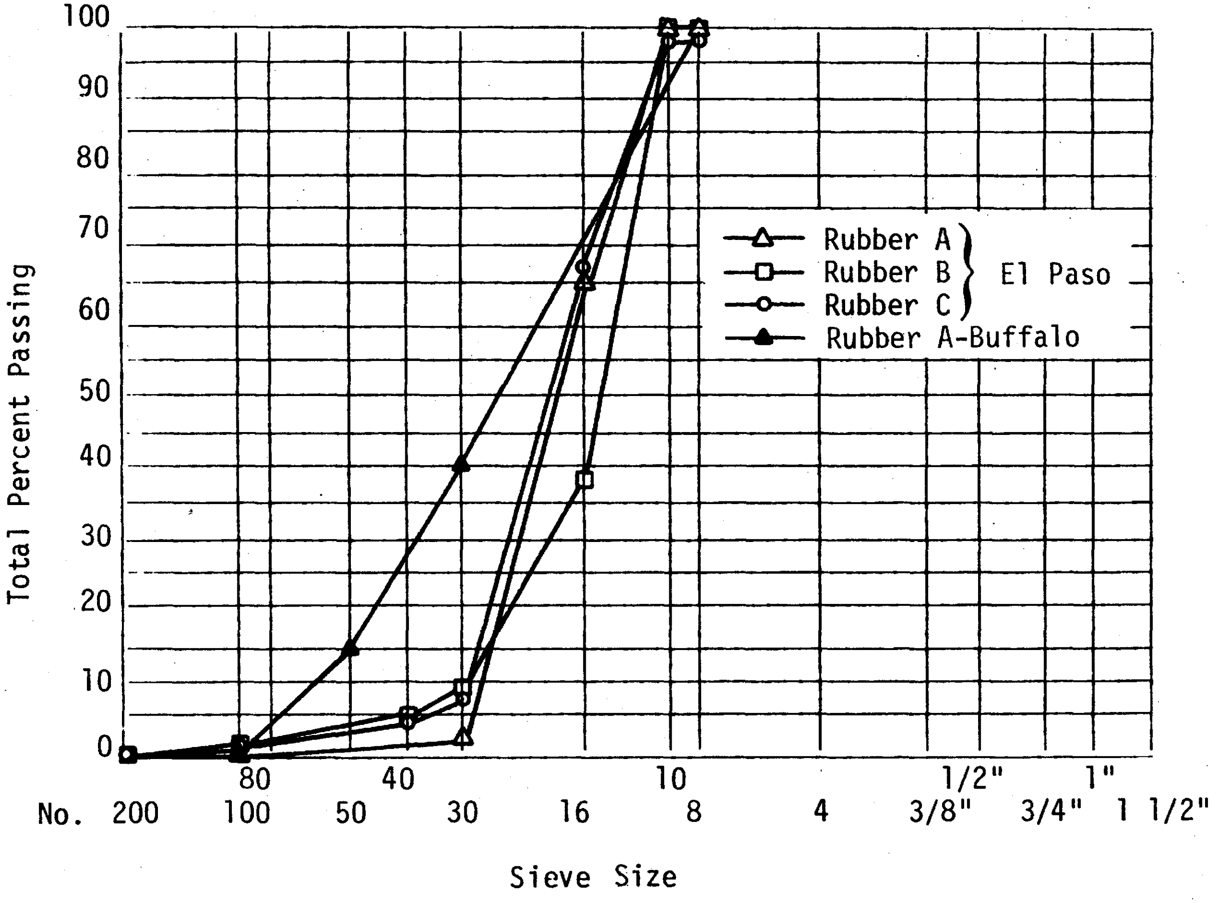


Figure 1. Rubber Gradations

Table 4. Rubber Properties.

	El Paso		
	D	D/E	D/E
Specific Gravity	1.165	1.153	1.150
Total Extract, % by weight	15.45	19.47	24.50
Ash, % by weight	5.71	3.49	2.41
Free Carbon, % by weight	29.21	30.75	31.31
Total Sulfur, % by weight	1.17	1.02	1.10
Rubber Polymer:			
Natural Rubber, % by weight	30	20	0
Styene butadiene, % by weight	60	80	55
Polybutadiene, % by weight	10	0	45
	------	------	------
	100	100	100
Rubber Hydrocarbon, % by volume	60.92	55.89	50.76

Table 4. Rubber Properties. (Continued)

	Buffalo		Brownsville
	D	D/E*	D/E*
Specific Gravity	1.160	1.48	1.15
Total Extract, % by weight	15.41	12.75	13.27
Ash, % by weight	5.68	4.86	5.03
Free Carbon, % by weight	29.00	28.35	28.53
Total Sulfur, % by weight	1.15	1.17	1.18
Rubber Polymer:			
Natural Rubber, % by weight	30	61	54
Styene butadiene, % by weight	60	35	40
Polybutadiene, % by weight	10	4	6
	100	100	100
Rubber Hydrocarbon, % by volume	61.02	58.46	58.95

*Combination of Rubber Types D&E as shown in Table 2.

Particle size gradations of interlayer and asphalt concrete aggregates appear in Figure 2. Both materials conform to Texas SDHPT Item 302 Grade 4 and Item 340 Type D specification limits, respectively. Physical properties of mineral aggregates conform to Texas SDHPT specifications as shown in Table 5.

Samples of the asphalt concrete overlay were obtained by coring each test section approximately two weeks after construction. Characteristics of the overlay asphalt concrete are as shown in Table 6. Figure 3 indicates the variation of asphalt concrete resilient modulus with temperature.

Buffalo Test Road

Asphalt used for asphalt-rubber blending was an AC-10 asphalt cement supplied by Texas Fuel and Asphalt, Corpus Christi, Texas. Asphalt for asphalt concrete production was an AC-20 asphalt cement supplied by Trumbull Asphalt of Houston, Texas. These asphalts meet the Texas SDHPT specification requirements for AC-10 and AC-20 viscosity graded materials as shown in Table 1. A flux oil, Sundex 790, from Sun Oil Corporation, Houston, Texas, was blended with the AC-10 asphalt prior to blending with rubber.

One rubber source was used to produce the asphalt-rubber placed on the Buffalo Test Road. This material is described as Rubber A Designation C106 in Table 2. This rubber has the same chemical properties as Rubber Type A Designation C104 used at the El Paso Test Road. However, particle size gradation differs. Sieve analysis of the rubber is shown in Figure 1. Note the finer size gradation of the Buffalo Type A rubber compared with El Paso Type A.

Limestone mineral aggregates used for construction of interlayer and asphalt concrete were obtained from the Yelberton Pit near Mexia, Texas. Interlayer aggregates were precoated with approximately 0.50 percent AC-20 immediately prior to application.

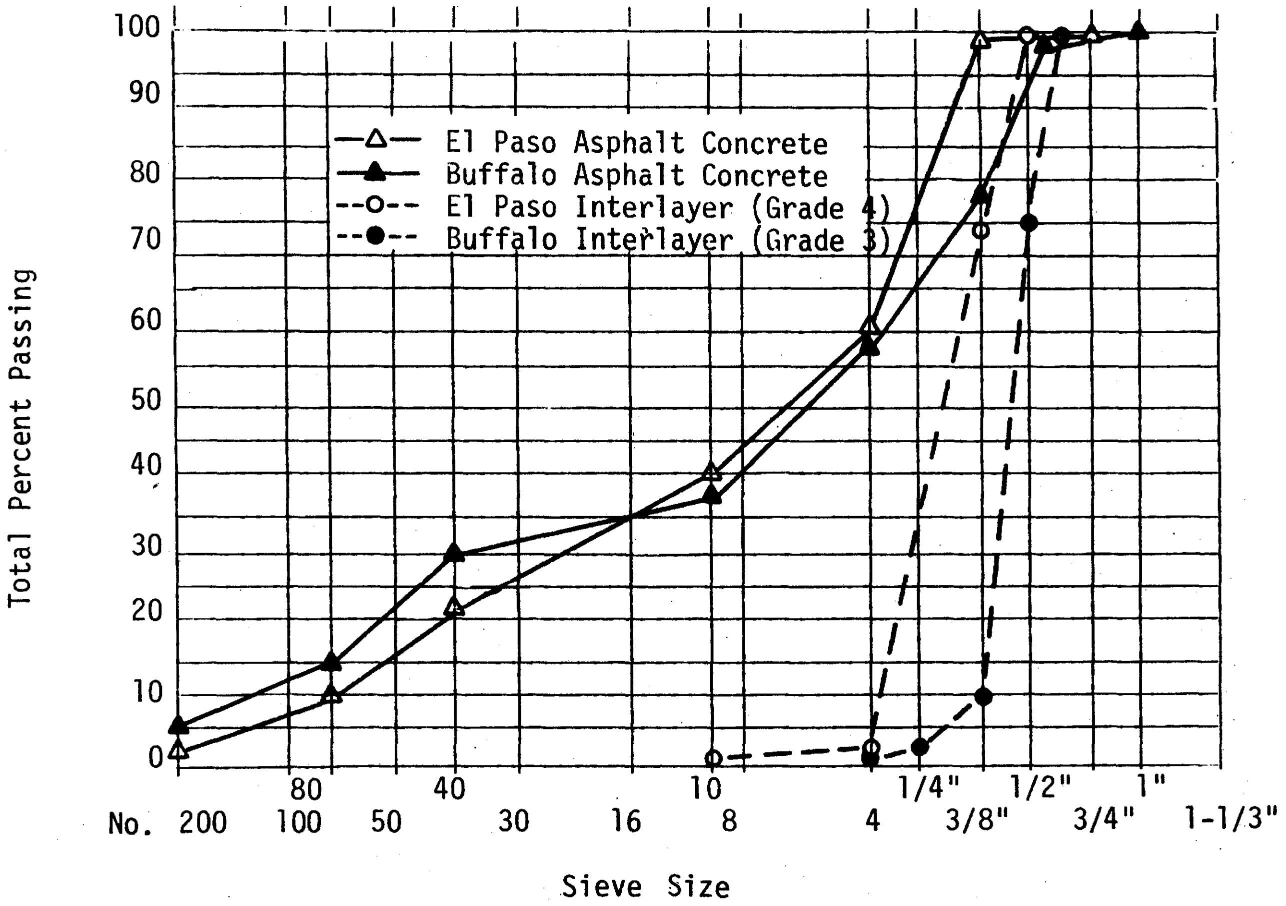


Figure 2. Aggregate Gradations

Table 5. Mineral Aggregate Properties

	Seal Coat				Asphalt Concrete			
Test	El Paso Grade 4	Buffalo Grade 3	Brownsville Grades 3 & 4	Spec (12)	El Paso Type D	Buffalo Type C	Brownsville Type D	Spec (12)
Unit Weight,pcf Tex-404A	84.6	81.5	N/A	N/A	91.4	85.2	N/A	35, min
L. A. Abrasion,% Tex-410A	21	33	N/A	35, max	21	33	N/A	40, max
Polish Value,% Tex-438A	35	45	N/A	N/A	35	45	N/A	N/A
Decant.,% Tex-217F,II	0.4	0.8	.3	5, max	0.8	0.8	0.5	1, max
Plasticity Index Tex-106E	N/A	N/A	N/A	N/A	3	1	1.5	6, max
Sand Equivalent	N/A	N/A		N/A	N/A	N/A	60	45, min

Table 6. Asphalt Concrete Properties.

	El Paso	Buffalo	Brownsville
Hveem Stability (Texas Method)	33	19	46
Indirect Tensile Modulus, 77F, psi x 10^3	34.9	11.8	10.4
Indirect Tensile Modulus after Lottman Freeze-Thaw, 77F, psi x 10^3	30.2	12.0	12.4
Resilient Modulus, 77F, psi x 10^3	328	266	137
Resilient Modulus after Lottman Freeze-Thaw, psi x 10^3	242	188	155
Asphalt Content, % by weight	5.0	4.9	5.4
Unit Weight, pcf	144.7	139.5	136.9
Absorbed Asphalt, %	1.1	0.9	N/A
Effective Asphalt, %	3.9	4.0	N/A
VMA, %	14.6	19.6	N/A
Air Voids, %	5.5	9.2	9.4

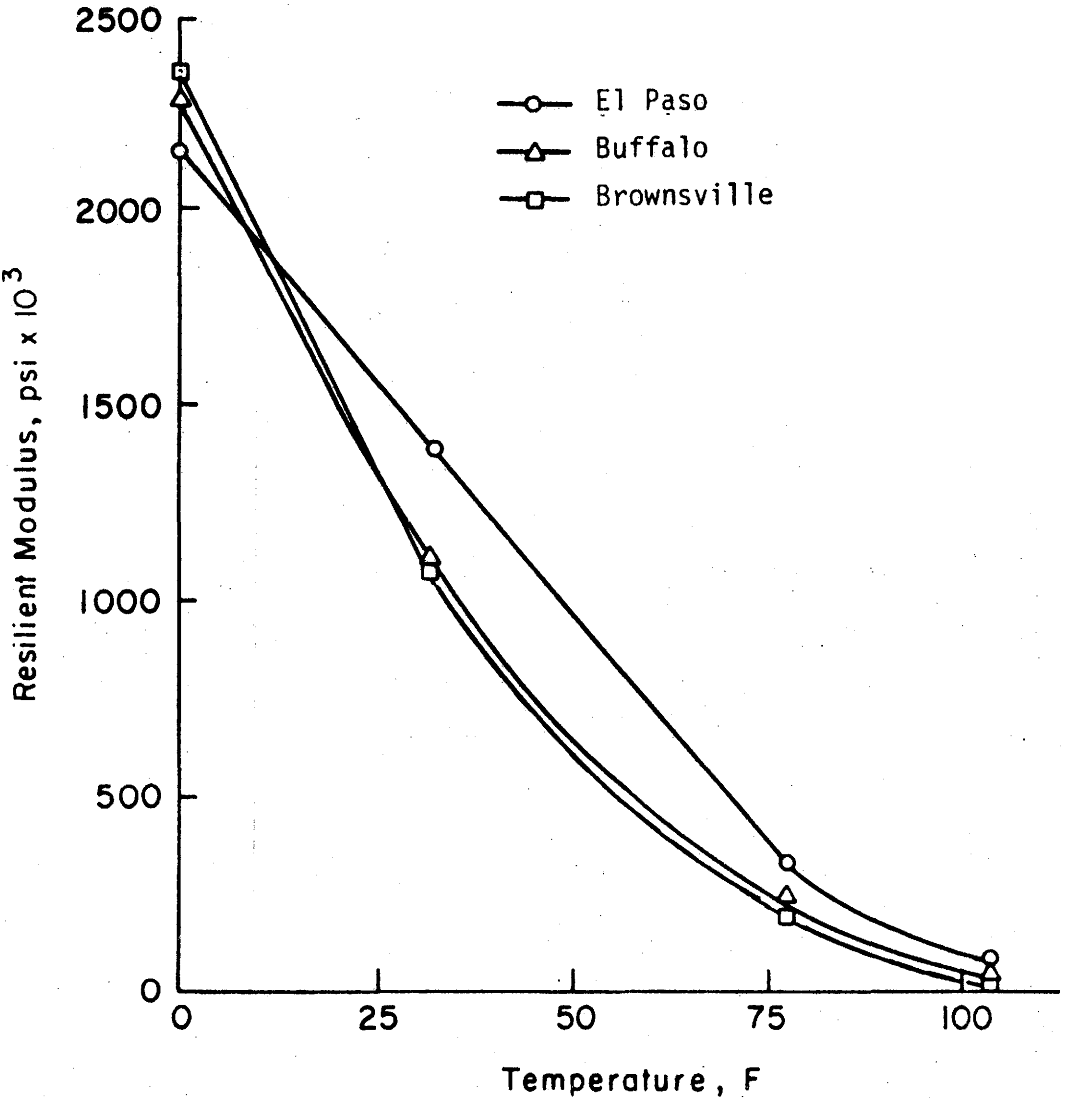


Figure 3. Asphalt Concrete Resilient Modulus

Particle size gradations of aggregates are shown in Figure 2. Materials conform to Texas SDHPT Grade 3 Item 302 seal coat and Type C Item 340 asphalt concrete specification limits, respectively, as shown in Table 4. Physical properties of the limestone are shown in Table 5.

Core samples of the asphalt concrete overlay were obtained within each test section approximately two weeks after construction. Laboratory properties of the asphalt concrete are summarized in Table 6 and represented graphically in Figure 3.

Brownsville Test Road

Asphalt used for asphalt-rubber blending was an AC-10 from Texas Fueld and Asphalt, Corpus Christi, Texas. An AC-20 was obtained from the same source for asphalt concrete production. These asphalts meet Texas SDHPT specification requirements as shown in Table 1. Sundex 790 from Sun Oil Corporation was blended with the AC-10 asphalt at 6 percent by volume. Control sections were placed with non-modified AC-10 and polymer modified emulsion, designated HFRS-2, from Texas Emulsions, Austin, Texas.

The rubber used to produce the asphalt-rubber was a blend of 60 percent Type A and 40 percent Type B as shown in Table 2. Properties of the blended rubber appear in Table 4. Sieve analysis of this rubber blend appears in Figure 1.

Mineral aggregates for asphalt concrete were obtained from the San Juan Plant. Seal coat aggregates were sampled from the Fordyce Company, Spaulding Pit. Approximately 1 percent lime from Redland Worth Corporation was added to the asphalt concrete.

Particle size gradation of aggregates appear in Figure 2. Asphalt concrete aggregates conform to Texas SDHPT Type D, and interlayer aggregates conform to Grades 3A and 4, respectively. Physical properties of aggregates appear in Table 5.

Laboratory properties of core samples obtained by District 21 personnel appear in Table 6 and Figure 3.

CHAPTER III

EXPERIMENT DESIGN

The following discussion relates to the statistical design of two experimental test roads. Subscripts within the mathematical models are associated with main factors and replicates.

A major portion of this research was dedicated to establishing statistically designed field and laboratory experiments which could form the basis for future correlations between field performance and laboratory test results.

El Paso Test Road - Field Responses

This experiment was designed as a Latin Square (21) with three samples per treatment. The statistical model for the analysis of this design is formulated as follows:

$$Y_{ijk} = \mu + R_i + C_j + A_k + e_{ijk}$$

where:

Y_{ijk} = response to ith rubber, jth concentration and kth application rate.

μ = effect on response of the overall mean

R_i = effect on response of the ith rubber, $i = 1,2,3$

C_j = effect on response of the jth concentration, $j = 1,2,3$

A_k = effect on response of the kth application rate, $k = 1,2,3$

e_{ijk} = random error

Note: This Latin Square was designed without replication. Therefore, estimation of interaction effects is not possible as the model above reflects. As a first approximation, this experiment estimates main factor effects only, and assumes no interactions.

Levels of the independent variables are as follows:

- I. Rubber Type, R_i
  - A. Type A (Table 2)
  - B. Type B (Table 2)
  - C. Type C (Table 2)
- II. Rubber Concentration, %, C_j
  - A. 22
  - B. 24
  - C. 26
- III. Application Rate, gsy, A_k
  - A. 0.35
  - B. 0.40
  - C. 0.45

The matrix arrangement shown in Figure 4 depicts all combinations of variables investigated for field response at the El Paso Test Road.

El Paso Test Road - Laboratory Responses

Two experiments were designed for this phase of the research. One deals with asphalt-rubber material prepared in the field and the other deals with asphalt-rubber prepared in the laboratory. Both experiments are full factorial designs with fixed factors and three replicates.

Models for analysis of these respective experiment designs are as follows:

Field Mixed Asphalt-Rubber

$$Y_{ijk} = \mu + R_i + C_j + RC_{ij} + e_{ijk}$$

where terms are as indicated previously and RC_{ij} represents the interaction effect of the ith rubber and jth concentration. A

		Rubber Concentration, C_j		
		22	24	26
Application Rate, A_k	0.35	C Section 2	B Section 9	A Section 8
	0.40	B Section 4	A Section 1	C Section 6
	0.45	A Section 5	C Section 7	B Section 3

Rubber Type, R_i

Control
(No Interlayer)

Section 10

Figure 4. El Paso Field Response Experiment

matrix representation is shown in Figure 5.

Laboratory Mixed Asphalt-Rubber

$$Y_{ijkm} = \mu + R_i + C_j + D_k + RC_{ij} + RD_{ik} + CD_{jk} + RCK_{ijk} + e_{ijkm}$$

where:

D_k = effect on response of the k_{th} digestion condition, k = 1,2,3

and other terms are as before with interactions occurring for all combinations of main effects. Figure 6 is a matrix representation of this experiment.

Three digestion conditions were produced in the laboratory. These digestion conditions were varied from low to moderate to high to provide a range from which simulation of field digestion could be approximated. The basis for this lab variation was an effort to provide asphalt-rubber lab mixes with properties of field prepared mixes.

Buffalo Test Road - Field Responses

This experiment was designed as a full factorial with two fixed factors and two replications. The model for analysis of this design is as follows:

$$Y_{ijk} = \mu + C_i + D_j + CD_{ij} + e_{ijk}$$

where terms are as before.

Levels of the independent variables are as follows:

I. Concentration of Rubber, C_i

A. 18

		Rubber, R_i		
		A	B	C
Concentration, C_j	22	— — —	— — —	— — —
	24	— — —	— — —	— — —
	26	— — —	— — —	— — —

Figure 5. El Paso Laboratory Response to Field Mixed Material

Rubber, R_i	A			B			C		
Concentration, C_j / Digestion, D_k	22	24	26	22	24	26	22	24	26
Low	— — —	— — —	— — —	— — —	— — —	— — —	— — —	— — —	— — —
Med	— — —	— — —	— — —	— — —	— — —	— — —	— — —	— — —	— — —
High	— — —	— — —	— — —	— — —	— — —	— — —	— — —	— — —	— — —

Figure 6. El Paso Laboratory Response to Laboratory Mixed Material

B. 22

II. Digestion, D_j

A. Low

B. High

In this experiment, rubber type and application rate are held constant. The resulting four treatments are replicated providing eight experimental test sections. Four additional test sections were included as control sections. Two sections were constructed using a conventional asphalt cement as the interlayer binder and the other two sections contain no interlayer.

Buffalo Test Road - Laboratory Responses

This experiment was designed to evaluate laboratory responses of field mixed and laboratory mixed asphalt-rubber materials as in the El Paso experiment. The experiment is a replicated, full factorial with fixed factors analyzed according to the model appearing below:

$$Y_{ijk} = \mu + C_i + D_j + CD_{ij} + e_{ijk}$$

where terms are as previously described. The matrix representation of the field and laboratory experiments for this model appear as shown in Figures 7 and 8.

The model used for analysis of the laboratory response to field prepared asphalt-rubber is shown below:

$$Y_{ijk\ell} = \mu + C_i + D_j + R_k + CD_{ij} + CR_{ik} + DR_{ik} + CDR_{ijk} + \varepsilon_{ijk\ell}$$

where terms are as previously described and,

		Concentration, %	
		18	22
Digestion, D_j	High	1 8	7 12
	Low	9 11	6 10

Controls (AC Binder)
2 5

(No Interlayers)
3 4

Note: Numbers shown are test section numbers noted on Figure 13.

Figure 7. Buffalo Field Response Experiment.

		Concentration, %	
		18	22
Digestion	Low	- - -	- - -
	Med	- - -	- - -
	High	- - -	- - -

Figure 8. Buffalo Laboratory Response to Laboratory Mixed Material

R_k = effect on response to k^{th} field replicate, k = 1,2

This third main effect is added to the model such that judgement regarding replicate batches of field mixed asphalt-rubber is possible. Matrix representation of this experiment is as shown in Figure 9. Field replicates of each treatment were fabricated to judge variability within each material type. For example, test sections 1 and 8 represent two separate batches, or truck loads, of High Digestion, 18 percent, asphalt-rubber. These replicates will allow future comparison of field performance within a given treatment such that variability can be judged between treatment types. In this study, it was desired to see whether laboratory responses differed significantly for replicate materials fabricated in supposedly the same manner.

Brownsville Test Road - Field Responses

The Brownsville Test Road was designed to evaluate field performance of two aggregate grades in single and double applications as interlayers. Asphalt-rubber formulation was not varied in this experiment. Control sections are composed of interlayer binders of polymer modified asphalt and conventional asphalt cement.

All combinations of interlayers applied at the Brownsville Test Road are described in the following table:

Binder Application	Binder Type	Top Aggregate Grade	Bottom Aggregate Grade
Single	A-R	3	N/A
Single	A-R	4	N/A
Single*	A-R	4	4
Double	A-R	3	3
Double	A-R	4	3
Double	A-R	4	4
Double	AC	4	3
Double	Polymer	4	4

*Grade 4 aggregate was applied two layers deep in one application over one application of binder.

Brownsville Test Road - Laboratory Response

The asphalt-rubber binder at Brownsville Test Road is composed of the same asphalt and rubber as Buffalo Test Road for the Genstar/Baker blend except Brownsville contains a 60:40 ratio of Genstar to Baker compared with a 50:50 ratio at Buffalo.

The laboratory mixes are compared for low, moderate and high digestion, similarly to El Paso and Buffalo mixes.

Field Replicate	1		2	
Concentration, %	18	22	18	22
Digestion				
Low	- - -	- - -	- - -	- - -
High	- - -	- - -	- - -	- - -

Figure 9. Buffalo Laboratory Response to Field Mixed Material

CHAPTER IV

SITE SELECTION

Location of both field test roads was accomplished in cooperation with the Texas SDHPT. A list of sites was obtained from highway districts planning asphalt-rubber interlayer construction and from this list potential test sites were selected. Criteria used to judge the adequacy of sites are listed in order of importance below:

1. Willingness of district and contractors to participate in experiment.
2. Size of project.
3. Time until next planned rehabilitation.
4. Pavement substructure uniformity.
5. Overlay thickness and uniformity.
6. Distress uniformity.

A contract had been awarded on the project which would become the El Paso Test Road when initial contact with the El Paso Highway District was made. Since significant changes in the original contract were required to accomodate the planned experiments, it was crucial that a cooperative spirit exist between highway department, contractor, and research personnel. Planning the Buffalo Test Road began before there was a contract between the highway department and a contractor. Therefore, requirements of test section construction were included in job specifications and subject to competitive bidding.

A full distributor of asphalt-rubber was desired for use in application of each test section for both test roads. This was desirable for reasons listed below:

1. A more representative blend of asphalt-rubber could be expected compared with partial loads,

2. Test section length of approximately one lane-mile resulted from approximately 4200 gallon distributor loads. These lengths provided transitions before and after the 1500 feet of photologs contained in each

test section. This further enhanced the potential for representative materials placed over photologs.

3. Production rate was not appreciably slowed. This enhanced the desired cooperative spirit between contractor and research personnel.

Project size was an important factor for both test roads since it was desired to place test sections in lanes having consistent traffic volumes and loads. Both projects were of sufficient length to accomodate approximately nine lane miles for the El Paso Test Road and over ten lane miles for the Buffalo Test Road.

El Paso Test Road

The El Paso Test Road is part of Texas Project FR-10-1(168)079 located on Interstate Highway 10 (IH-10) in Hudspeth County, approximately 80 miles east of El Paso between the McNary interchange and FM 34 as shown on Figure 10. Test sections are each approximately 0.90 mile in length in the travel lanes as shown in Figure 11.

Original pavement structure for eastbound lanes was U. S. Highway 80 consisting of a 20 foot wide portland cement concrete pavement constructed in 1932. Conversion of the original highway to the interstate system in 1963 added westbound lanes consisting of 6 inches dense graded asphalt concrete over 6 inches cement treated base and 6 inches cement treated subgrade. An overlay of original portland cement concrete pavement in 1963 consisted of 6 inches dense graded asphalt concrete in which 3 inch by 6 inch Number 10 welded wire fabric was embedded in the lower 1-1/2 inches.

Distress consisted of slight to severe transverse cracking at random intervals, and combinations of longitudial and alligator cracking distributed throughout.

Traffic on the El Paso Test Road consisted of a total traffic volume of 7900 average daily traffic (ADT) in 1983. Truck volume was

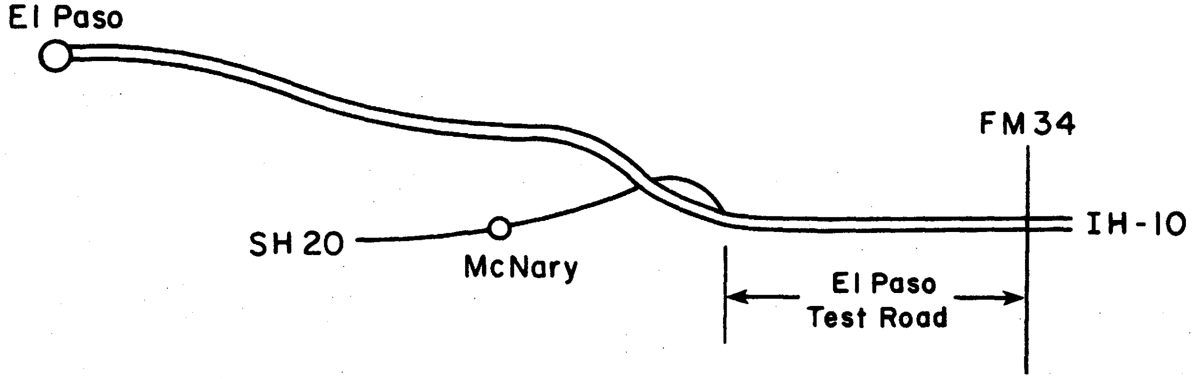


Figure 10. El Paso Test Road Location

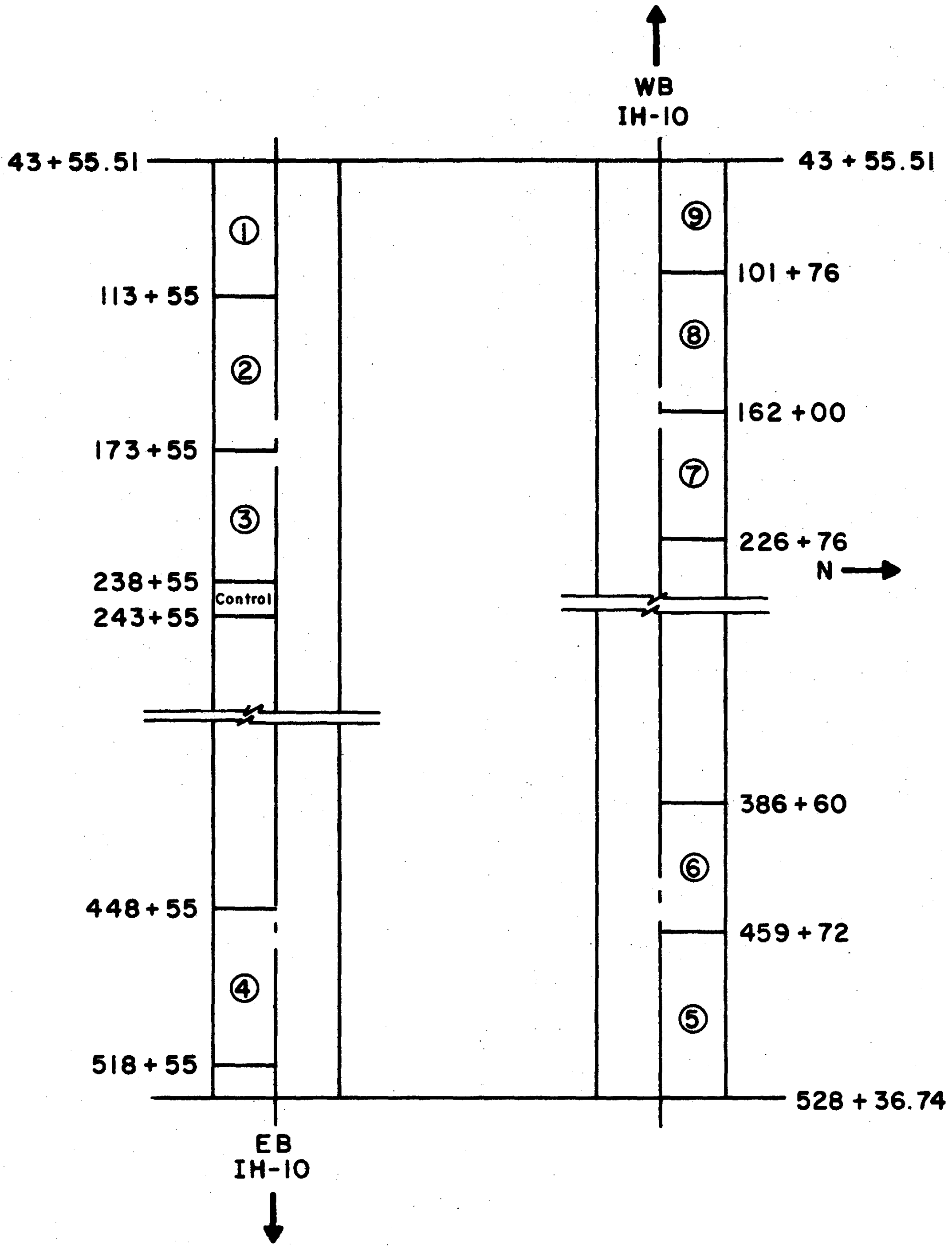


Figure 11. El Paso Test Sections

approximately 25 percent of this value with five axle semi-trucks accounting for approximately 60 percent of all trucks.

Subgrade soils on the El Paso Test Road are poorly graded sands and gravels, some containing plastic fines, classified by the Unified Soil Classification System as GP-GC and SP-SC for gravels and sands, respectively.

Buffalo Test Road

Buffalo Test Road State project designation is FRI-45-2(68)180 located on Interstate Highway 45 (IH-45) in Freestone County, from the Leon county line to US 84 as shown in Figure 12. Test sections are each approximately 0.80 mile in length in the northbound travel lane as shown in Figure 13.

The Buffalo Test Road is constructed on 8 inches of continuously reinforced concrete pavement over 4 inches of asphalt treated basecourse and 6 inches lime treated subgrade. The original pavement structure was constructed in 1971.

Distress consisted of typical hairline random transverse cracks at 3 to 6 foot intervals, and infrequent punchouts.

Traffic on the Buffalo Test Road was measured by Texas SDHPT in 1983 at approximately 15,000 ADT. The total volume of trucks is approximately 20 percent, Volume by individual truck type has not been measured in this area and is therefore, not available.

Subgrade soil types along the Buffalo Test Road alignment were obtained from recently recorded Soil Conservation Service logs (23). Classification of subgrade soils by the Unified System are as low plasticity clays and silty clays, ML-CL, along much of the alignment with some clays bordering on high plasticity.

Brownsville Test Road State project designation is MW 017(2) located on State Highway (SH4) in Cameron County from the International Bridge

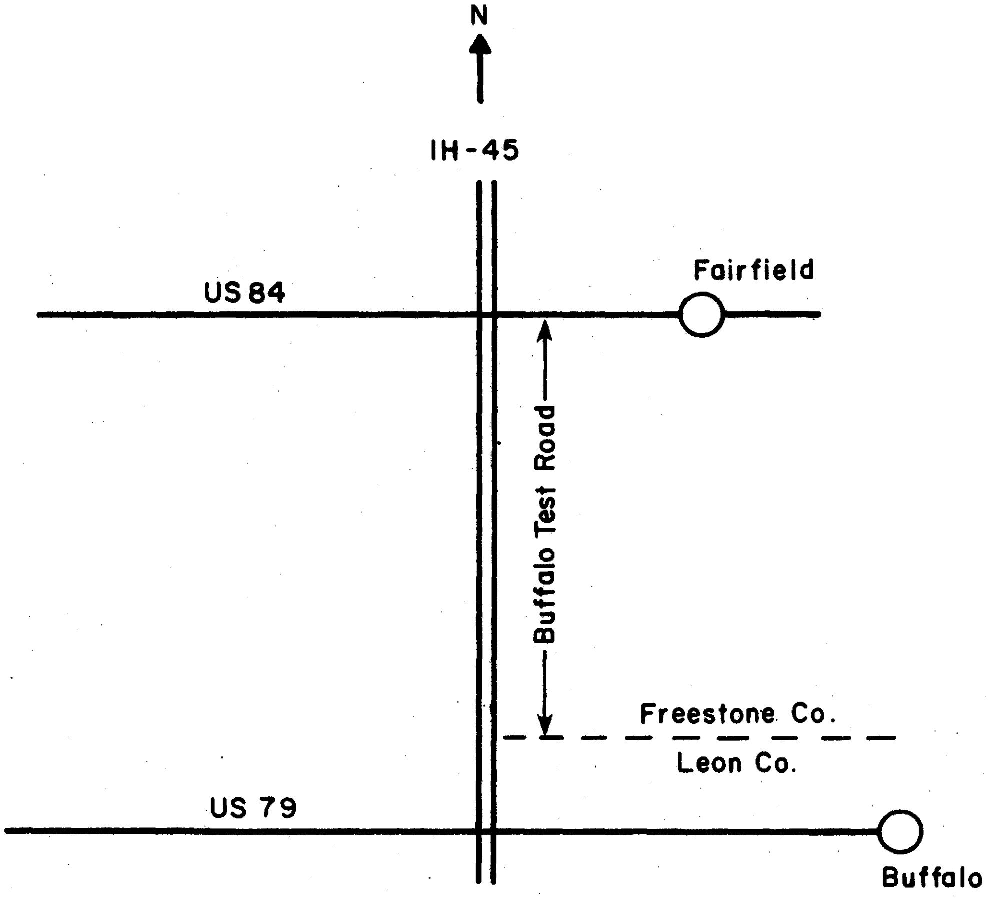


Figure 12. Buffalo Test Road Location

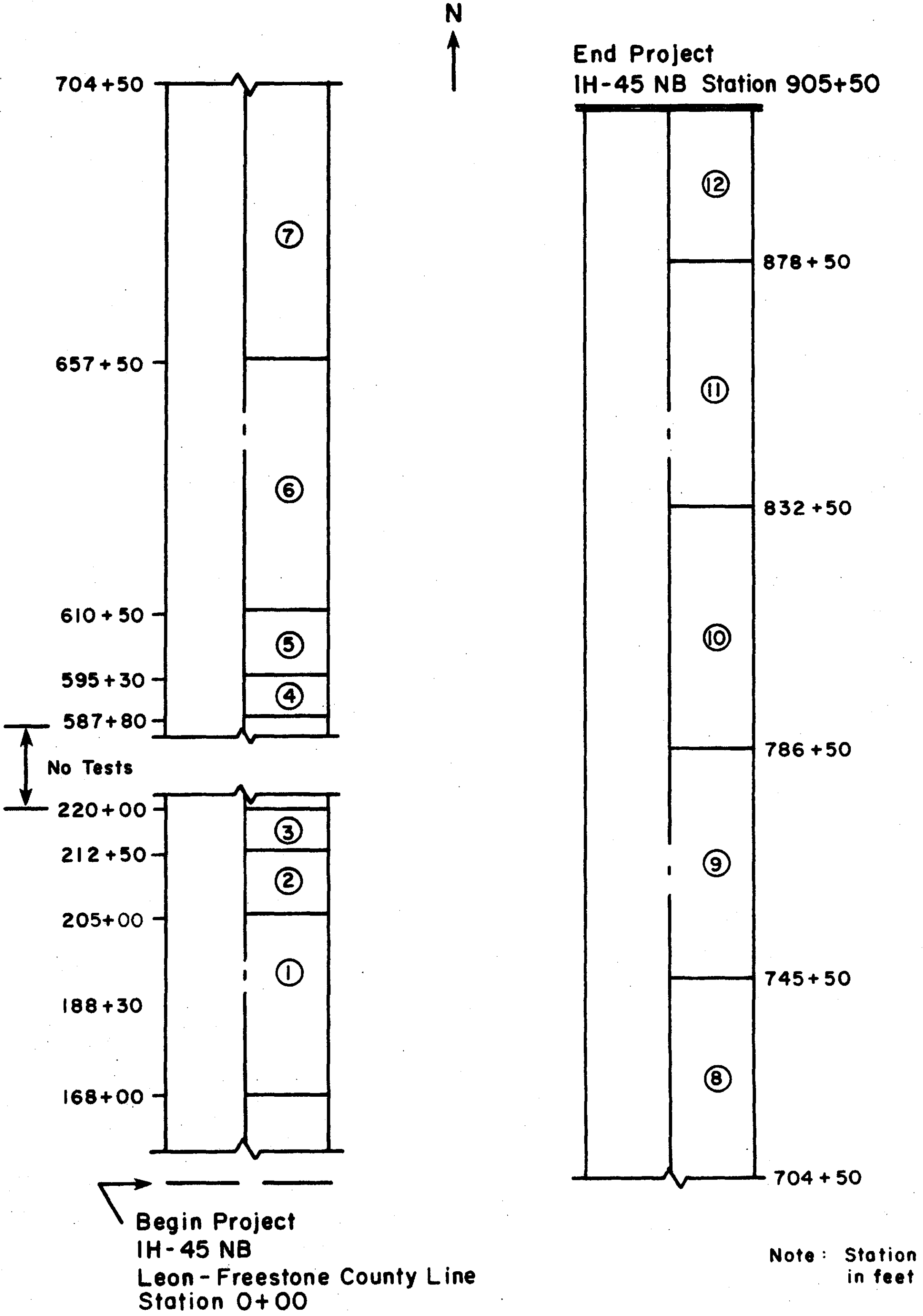


Figure 13. Buffalo Test Sections

north approximately two miles. Test sections are located in travel and passing lanes both north and southbound as shown in Figure 14.

The existing pavement structure prior to rehabilitation consisted of approximately 4 inches of asphalt concrete placed over 8 inches of crushed stone base over 8 inches of soils of ADT river sand.

Traffic on the Brownsville Test Road was measured in 1983 by Texas SDHPT at approximately 23,000 ADT.

Subgrade soil types along the Test Road alignment are clarrified as CL and ML from Station 15 + 00 to approximately 55 too. Soils become more plastic to the north, classified as CH and MH from Station 75 + 00 to 110 + 00.

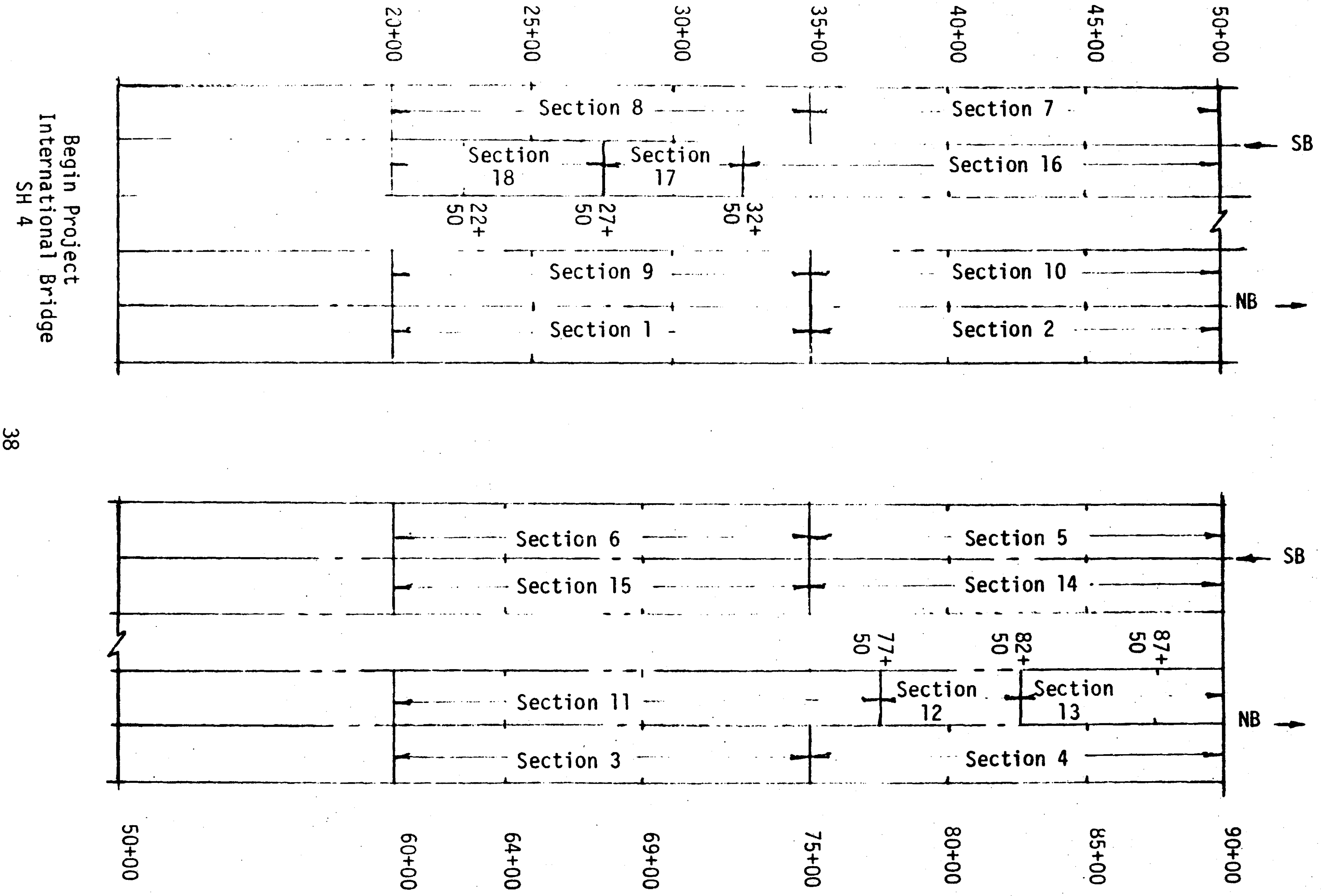


Figure 14. Brownsville Test Road - Test Section Locations

CHAPTER V

TEST ROAD CONSTRUCTION

El Paso-Preconstruction

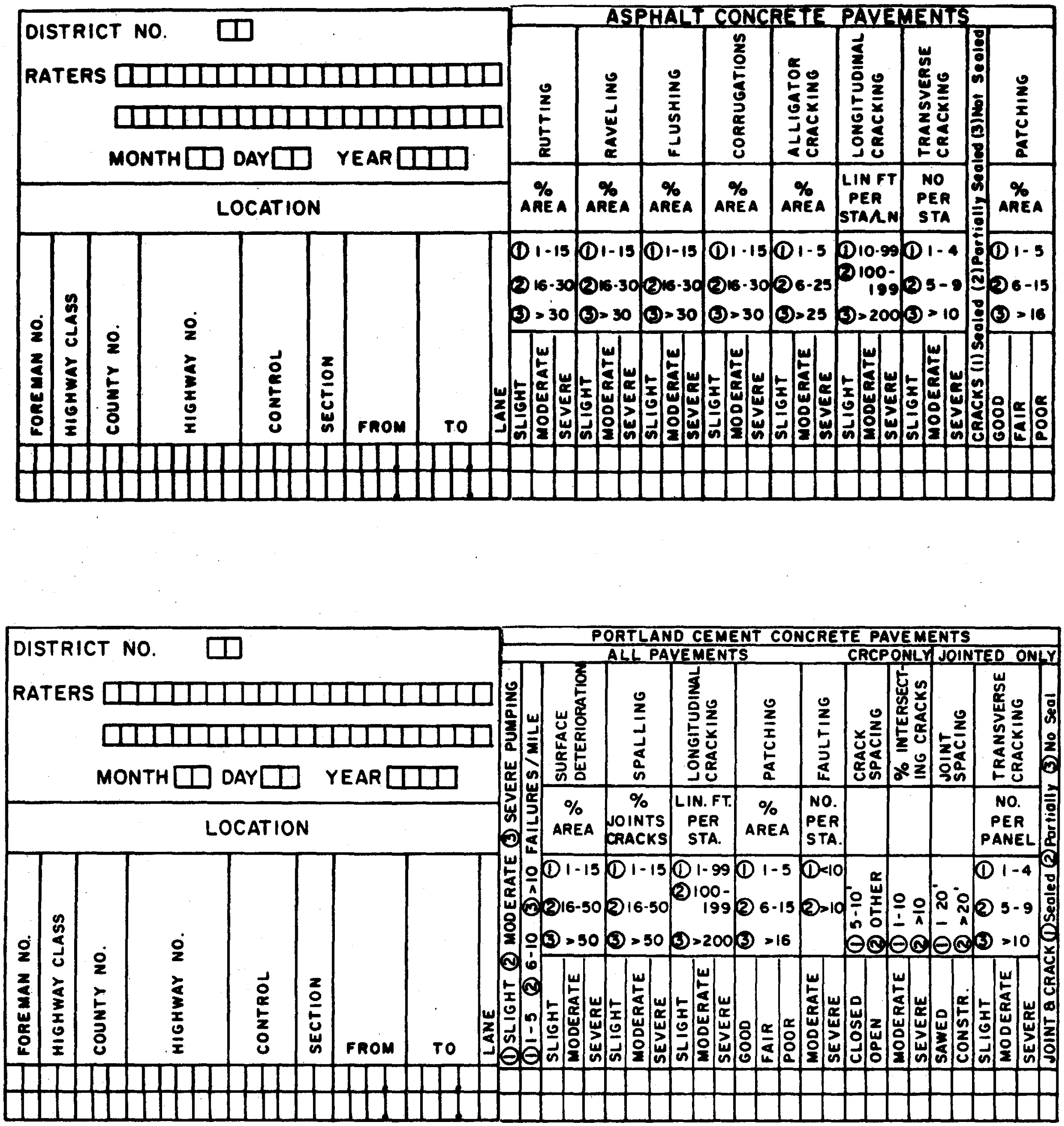
Prior to construction three segments of pavement each 500 feet in length were located within each test section. These sections were surveyed by photographing the 12 foot wide and 500 foot long pavement section prior to rehabilitation. The locations of these photolog segments within each test section are as shown in Table 7.

Photolog equipment consisted of a test vehicle equipped with a motorized 35 mm camera mounted in front of the vehicle in a vertical position over the pavement. The camera and vehicle speed were synchronized such that each photographic frame recorded pavement measuring 8 by 12 feet with a six inch overlap for adjacent segments. All photgraphs are on file at Texas Transportation Institute, College Station, Texas. Each photograph of the test sections was studied to determine the extent of distress present prior to construction. Distress types and levels of severity were recorded for each test section following the criteria described by Epps, et al. (13). Results of the photolog summary appear in Appendix A. An index of pavement condition has been described (14) which quantifies all forms and levels of pavement distress. Based on maintenance costs, this index, or Pavement Rating Score (PRS), allows numerical comparison of pavement condition. A PRS value of 100 describes a pavement with no distress. Progressively lower PRS values describe pavement condition with more severe forms of distress. The form shown in Figure 15 is used to catalog distress observed on the pavement. Deduct values are assigned to each type and level of distress according to Table 8. The sum of deduct values is subtracted from 100 resulting in the pavement ratio score (PRS).

The results of this analysis for the ten El Paso test sections appear in Table 9.

Table 7. El Paso Photolog Locations.

Test Section	Photolog	Station	
		From	To
1	1	68+65.5	73+65.5
	2	86+00	91+00
	3	104+00	109+00
2	4	136+00	141+00
	5	145+00	150+00
	6	150+00	155+00
3	7	180+00	185+00
	8	186+00	191+00
	9	191+00	196+00
4	10	485+00	490+00
	11	490+00	495+00
	12	520+00	525+00
5	13	510+00	505+00
	14	490+00	495+00
	15	480+00	475+00
6	16	460+00	455+00
	17	455+00	450+00
	18	450+00	445+00
7	19	180+00	175+00
	20	175+00	170+00
	21	170+00	165+00
8	22	120+00	115+00
	23	115+00	110+00
	24	110+00	105+00
9	25	95+00	90+00
	26	80+00	75+00
	27	75+00	70+00
Control	28	238+55	243+55



DISTRICT NO. ☐☐

RATERS ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐

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MONTH ☐☐ DAY ☐☐ YEAR ☐☐☐

LOCATION

FOREMAN NO.	HIGHWAY CLASS	COUNTY NO.	HIGHWAY NO.	CONTROL	SECTION	FROM	TO	LANE

ASPHALT CONCRETE PAVEMENTS

RUTTING	% AREA	① 1-15 ② 16-30 ③ >30	SLIGHT MODERATE SEVERE
RAVELING	% AREA	① 1-15 ② 16-30 ③ >30	SLIGHT MODERATE SEVERE
FLUSHING	% AREA	① 1-15 ② 16-30 ③ >30	SLIGHT MODERATE SEVERE
CORRUGATIONS	% AREA	① 1-15 ② 16-30 ③ >30	SLIGHT MODERATE SEVERE
ALLIGATOR CRACKING	% AREA	① 1-5 ② 6-25 ③ >25	SLIGHT MODERATE SEVERE
LONGITUDINAL CRACKING	LIN FT PER STA/LN	① 10-99 ② 100-199 ③ >200	SLIGHT MODERATE SEVERE
TRANSVERSE CRACKING	NO PER STA	① 1-4 ② 5-9 ③ > 10	SLIGHT MODERATE SEVERE
CRACKS (1) Sealed (2) Partially Sealed (3) Not Sealed			
PATCHING	% AREA	① 1-5 ② 6-15 ③ >16	GOOD FAIR POOR

DISTRICT NO. ☐☐

RATERS ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐

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MONTH ☐☐ DAY ☐☐ YEAR ☐☐☐

LOCATION

FOREMAN NO.	HIGHWAY CLASS	COUNTY NO.	HIGHWAY NO.	CONTROL	SECTION	FROM	TO	LANE

PORTLAND CEMENT CONCRETE PAVEMENTS

① SLIGHT ② MODERATE ③ SEVERE PUMPING

① 1-5 ② 6-10 ③ >10 FAILURES/MILE

ALL PAVEMENTS	SURFACE DETERIORATION	% AREA	① 1-15 ② 16-50 ③ >50	SLIGHT MODERATE SEVERE
	SPALLING	% JOINTS CRACKS	① 1-15 ② 16-50 ③ >50	SLIGHT MODERATE SEVERE
	LONGITUDINAL CRACKING	LIN. FT. PER STA.	① 1-99 ② 100-199 ③ >200	SLIGHT MODERATE SEVERE
	PATCHING	% AREA	① 1-5 ② 6-15 ③ >16	GOOD FAIR POOR
	FAULTING	NO. PER STA.	① <10 ② >10	MODERATE SEVERE
CRCP ONLY	CRACK SPACING		① 5-10' ② OTHER	CLOSED OPEN
	% INTERSECTING CRACKS		① 1-10 ② >10	MODERATE SEVERE
JOINTED ONLY	JOINT SPACING		① 1 20' ② >20'	SAWED CONSTR.
	TRANSVERSE CRACKING	NO. PER PANEL	① 1-4 ② 5-9 ③ >10	SLIGHT MODERATE SEVERE

JOINT & CRACK ① Sealed ② Partially ③ No Seal

Figure 15. Pavement Rating Forms

Table 8. Pavement Rating Deduct Values.

Type of Distress	Degree of Distress	Extent of Distress * (1)	(2)	(3)
Rutting	Slight	0	2	5
	Moderate	5	7	10
	Severe	10	12	15
Raveling	Slight	5	8	10
	Moderate	10	12	15
	Severe	15	18	20
Flushing	Slight	5	8	10
	Moderate	10	12	15
	Severe	15	18	20
Corrugations	Slight	5	8	10
	Moderate	10	12	15
	Severe	15	18	20
Alligator Cracking	Slight	5	10	15
	Moderate	10	15	20
	Severe	15	20	25
Patching	Good	0	2	5
	Fair	5	7	10
	Poor	7	15	20

Deduct Points for Cracking

Longitudinal Cracking

	Sealed			Partially Sealed			Not Sealed *		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
Slight	2	5	8	3	7	12	5	10	15
Moderate	5	8	10	7	12	15	10	15	20
Severe	8	10	15	12	15	20	15	20	25
Transverse Cracking									
Slight	2	5	8	3	7	10	3	7	12
Moderate	5	8	10	7	10	15	7	12	15
Severe	8	10	15	10	15	20	12	15	20

* Numbers in parentheses refer to quantity of distress observed as indicated on Figure 1.

Table 9. El Paso Preconstruction Pavement Rating Scores.

Test Section	Photolog	Cracking PRS Trans.	Long.	Allig.	Overall PRS
1	1	7	63	65	-1
	2	70	88	70	23
	3	63	93	85	36
2	4	60	65	85	8
	5	75	93	85	48
	6	95	93	95	78
3	7	78	88	80	29
	8	73	88	80	26
	9	75	93	95	56
4	10	63	70	60	-39
	11	83	98	100	81
	12	63	70	70	-17
5	13	75	80	60	3
	14	90	78	65	28
	15	87	88	80	43
6	16	83	88	65	12
	17	83	93	80	48
	18	83	88	80	38
7	19	78	78	85	16
	20	90	88	95	63
	21	90	93	90	61
8	22	90	93	95	68
	23	78	93	95	56
	24	90	93	90	63
9	25	75	88	85	43
	26	90	70	80	28
	27	68	88	80	19
10	28	95	98	98	86

Table 9 contains the PRS values obtained by measuring all combined forms of distress present in each test section. PRS values are also shown which were obtained by measuring individual types of cracking. These cracking PRS ratings are presented such that a more precise comparison may be made between test sections for crack related distress. The asphalt-rubber interlayer is intended to reduce the rate at which cracks in the underlying pavement propagate the new asphalt concrete overlay. The "cracking PRS" values, therefore, will provide a basis for which future condition surveys can be compared. By comparing PRS values for transverse, longitudiual and alligator cracks, a measure of interlayer performance within and between test sections can be obtained based on percent original PRS.

El Paso-Construction

Asphalt-rubber interlayers were placed on June 23, 24 and 27, 1983 by International Surfacing, Inc., Phoenix, Arizona. Sections 5 to 9 were placed June 23, 1983, followed by sections 1 to 3 on June 24, 1983. Section 4 was placed June 27, 1983. Environmental conditions during construction were favorable with early morning temperatures of approximately 70F and afternoon temperatures of 100F.

Observations and tests made during construction included the following:

I. Asphalt-rubber mixing
  A. Assuring desired rubber types were used in asphalt-rubber to be placed over selected test section locations.
  B. Proportion of asphalt and rubber.
  C. Blending time.
  D. Blending temperature.
  E. Viscosity prior to application.
  F. Sampling of asphalt and rubber.

II. Asphalt-rubber application.
  A. Asphalt-rubber spray rate.

B. Aggregate spread rate.

C. Asphalt-rubber cooling rate.

D. Sampling of asphalt-rubber.

Considerable coordination was necessary during construction to assure that the desired asphalt-rubber combinations and application rates, as shown in Figure 4, were placed over photolog locations appearing in Table 7. This required adjusting distributor volumes such that materials could be placed contiguously with minimum disruption to construction procedures.

Asphalt arrived at the mixing site by highway transport where it was pumped into a storage container. Granulated rubber was shipped from the three manufacturers in 50 or 60 pound bags.

Blending of the asphalt and rubber required two pieces of equipment. Initial mixing of asphalt and rubber occurred in a pre-blending device which combines asphalt and rubber in the approximate pre-blend proportions desired. After the asphalt and rubber are pre-blended, the material is pumped to the asphalt distributor. The flow of blended asphalt and rubber are continuous from pre-blender to distributor in the approximate proportions desired. Final proportioning is accomplished after all of the rubber is in the distributor by adding additional asphalt.

A sample calculation follows which describes how the number of bags of rubber and gallons of asphalt cement are determined to achieve a blend containing 22 percent rubber by weight of blend.

Assumption:

Distributor volume	4500 gallons
Rubber Bag Weight	50 pounds
Unit Weight Asphalt Cement @ 350F	7.54 pounds/gallon
Unit Weight Asphalt-Rubber @ 350F	7.54 pounds/gallon

Find: Number of bags of rubber and gallons of asphalt cement to yield a 4500 gallon asphalt-rubber blend at 22% rubber by weight of blend.

Rubber: $$\frac{4500 \times 7.54 \times .22}{50} = 149.3 \text{ bags}$$

Asphalt Cement: $$\frac{4500 \times 7.54 \times .78}{7.54} = 3510 \text{ gallons}$$

Specific gravity of asphalt-rubber was measured at various temperatures in the laboratory following procedures described by ASTM D70 (25). Weight to volume conversions were done with a high boiling point oil such that specific gravity could be measured above 212F. The graph shown in Figure 16 of asphalt-rubber specific gravity was used in the calculation above for the required volume to weight conversion. Note the difference in asphalt-rubber specific gravity as measured and that calculated from cubical coefficient of expansion data. A 95 percent confidence limit on measured values encompasses calculated values. This seems to indicate volume change in asphalt-rubber is due to combined thermal expansion of the constituents. The large variation in specific gravity results shown in Figure 16 indicates this test is probably of limited use for quality control unless more precise results can be achieved.

Results of observations and tests performed during mixing of the asphalt-rubber appear in Table 10. Note that the field viscosity of the asphalt-rubber blend appears to depend on rubber content as shown in Table 10 and plotted in Figure 17. Note that the type of rubber affects the viscosity of the blend as shown in Figure 17. Viscosity tests were performed using a portable Haake rotational viscometer on samples of asphalt-rubber obtained directly from the distributor truck approximately 50 minutes after all rubber had been added to the truck.

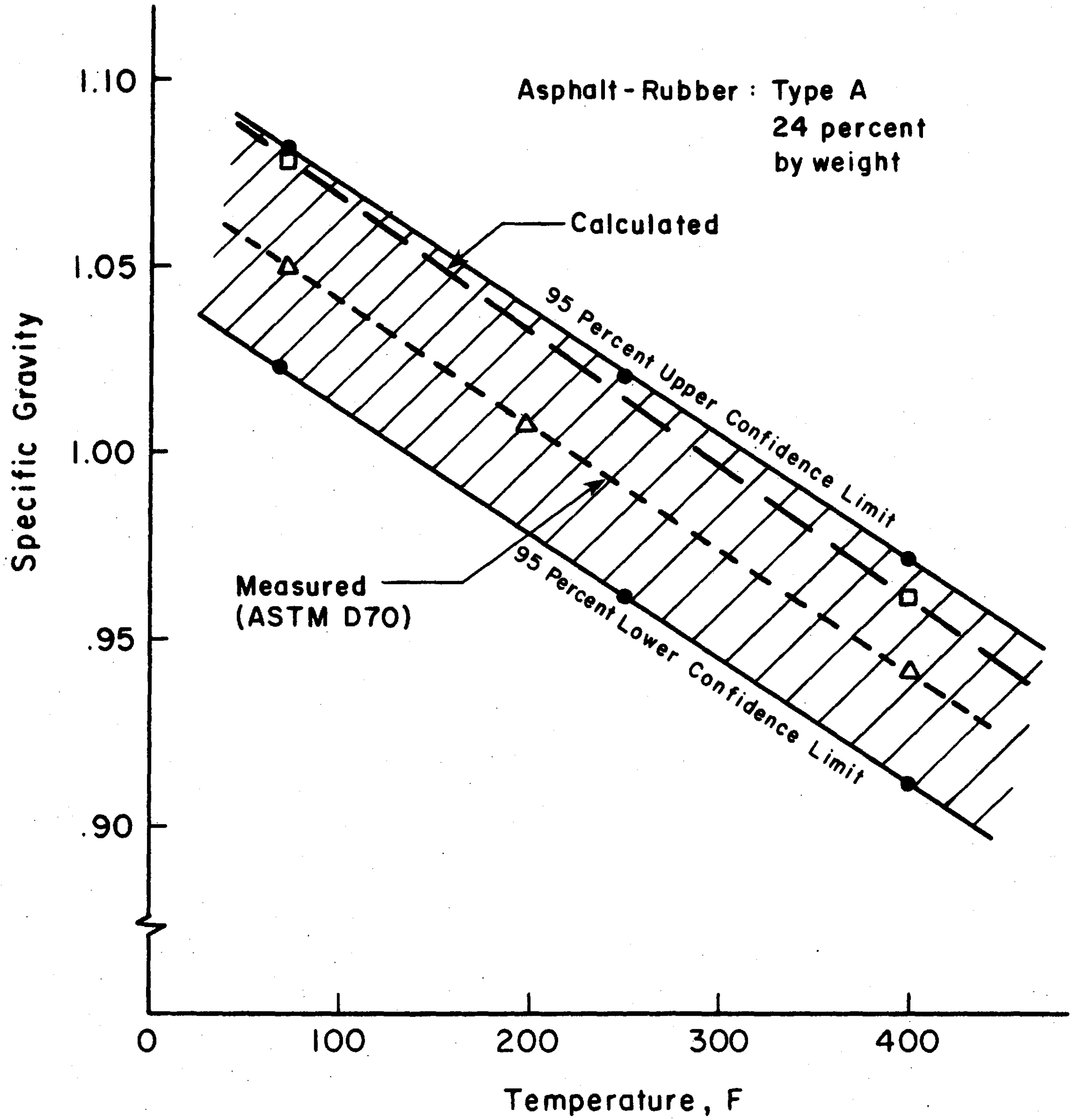
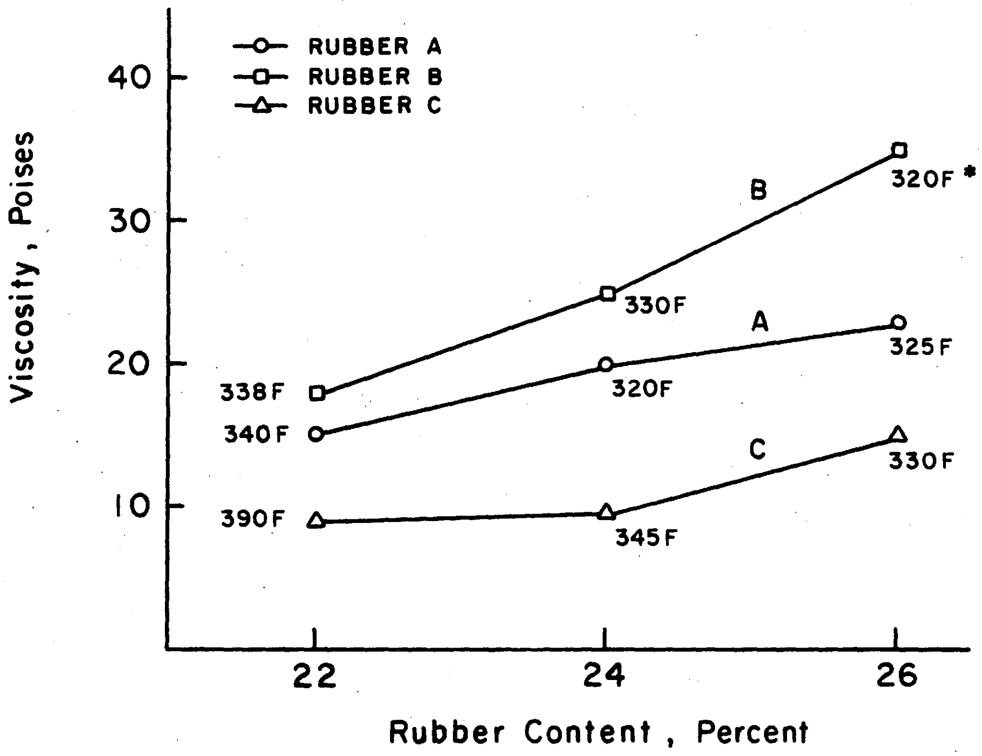


Figure 16. Asphalt-Rubber Specific Gravity

Table 10. El Paso Mixing Observations and Test Results.

Test Section	Beginning Date	Beginning Time of Day	Time Req'd to Fill Truck w/ Blend, min.	Time Between Full Truck & Application, min.	Temp, F Prior to Application	Viscosity Prior to Application, poises	Rubber Type	Rubber Content, Percent
1	6/24/83	4:35am	40	105	320	20	A	24
2	6/24/83	5:20am	40	95	390	9	C	22
3	6/24/83	6:02am	53	90	320	35	B	26
4	6/27/83	11:40am	35	110	338	18	B	22
5	6/23/83	5:25am	55	85	340	15	A	22
6	6/23/83	6:25am	55	90	330	15	C	26
7	6/23/83	11:20am	30	160	345	10	C	24
8	6/23/83	1:15pm	30	135	325	23	A	26
9	6/23/83	1:50pm	30	125	330	25	B	24



* TEMPERATURES SHOWN ARE VALUES CORRESPONDING TO VISCOSITY MEASUREMENTS

Figure 17. El Paso Asphalt - Rubber Viscosity

Rubber Type C in addition to generating the lowest asphalt-rubber viscosity relationship, also caused a considerable volume increase in the blend as mixing progressed. This was manifested in overflows of asphalt-rubber from the top batch of the 4500 gallon distributor truck for test section mixes 6 and 7. The overflows occurred during routine pumping of the blend after approximately 2300 gallons had been loaded. Overflow was avoided for the third blend containing Rubber C by loading the first half of the blend at a slower rate. Moisture contained in the rubber is thought to be the cause of this adverse reaction and may be related to the cryogenic processing technique.

Asphalt-rubber temperature measurements were obtained to determine the rate at which the binder loses heat prior to aggregate application. Temperatures were measured using a Fluke digital thermometer under varying ambient temperature conditions. These data are plotted on Figure 18 with calculated theoretical values (15).

Temperature loss in the asphalt-rubber binder is rapid as shown by Figure 18. Binder temperature decreases to near the initial pavement temperature in approximately 90 seconds under the conditions of the test.

Verification of binder aggregate application quantities was accomplished by Texas SDHPT personnel. During construction, measurement of the application quantity was accomplished at approximately 1000 to 3500 foot intervals until the proper application rate was achieved. Measurement of application rate was accomplished using calibrated metering rods accompanying each distributor truck. Measurement of aggregate spread quantity was accomplished at similar intervals by volume of aggregate. Rates of binder and aggregate within each test section are shown in Table 11.

Research binders as shown in Figure 4 were applied over photologs in appropriate test sections at the rates shown in Table 11. However, the distributor truck emptied its contents before reaching photolog 12 in

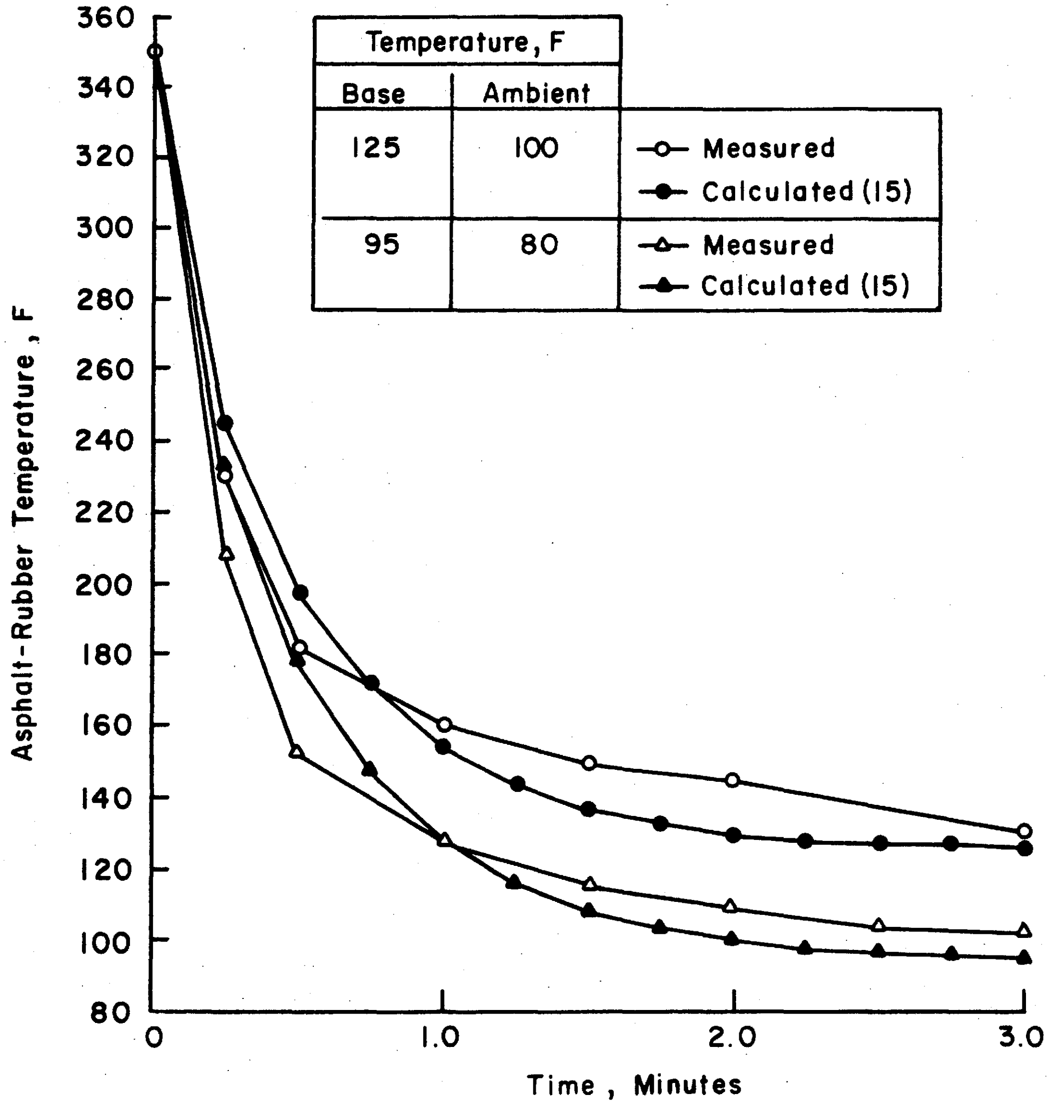


Figure 18. El Paso Asphalt-Rubber Temperature Loss After Application

Table 11. El Paso Application Quantities.

Test Section	Photolog	Measured Asphalt-Rubber Rate, gsy	Desired Asphalt-Rubber Rate, gsy
1	1	0.36	0.40
	2	0.41	
	3	0.41	
2	4	0.35	0.35
	5	0.38	
	6	0.38	
3	7	0.45	0.45
	8	0.45	
	9	0.45	
4	10	0.38	0.40
	11	0.38	
	12	*	
5	13	0.44	0.45
	14	0.44	
	15	0.44	
6	16	0.41	0.40
	17	0.41	
	18	0.41	
7	19	0.44	0.45
	20	0.44	
	21	0.44	
8	22	0.36	0.35
	23	0.36	
	24	0.36	
9	25	0.36	0.35
	26	0.36	
	27	0.35	
Control	28	N/A	N/A

* Distributor truck emptied contents before reaching photolog No. 12.

Note: Aggregate spread quantities were uniform throughout project ranging from 116 sq.yd./cu.yd. to 117 sq.yd./cu.yd. (19.5 to 19.7 lb./sq.yd.).

Test Section 4 and therefore, no research binder is present over photolog 12.

Placement of overlay asphalt concrete began July 18, 1983, approximately four weeks after asphalt-rubber application. Core specimens were obtained from each test section to determine overlay thickness and provide samples for evaluation of physical properties as reported in Tables 6 and Figure 3. Results of thickness measurements are shown in Table 12.

Locations of test sections were preserved after construction for future reference. Monuments consisting of 4 inch by 4 inch by 8 feet cedar posts were located at the beginning of each test section along the highway right-of-way. Posts were painted white and contain black lettering denoting stationing shown on Figure 11 of specific locations of test section boundaries. Location of photologs within test sections for future condition surveys will be simplified by reference to these monuments.

Buffalo-Preconstruction

Eight sections of pavement each approximately 0.80 lane mile in length were selected to receive the various asphalt-rubber blends shown in Figure 7. Four additional pavement sections, each 750 feet in length, were selected as control sections. Three segments of pavement each 500 feet in length were selected in each of the eight test sections for photolog surveys as previously described for El Paso Test Road. The entire length of the control sections were photologged. Locations of photologs are as shown on Table 13. Photolog equipment was as used on the El Paso Test Road.

Condition surveys on site were combined with cracking data obtained from photologs to provide PRS values for test and control sections. Table 14 contains PRS values obtained after completing the condition survey and photolog interpretation. All photographs obtained during

Table 12. El Paso Overlay Thicknesses.

Test Section	Photolog	Overlay Thickness, in.
1	1	1.75
	2	1.25
	3	1.25
2	4	1.25
	5	1.25
	6	1.25
3	7	1.50
	8	1.50
	9	1.25
4	10	1.75
	11	2.25
	12	*
5	13	1.75
	14	2.75
	15	2.00
6	16	1.25
	17	1.25
	18	1.00
7	19	1.75
	20	1.50
	21	1.25
8	22	1.50
	23	1.50
	24	1.50
9	25	1.50
	26	1.50
	27	1.25
Control	28	1.50

* Photologged, but no research binder in this area.

Table 13. Buffalo Photolog Locations.

Test Section	Photolog	Station	
		From	To
1	1 to 3	188+30	201+24
2	4 to 5	205+00	212+50
3	6 to 7	212+50	220+00
4	8 to 9	587+80	595+30
5	10 to 11	595+30	604+40
6	12 to 14	631+20	645+50
7	15 to 17	683+00	698+50
8	18 to 20	714+15	729+50
9	21 to 23	755+60	770+70
10	24 to 26	810+00	825+00
11	27 to 29	860+00	875+00
12	30 to 32	889+00	904+00

Table 14. Buffalo Preconstruction Pavement Rating Scores.

Photolog	PRS
1	90
2	90
3	90
.	.
.	.
.	.
10	90
11	100
12	100
13	100
14	90
.	.
.	.
.	.
21	90
22	100
23	90
24	100
25	90
26	90
27	90
28	100
29	100
30	100
31	90
32	100

Note: Much of the distress on Buffalo Test Road consisted of random transverse cracks at less than 5 foot intervals. In most cases cracks were closed and not "working" significantly. This results in a deduct score of 10. Deduct scores of 0 resulted from closed cracks occurring at between 5 and 10 intervals.

surveys are on file at Texas Transportation Institute, College Station, Texas.

Buffalo-Construction

Asphalt-rubber was placed over test sections August 20, 21 and 22, 1984 by Arizona Refining Company, Phoenix, Arizona. Environmental conditions during construction were favorable with early morning temperatures of approximately 70F and afternoon temperatures approaching 100F.

Observations and tests made during construction were identical to those for the El Paso Test Road. Similar coordination was required of contracting efforts such that asphalt-rubber combinations desired as shown in Figure 7 were placed in appropriate locations over photologs as shown in Table 13. Distributor volumes were adjusted as for El Paso such that the desired asphalt-rubber mixes were placed at appropriate locations on test sections.

Blending of asphalt and Sundex 790 at 6 percent Sundex by blend volume was accomplished prior to blending with rubber. Pre-blending of asphalt-rubber was accomplished as on the El Paso project prior to pumping the blend into distributor trucks. Here the asphalt-rubber blend remained in the trucks for the desired digestion period prior to application.

Digestion was varied as a control variable in this experiment as explained previously for laboratory prepared mixes. Two levels of digestion were achieved. "Low" digestion describes blends of 2 to 2 3/4 hours. "High" digestion describes blends of 16 to 16 1/2 hours.

Rubber concentrations of 18 and 22 percent by weight of the blend were used.

Results of observations and tests performed during mixing of the asphalt-rubber appear in Table 15. Viscosity and rubber content appear to be directly proportional as occurred for El Paso blends. However,

Table 15. Buffalo Mixing Observations and Test Results.

Test Section	Beginning Date	Beginning Time of Day	Time Req'd to Fill Truck w/ Blend, min.	Time Between Full Truck & Application, hrs-min.	Temp, F Prior to Application	Viscosity Prior to Application, poises	Rubber Type	Rubber Content, Percent
1	8/22/84	5:30pm	50	15-40	390	11	A	18
6	8/21/84	7:05am	35	2-55	390	48	A	22
7	8/20/84	7:07pm	45	15-53	400	21	A	22
8	8/20/84	8:21pm	40	15-14	400	7	A	18
9	8/20/84	11:45am	45	2-5	400	14	A	18
10	8/21/84	1:00pm	105	2-5	400	45	A	22
11	8/21/84	:45pm	35	2-10	402	13	A	18
12	8/21/84	6:30pm	40	15-50	390	19	A	22

viscosity appears to be inversely proportional to digestion period. The results of these tests are plotted in Figure 19.

Temperature loss of the asphalt-rubber was measured as for the El Paso Test Road. Results of these tests are shown on Figure 20. Results are similar to those observed at El Paso. Texas SDHPT personnel verified binder and aggregate quantities as part of routine quality control procedures. However, unlike El Paso, binder quantities were determined by weight rather than volume. Each asphalt-rubber distributor was weighed prior to, and after application. The difference in weight was converted to volume and the corresponding application rate determined for the measured pavement area covered. Therefore, application rates shown in Table 16 reflect averages throughout each test section.

Buffalo overlay asphalt concrete consists of a Texas Type C leveling course and a one-inch Texas Type D surface course. Placement of the levelling course began September 10, 1984 and was completed November 16, 1984. Each test section was sampled by coring to obtain laboratory specimens and to verify overlay thickness. Physical properties of the asphalt concrete are reported in Table 6 and Figure 3. Results of thickness measurements of core samples are shown in Table 17.

Locations of photologs within test sections are permanently marked using raised reflective pavement buttons positioned on the right shoulder of the northbound lane. Precise location of photologs for future condition surveys is therefore possible by reference to these pavement markers.

Brownsville - Preconstruction

Twelve pavement sections were selected to receive asphalt-rubber and various combinations of aggregates. The asphalt-rubber binder formulation was held constant for this experiment. Rubber was blended at 60 percent Type D and 40 percent Type E as described in Tables 2 and 4. Six additional sections were selected as controls. Control sections consisted of: 1) no treatment, 2) asphalt cement interlayer, 3)

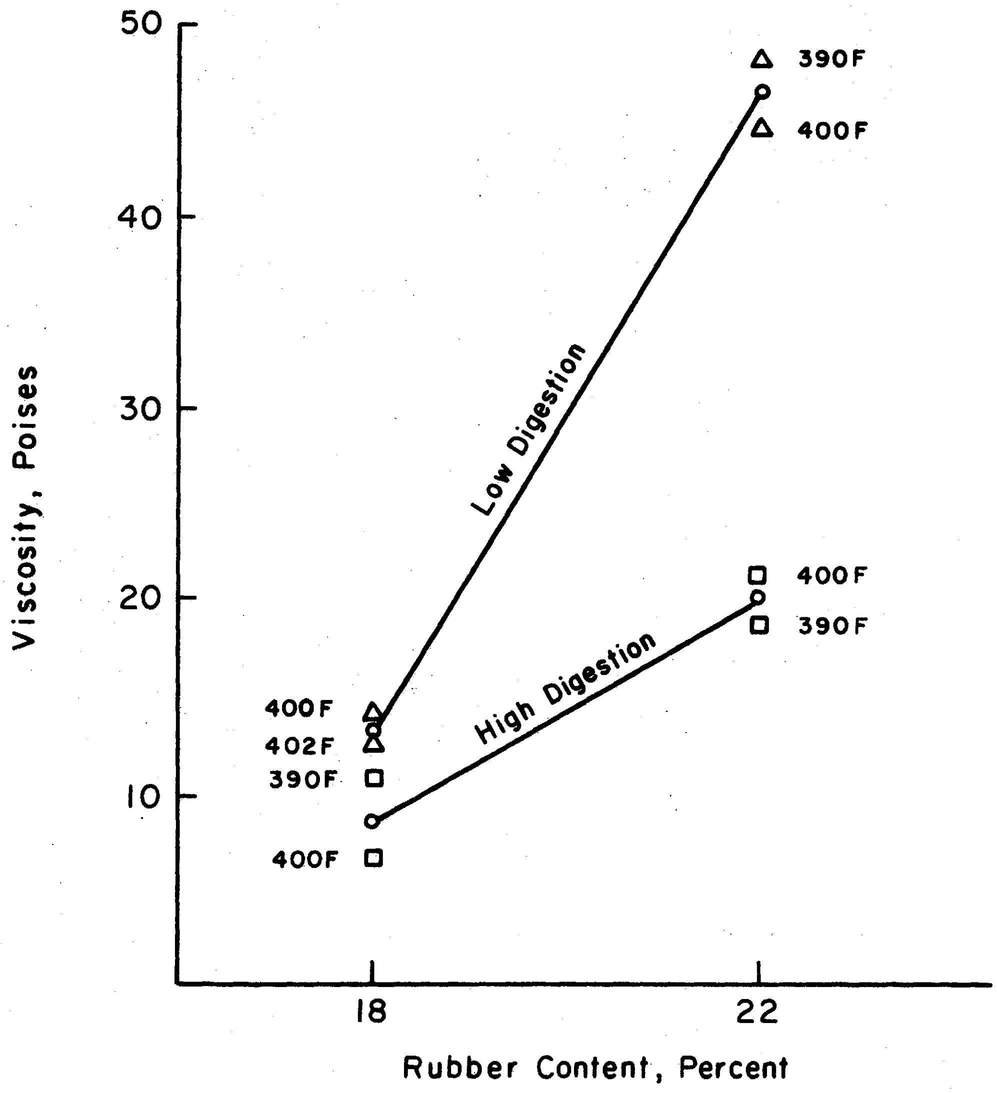
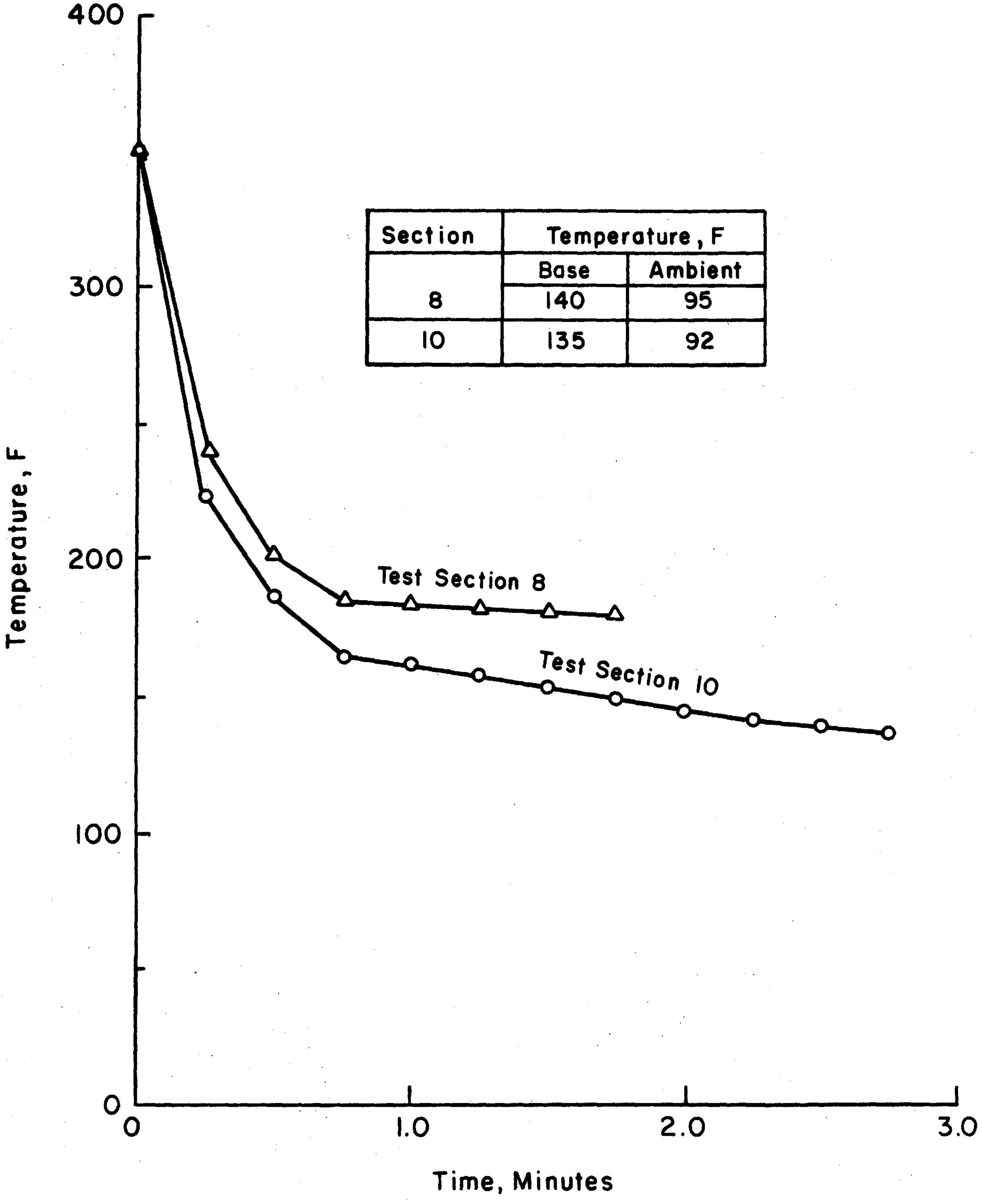


Figure 19. Buffalo Asphalt-Rubber Viscosity



Section	Temperature, F	
	Base	Ambient
8	140	95
10	135	92

Figure 20. Buffalo Asphalt-Rubber Temperature Loss After Application

Table 16. Buffalo Application Quantities.

Test Section	Binder Rate, gsy	Aggregate Rate, sy/cy
1	0.58	95
2	0.57	90
3	No Binder	No Aggregate
4	No Binder	No Aggregate
5	0.55	80
6	0.57	77
7	0.56	79
8	0.57	77
9	0.52	75
10	0.59	80
11	0.54	78
12	0.56	79

Table 17. Buffalo Overlay Thickness.*

Test Section	Photolog	Overlay Thickness, in
1	1	2.4
	2	2.5
	3	2.3
2	4	2.5
	5	2.6
3	6	2.6
	7	3.3
4	8	3.5
	9	3.8
5	10	3.8
	11	3.8
6	12	3.8
	13	3.5
	14	3.3
7	15	3.4
	16	3.5
	17	3.5
8	18	3.3
	19	3.3
	20	3.1
9	21	3.4
	22	3.5
	23	3.8
10	24	3.4
	25	3.4
	26	3.4
11	27	3.0
	28	3.1
	29	3.1
12	30	4.0
	31	4.0
	32	4.0

*Thickness after construction in 1984. A 1" surface course was applied over entire pavement in 1985.

polymer asphalt interlayer. All sections were replicated to provide a statistical bsis for later analysis of performance betwen sections. A description of all materials used is shown in Table 18.

A 500 foot photolog was recorded in each test section. Locations of photologs are as shown in Table 19. Photolog equipment and technique was used at Buffalo and El Paso.

Condition surveys on site were combined with cracking data from photologs to provide PRS values. Table 20 contains these PRS data.

Brownsville - Construction

Asphalt-rubber was first placed over non-experimental pavement sections such that binder shot rate and aggregate spread rates could be adjusted. After calibration was completed, test section construction began. Asphalt-rubber was placed on all test sections by October 12, 1984 by Arizona Refining Company, Phoenix, Arizona. Control sections were placed by SDHPT personnel by October 26, 1984.

Observations and tests made during construction were identical to those for the El Paso and Buffalo Test Roads. Similar coordination was required of contracting efforts such that asphalt-rubber seal coat combinations desired were placed in appropriate locations over photologs.

Blending of asphalt and Sundex 790 at 6% Sundex by blend volume was accomplished prior to blending with rubber. Pre-blending of asphalt-rubber was accomplished as on the El Paso and Buffalo projects prior to pumping the blend into distributor trucks. Here the asphalt-rubber blend remained in the trucks during digestion prior to application.

Digestion remained constant in this experiment. Rubber and asphalt were blended for approximately 1 hour after all rubber was added to the blend for each test section.

Rubber concentration remained constant at 18 percent by weight of the asphalt-rubber blend. Texas SDHPT personnel verified binder and

Table 18. Brownsville Test Section Materials

Test Section	Binder	Aggregate Application	Aggregate Size Bottom/Top	Overlay Thickness, in
1	A-R	Double	Grade 3/Grade 3	N/A
2	A-R	Single	Grade 3	N/A
3	A-R	Double	Grade 3/Grade 4	N/A
4	AC	Double	Grade 3/Grade 4	N/A
5	A-R	Double	Grade 3/Grade 3	1.4
6	A-R	Single	Grade 3	1.2
7	A-R	Double	Grade 3/Grade 4	1.1
8	AC	Double	Grade 3/Grade 4	1.3
9	A-R	Double	Grade 4/Grade 4	1.3
10	A-R	Single	Grade 4	1.0
11	A-R	Single	Grade 4 Two deep	1.1
12	None	None	N/A	1.2
13	Polymer	Double	Grade 4/Grade 4	1.6
14	A-R	Double	Grade 4/Grade 4	N/A
15	A-R	Single	Grade 4	N/A
16	A-R	Single	Grade 4 Two deep	N/A
17	None	None	N/A	N/A
18	Polymer	Double	Grade 4/Grade 4	N/A

Table 19. Brownsville Photolog Locations

Test Section/Photolog	Location
1	25+00 to 30+00
2	40+00 to 45+00
3	64+00 to 69+00
4	80+00 to 85+00
5	85+00 to 80+00
6	69+00 to 64+00
7	45+00 to 40+00
8	30+00 to 25+00
9	25+00 to 30+00
10	40+00 to 45+00
11	64+00 to 69+00
12	77+50 to 82+50
13	82+50 to 87+50
14	85+00 to 80+00
15	69+00 to 64+00
16	45+00 to 40+00
17	32+50 to 27+50
18	27+50 to 22+50

Note: Stations are south to north.

Table 20. Brownsville Preconstruction Pavement Rating Scores.

Test Section	Cracking PRS Transv.	 Long.	 Allig.	Overall PRS
1	95	95	85	75
2	97	95	95	87
3	97	95	95	87
4	97	95	100	92
5	93	95	95	83
6	97	95	95	87
7	95	93	95	83
8	98	98	85	81
9	97	95	100	92
10	95	95	100	90
11	97	95	100	92
12	97	95	100	92
13	97	95	100	92
14	97	95	100	92
15	100	95	100	95
16	97	100	100	97
17	97	95	100	92
18	97	95	100	92

aggregate quantities as part of routine quality control procedures. At the beginning of the project, binder quantities were intended to be determined by volume. However, the trucks supplied by the asphalt-rubber contractor had not been calibrated, and some difficulty was experienced while attempting calibration on the job site. Therefore, shot rates were determined by weight. Each asphalt-rubber distributor was weighed prior to, and after application. The difference in weight was converted to volume and the corresponding application rate determined for the measured pavement area covered. Therefore, application rates shown in Table 21 reflect averages throughout each test section.

Brownsville overlay asphalt concrete consists of approximately 1 1/4 inches Texas Type D asphalt concrete. Placement of the 1 1/4 inches Texas Type D asphalt concrete. Placement of the overlay began after asphalt-rubber and control section seal coats had been in service at least one week. Each test section was core drilled to obtain laboratory specimens and to verify overlay thickness. Physical properties of the asphalt concrete are reported in Table 6 and Figure 3. Results of thickness measurements of core samples are shown in Table 22.

Locations of photologs are permanently marked using raised reflective pavement buttons position on the right shoulder. Precise location of photologs for future condition surveys is therefore possible by reference to these pavement markers.

Table 21. Brownsville Test Road Aggregate and Binder Application Rates.

Test Section	Design Aggregate Rate, sy/cy	Measured Aggregate Rate, sy/cy	Design Binder Rate, gsy	Measured Binder Rate, gsy	Measured Embedment Depth, %	Comments
1	80/80	56/56	0.71/0.69	0.77/0.85	38/40	Severe Flushing
2	80	56	0.69	0.78	-	Severe Flushing
3	115/80	83/56	0.53/0.69	0.48/0.71	-/52	Slight Flushing
4	115/80	56	0.27/0.36	0.60	-	Severe Flushing
5	80/80	56/56	0.71/0.69	0.67/0.65	14/43	No Distress
6	80	56	0.69	0.76	48	Slight Flushing
7	115/80	80/56	0.58/0.69	0.59/0.71	26/48	Severe Flushing
8	115/80	80/56	0.27/0.36	0.45/0.58	-	Severe Flushing
9	115/115	83/83	0.53/0.69	0.49/0.51	-/51	Severe Flushing
10	115	83	0.51	0.58	50	Severe Flushing
11	57	80	0.51	0.65	70	Severe Flushing
12	None	None	None	None	-	
13	115/115	83 *	0.27/0.25	0.48 *	-	Severe Flushing
14	115/115	83/80	0.53/0.51	0.56/0.52	24/47	Slight Flushing
15	115	83	0.51	0.56	53	Severe Flushing
16	57	80	0.51	0.66	50	No Distress
17	None	None	None	None	-	
18	115/115	83	0.27/0.25	0.53 *	-	Severe Flushing

Table 22. Theoretical and Measured Asphalt-Rubber Relative Viscosity.

Rubber Content, %	Measured Relative Viscosity Torque Fork	Calculated Relative Viscosity, η_{rel}		
		Einstein[1]	Brinkman[2]	Mooney[3]
22	1.85	1.73	1.86	2.58
24	2.23	1.82	1.99	3.03
26	2.60	1.92	2.12	3.64

[1] Einstein $\eta_{rel} = \exp(2.5\ \phi)$

[2] Brinkman $\eta_{rel} = (1 - \phi)^{-2.5}$

[3] Mooney $\eta_{rel} = \exp(\frac{2.5\phi}{1-1.91\phi})$

where,

ϕ = rubber percent by volume

CHAPTER VI

LABORATORY TESTS

Three laboratory tests were used to evaluate physical properties of asphalt-rubber blends prepared at both test roads and in the laboratory. The mixer used to blend asphalt and rubber in the laboratory also served as a rotational viscometer to evaluate rheological characteristics during blending.

The following chapter discusses the equipment used to test laboratory properties of asphalt-rubber blends. With the exception of the Haake rotational viscometer, testing equipment described herein represent custom fabricated or modified devices not commercially available. However, each device has been used in essentially similar form in other research where application of each has been demonstrated (6,7,8,9,17,18).

Torque Fork Mixer

A laboratory mixer of this type was first used for asphalt-rubber blending in 1977 (6). The system consists of a constant speed motor with stirrer assembly which is capable of recording torque changes as load varies on the stirrer. The resulting apparatus is a rotational viscometer which can measure relative changes in fluid viscosity during mixing. One difference between this device, shown in Figure 21, and commerically available viscometers is the speed at which mixing and viscosity readings occur, 500 RPM. Also, this device uses a mixing propeller for agitation and is primarily intended to be a mixer.

There is one difference between the device shown in Figure 21 and the prototype developed earlier (6). The device described here is fitted with a glass and teflon bearing where the stirring shaft enters the reaction kettle. This bearing assures a closed mixing environment to ensure a minimum of volatile loss during mixing. The mixer was altered

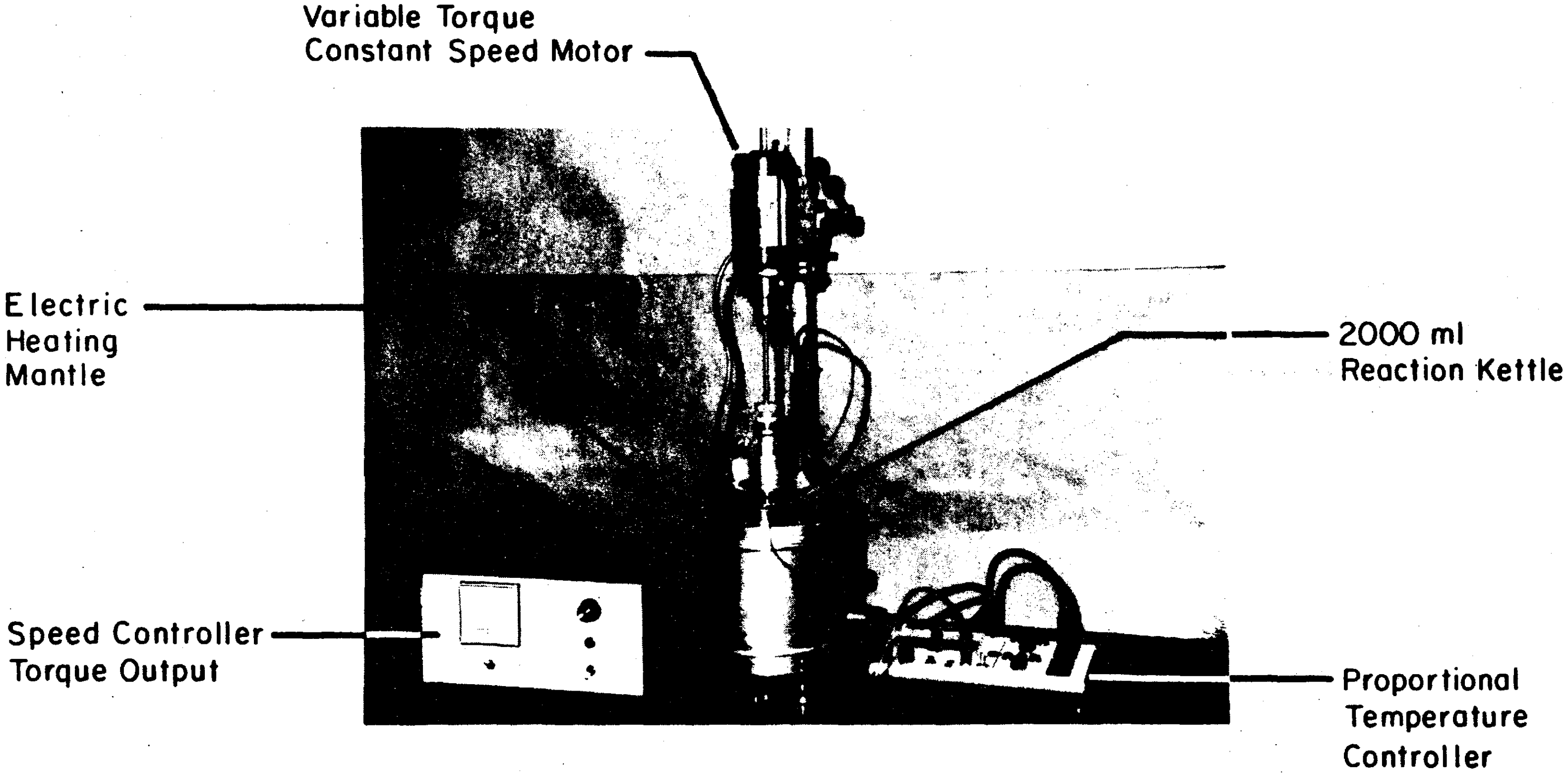


Figure 21. Torque Fork Mixer

to include this feature at the recommendation of the developers of the earlier prototype (6).

Temperature of the blend is proportionately controlled and heat transfer is accomplished by an electric mantle surrounding the reaction kettle.

Procedure

Asphalt cement obtained during test road construction was stored at OF. Sampling was accomplished by fracturing the cold, brittle asphalt and transferring an appropriate quantity to the reaction flask for melting prior to addition of rubber. The asphalt was slowly stirred during heating to avoid local overheating. Mixer speed was increased to 500 rpm when all asphalt had become liquid.

Upon reaching the desired digestion temperature, rubber was added to the heated asphalt cement in the desired proportion by weight of blend. Addition of rubber was as rapid as possible, requiring approximately 10 seconds. Digestion time was recorded beginning after all rubber had been added to the asphalt.

Upon completion of blending all asphalt-rubber was removed from the reaction flask and separated into 6-ounce ointment tins. The material was cooled to room temperature and "frozen" prior to further testing.

Recording of mixture temperature and relative viscosity was accomplished throughout blending by strip chart recorder. Mixer speed was maintained at 500 rpm throughout the mixing process.

Preparation of blends for evaluation by force ductility and softening point was accomplished for the three levels of digestion as shown below:

Blending Conditions

Digestion Level	Temperature, F	Time, min.
Low	325	30
Moderate	350	60
High	375	180

Haake Viscometer

A Haake portable rotational viscometer model VT-02 was used in the field and laboratory to determine the viscosity of both laboratory and field mixed asphalt-rubber blends. The Haake is a simple device which measures viscosity by the same principle as the torque fork mixer, except changes in torque are monitored by deflection of a calibrated spring rather than by increases in electrical current as with the torque fork.

The Haake consists of a constant speed motor to which a cylindrical viscometer cup is attached. The cup is submerged in the fluid which viscosity measurements are desired and the motor started. Drag forces on the cup as it rotates in the fluid are transmitted to the calibrated spring within the viscometer. Viscosity is measured directly in poises. A scale on the face of the instrument is calibrated in poises for fluid viscosity from 0.3 to 4000 poises. Three scales on the instrument face correspond to three sizes of viscosity cups sized proportionately for various fluid viscosities. Figure 22 shows a Haake viscometer with a Number 1 viscometer cup.

Procedure

Laboratory prepared mixes were tested after combining asphalt and rubber by blending in the torque fork apparatus. Field prepared mixes were tested in the field prior to application on the test sections. Results appear in Tables 10 and 15 and Figures 17 and 19 for El Paso and Buffalo mixes, respectively.

Asphalt-rubber was obtained in the field by filling a one gallon sample container from the spray bar of the distributor truck. The viscometer cup was immersed. The sample was stirred using an armored thermometer for 30 seconds. The temperature was recorded, the viscometer cup was attached to the viscometer and the viscometer motor started. A

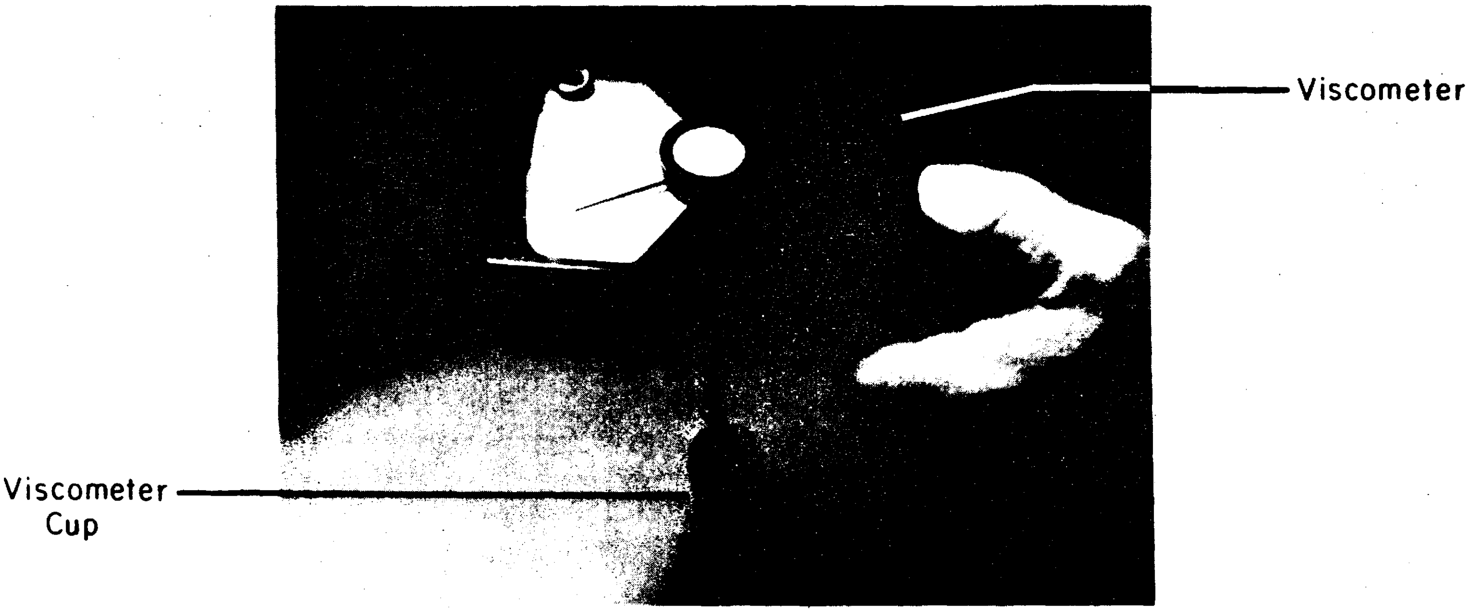


Figure 22. Haake Viscometer

rapid rise in the viscosity reading is noted immediately after starting the viscometer motor. This is believed to be due to inertial forces during acceleration of the viscometer cup. As cup velocity becomes constant, viscosity readings become constant. Viscosity readings were taken at this time, approximately three seconds after starting the viscometer. After approximately three to five seconds, viscosity readings begin to decrease. Viscosity continues to decrease until the asphalt-rubber begins to cool, when readings rise again. The lack of homogeneity of the asphalt-rubber mixes may be responsible for these observations. All readings reported here were taken three seconds after starting the viscometer motor.

Laboratory blended asphalt-rubber was tested by immersing the viscometer cup in the blend after digestion in the Torque Fork Mixer. The procedure for obtaining viscosity data was as for field prepared blends.

Force Ductility

The force ductility test is a modification of the asphalt ductility test (16). The test has been described (6,17) as a means to measure tensile load-deformation characteristics of asphalt and asphalt-rubber binders.

The test is performed as described by ASTM D113 (16) with certain changes. The principal alteration of the apparatus consists of adding two force cells in the loading chain. Figure 23 shows the modified ductility testing machine with load cells mounted parallel and in direct line of loading with test specimens. Specimens are maintained at 39.2F (4C) by circulating water through the ductility bath during testing.

A second major alteration of the standard ASTM procedure involves the test specimen shape. A standard ASTM specimen is as shown in Figure 24. The mold is modified for force-ductility testing by fabricating new pieces a and a'. Figure 25 shows the force-ductility mold with modified pieces a and a'. This mold produces a test specimen with a constant

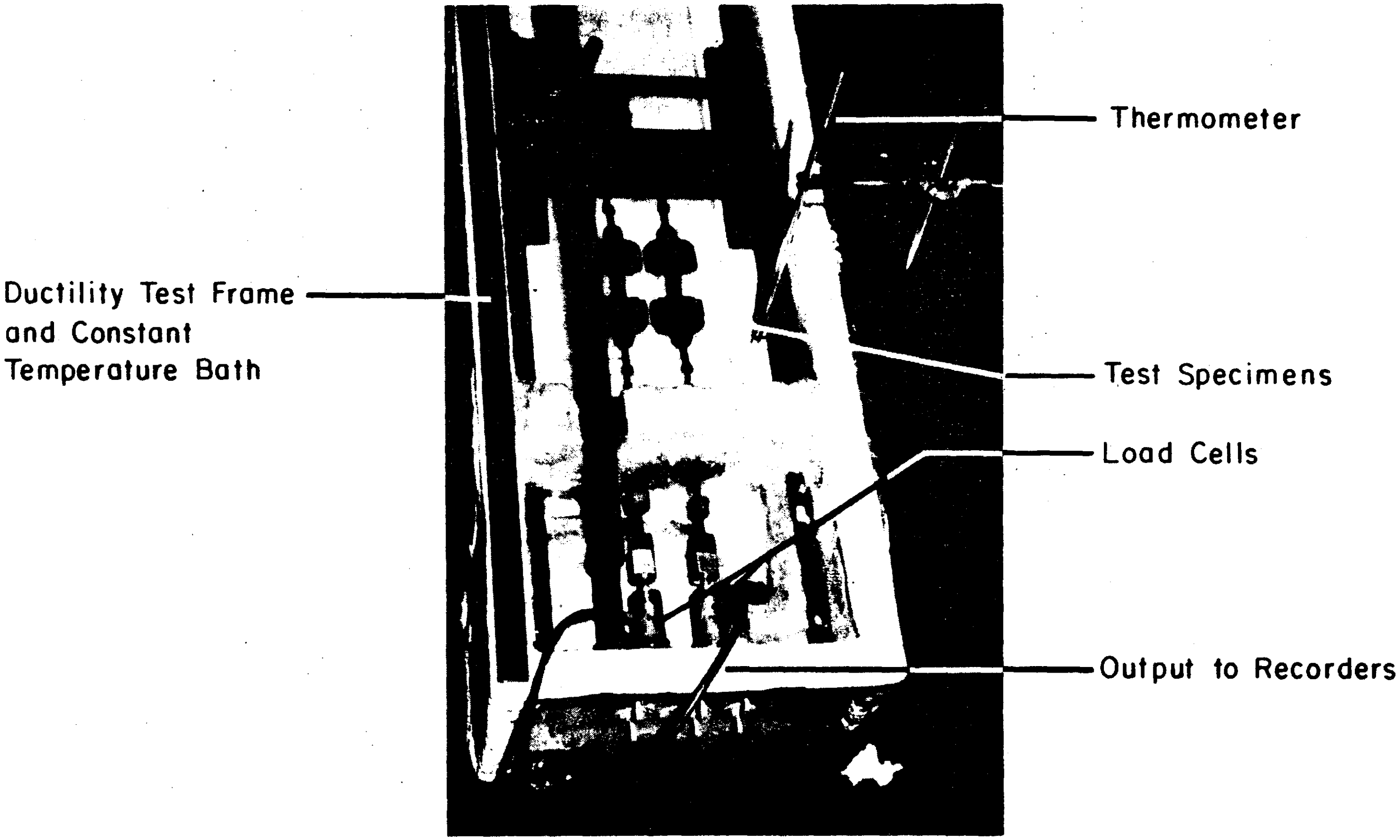


Figure 23. Force-Ductility Testing Machine

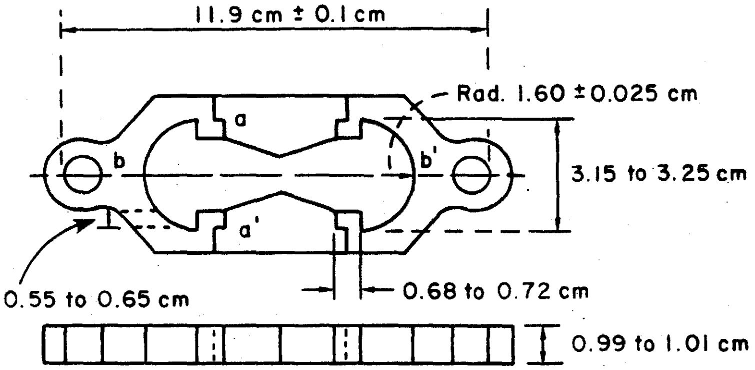


Figure 24. ASTM D113 Ductility Mold

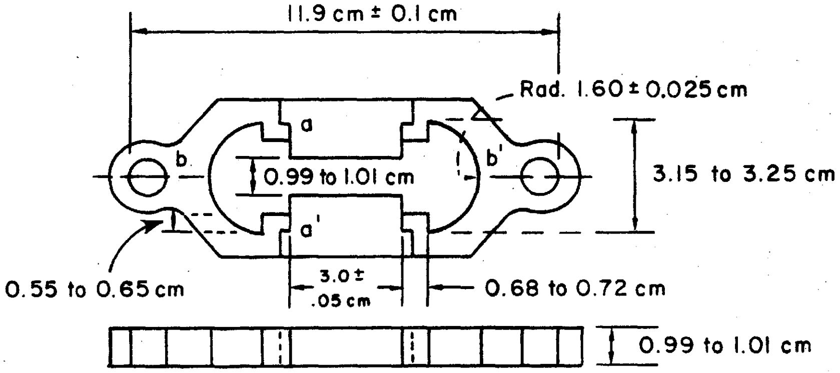


Figure 25. Force - Ductility Mold

cross-sectional area for a distance of approximately 3 centimeters. This mold geometry produces a deformation rate of 0.74 ± 0.01 cm/min. between the gage marks of the test specimen at a fixed grips test rate of 1 cm/min.

Force data is transferred from the load cells to analog recording equipment. Signals received by this equipment are then transferred to a microcomputer. Data are stored on magnetic computer disks for later reduction and analysis. Individual components of the force-ductility apparatus are shown in Figure 26.

Raw data obtained from the force ductility machine are initially in terms of a force-time relationship. However, the constant deformation rate of 0.74 cm/min. allows conversion of force-time information to force-strain data. Stress data is calculated using the initial one square centimeter cross sectional area. True stress is obtained by calculating the change in cross-section as the specimen increases in length. Engineering strain is obtained by dividing the change in gauge length by the original gauge length as follows:

$$\varepsilon_e = \frac{\Delta L_o}{L_o}$$

True strain is obtained by summing all engineering strains and evaluating the limit as L_o approaches zero or,

$$\varepsilon_L = \int_{L_o}^{L} \frac{dL_o}{L_o} = \ln (L) - \ln (L_o)$$

$$= \ln (\frac{L}{L_o}) = \ln (\frac{L_o + \Delta L_o}{L_o}$$

$$= \ln (1 + \varepsilon_e)$$

Modulus of elasticity was determined by evaluating the slope of the stress-strain curve. Two slopes were evaluated. The initial slope of the stress-strain curve in the linear region under primary loading will be referred to as the "asphalt modulus". A second slope was observed for certain blends which was characterized by secondary loading and will be

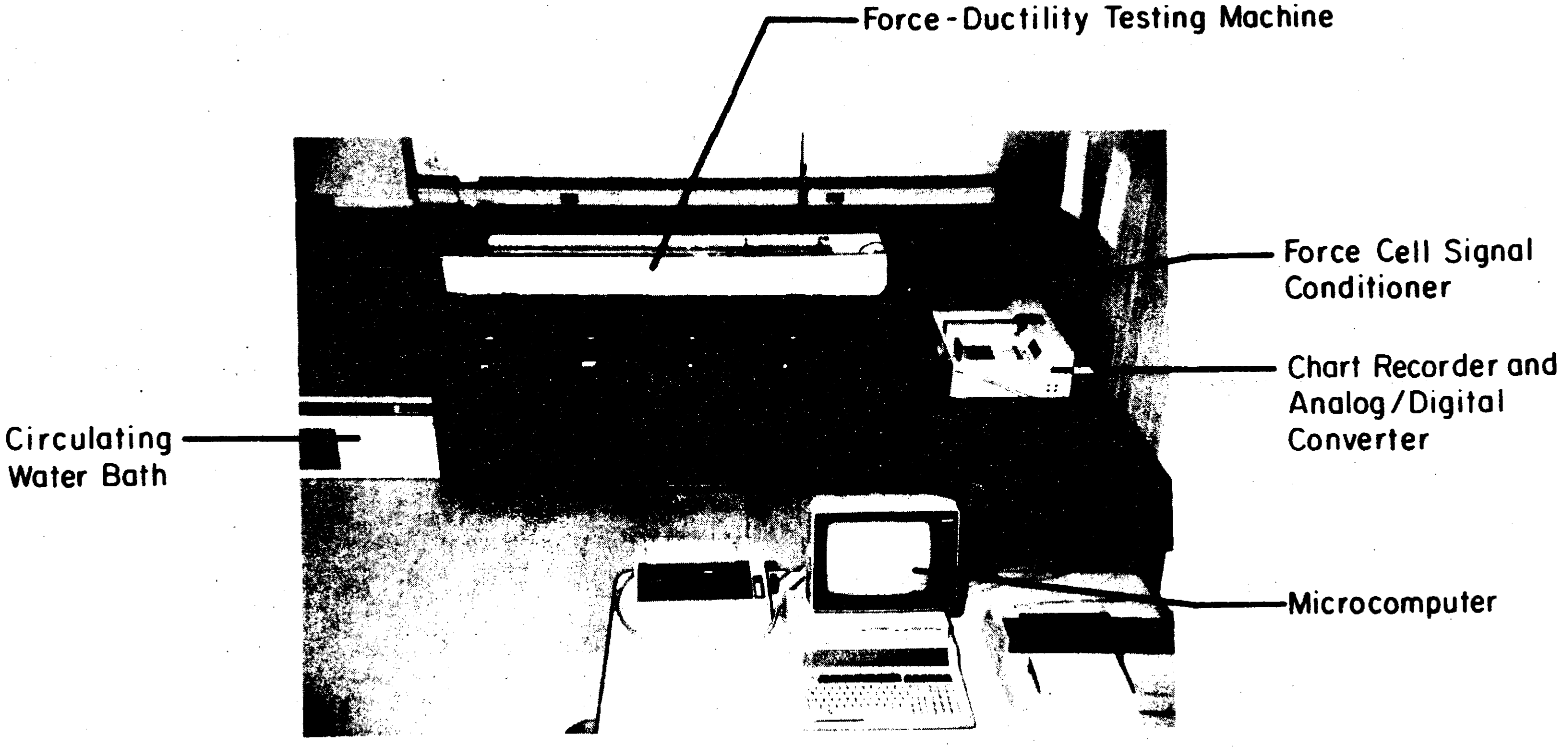


Figure 26. Force-Ductility Testing Apparatus

referred to as "asphalt-rubber modulus". An example of a typical stress-strain curve which depicts these parameters is shown in Figure 27.

Procedure

Asphalt-rubber was heated with constant stirring to 375F on a hot plate. Two specimen molds were assembled on a brass plate and, to prevent sticking, the plate and interior surfaces of pieces were coated with a glycerin-talc mixture. The heated asphalt-rubber was poured into the prepared molds from end to end until the molds were more than level full. The filled molds were allowed to cool to room temperature for 15 minutes and then placed in the water bath at test temperature of 39.2 F for 15 minutes. The excess asphalt-rubber was then trimmed with a hot putty knife to make each mold just level full. The trimmed specimens were returned to the water bath for 30 minutes before testing.

Side pieces a and a' were detached and the test specimens were removed from the brass plate. Each specimen was attached to a load cell and to the movable ductility testing carriage. Excess slack in the loading system was removed by recording a 0.10 pound load on each load cell. Testing proceeded at 1 cm/min. fixed grips rate until both specimens ruptured.

Software written to accomplish data transfer and reduction from the Hewlett Packard 86B microcomputer is included in Appendix C.

Double Ball Softening Point

This test is based on a concept proposed by Krchma (18) for characterization of asphalts. It is a modified version of the ASTM Ring and Ball Softening Point Test (19).

The double ball softening point test apparatus consists of two 3/8 inch diameter stainless ball bearings cemented together with the test material. One of the ball bearings is fixed to the ring holder of the

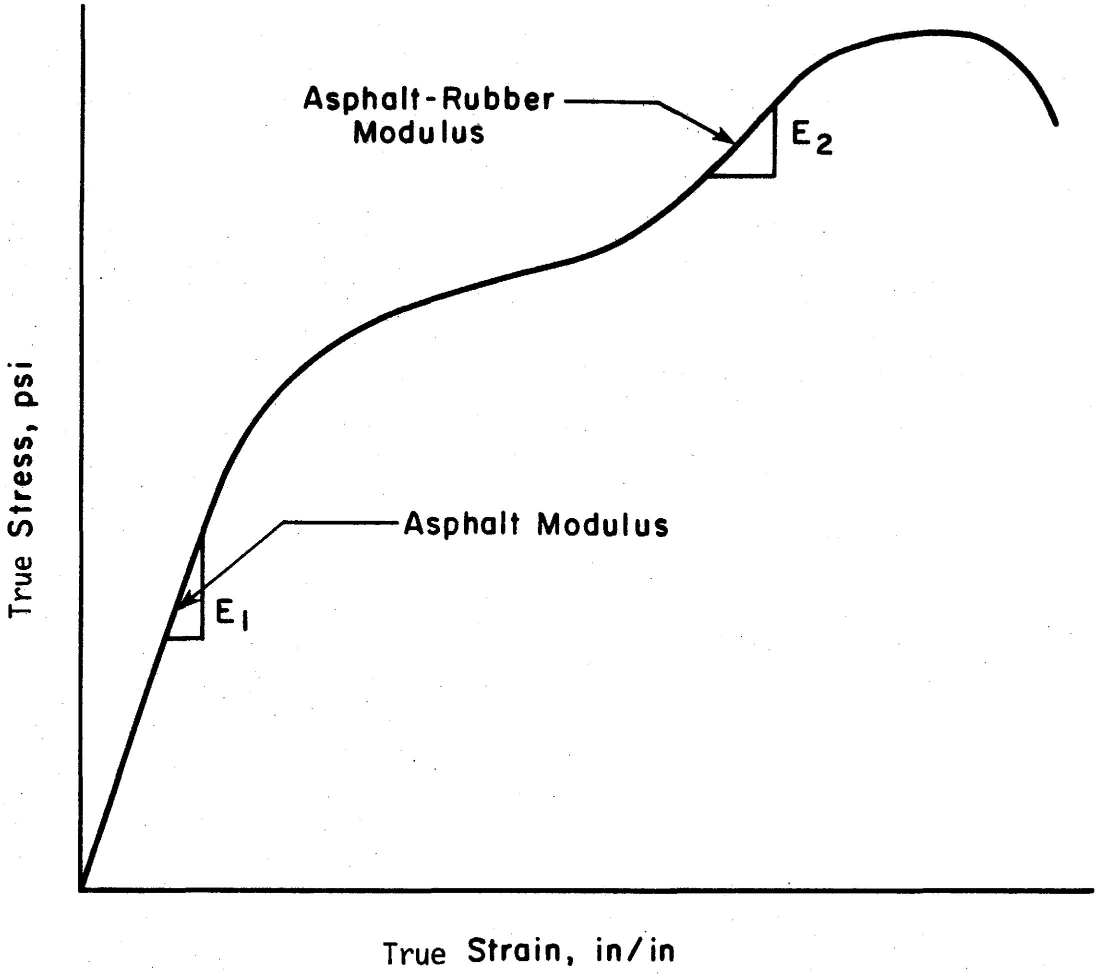


Figure 27. Representative Asphalt-Rubber Stress-Strain Curve

standard ring and ball assembly, the other ball is suspended from the first by the test material. Figure 28 is a schematic representation.

Heat is applied to the immersed assembly in the manner described by ASTM (19). As temperature rises in the apparatus, the weight of the lower ball begins to stretch the asphalt-rubber specimen. Double ball softening point is recorded as the temperature in the bath between the specimens as each suspended ball reaches the bottom plate of the assembly.

Procedure

A custom mold was fabricated to produce test specimens as shown in Figure 28. A block of aluminum was drilled and bored such that the height of the block was equal to the total length of asphalt-rubber specimen and attached ball bearings. The block is split to allow removal of the specimen. A ball bearing was inserted in a bored hole in the aluminum block. The block was positioned such that the ball lies at the bottom of the bored hole. A sample of asphalt-rubber heated to 375F was placed in the bored hole filling the space above the lower ball bearing. The top ball bearing was inserted in the bored hole and pushed down until the top of the bearing was flush with the top of the aluminum block. Excess asphalt-rubber exuding from around the ball bearings was removed. The molded specimens were allowed to cool at room temperature for 30 minutes, the halves of the aluminum block were separated, and the test specimens placed in a 39.2F water bath for 60 minutes.

Two specimens were tested in each beaker by suspending the upper ball from a magnet fixed in the ring and ball support stand. The support stand containing test specimens and thermometer were immersed in 39.2 F water in the beaker and testing begun. Testing progressed after this point in accordance with procedures described by ASTM D36 (19).

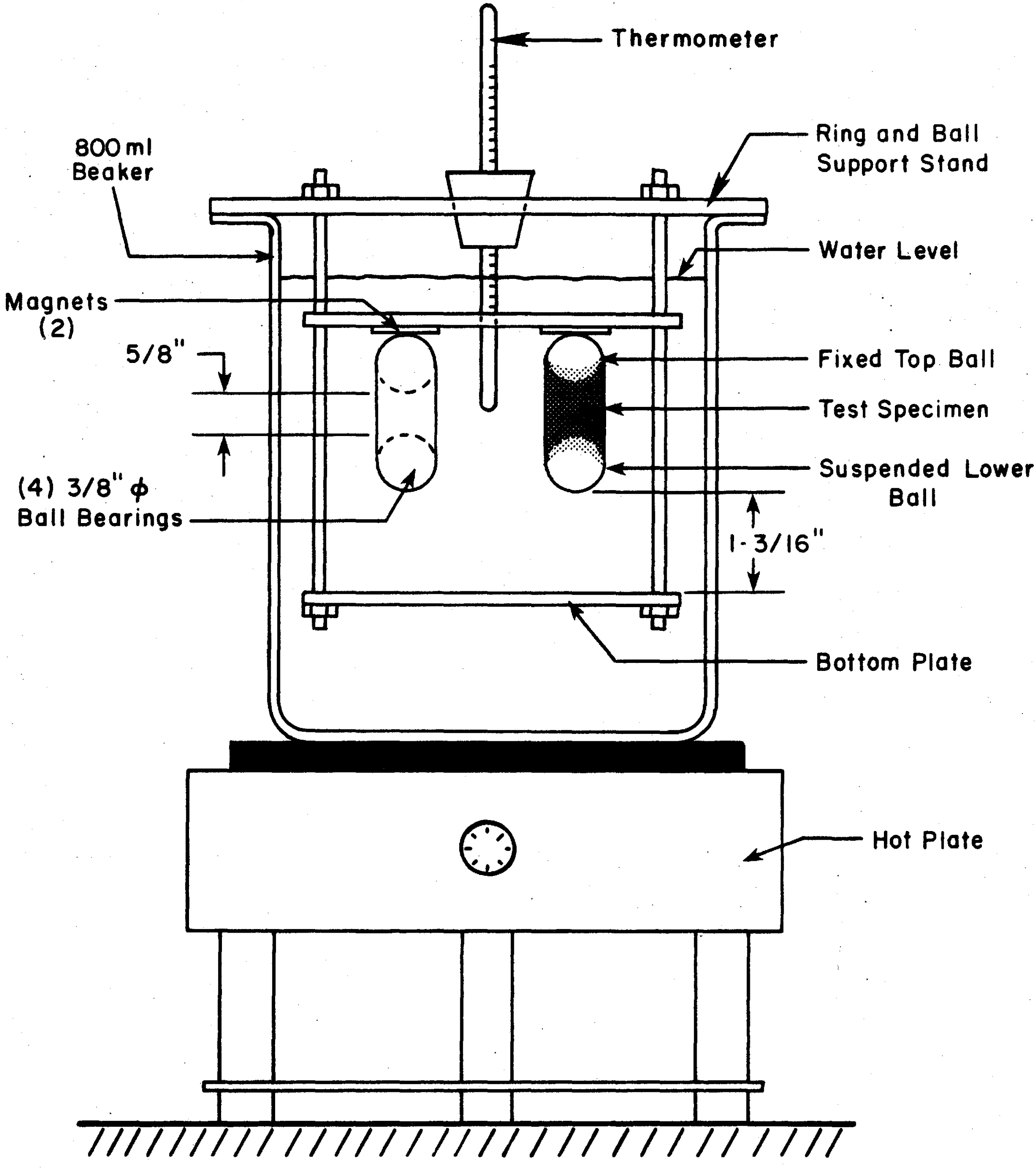


Figure 28. Double Ball Softening Point Apparatus

CHAPTER VII

LABORATORY TEST RESULTS

Force ductility and double ball softening point were performed with asphalt-rubber mixes prepared in the field and in the laboratory. Laboratory mixes were prepared using the Torque Fork Mixer. All testing was performed using a completely random sequence to minimize bias and help assure assumptions of analysis of variance were met. The following test results have, therefore, been analyzed assuming normal and independent random errors with homogeneous variance.

Torque Fork Mixer

All laboratory blends of asphalt-rubber were prepared in the torque fork as previously described. Twenty-seven blends were prepared for all combinations of variables as shown in Figure 6. Output from the torque fork is in terms of millivolts of electromotive force required to maintain a stirring speed of 500 rpm. This output is shown in Figures 29 to 31 for blends with 22 percent, 24 percent and 26 percent rubber by weight. Although millivolts may be used for a relative comparison of viscosity between blends, a more desirable unit of viscosity would be a poise or stoke. Therefore, a relationship between millivolts output and poises was established. This relationship should be used to compare only general correspondence between millivolts and poises for asphalt-rubber since the 'calibration' was accomplished with AC-10.

The AC-10 asphalt from the El Paso Test Road was stirred at 500 rpm using the torque fork at a range of temperatures. The resulting output in millivolts was recorded. Viscosity at a range of temperatures was determined using a Brookfield viscometer. A relationship was then determined between Brookfield viscosity and torque fork millivolts for this AC-10 asphalt as shown in Figure 32. Approximate viscosity of

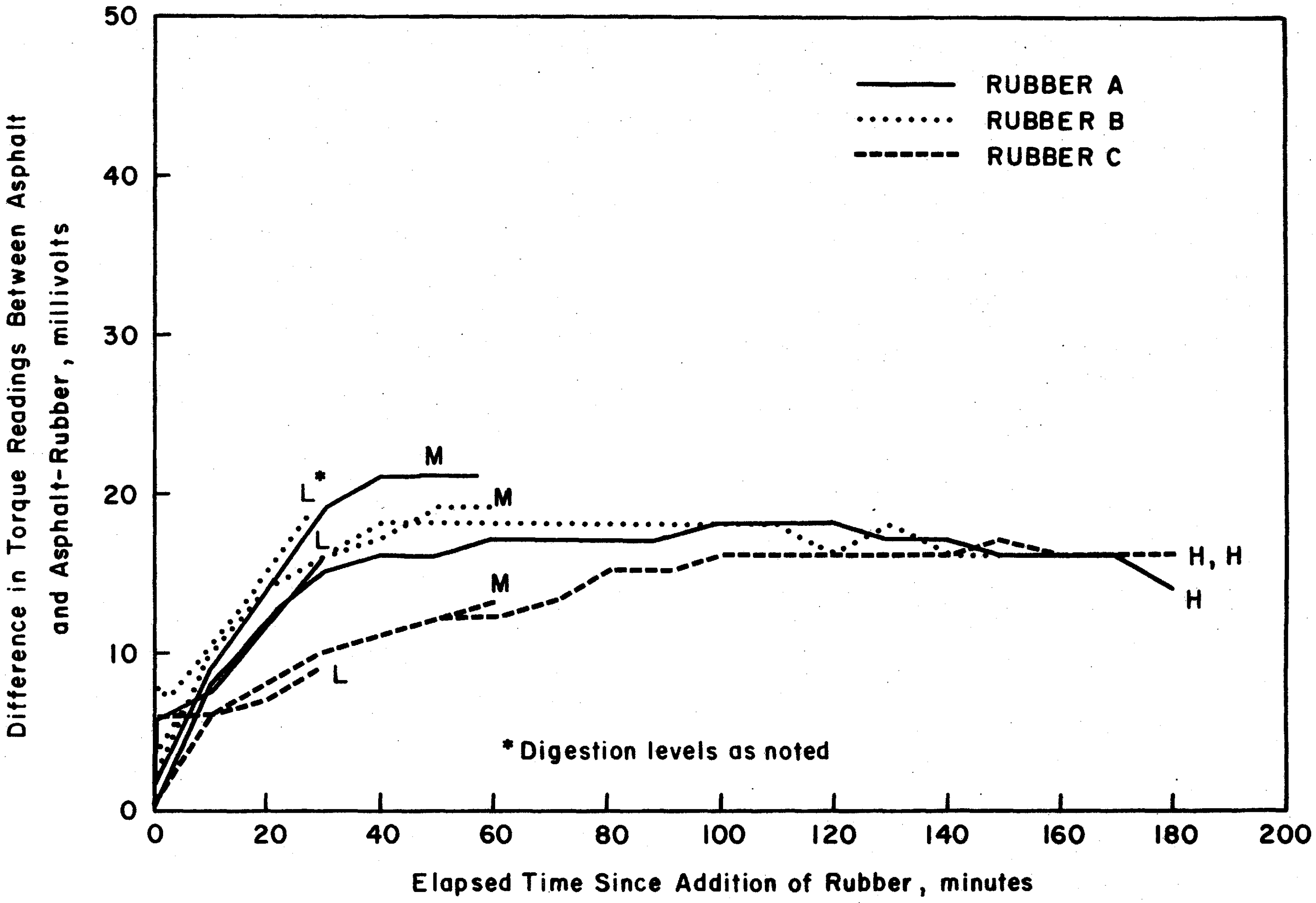


Figure 29. El Paso Torque Fork Output - 22 Percent Rubber

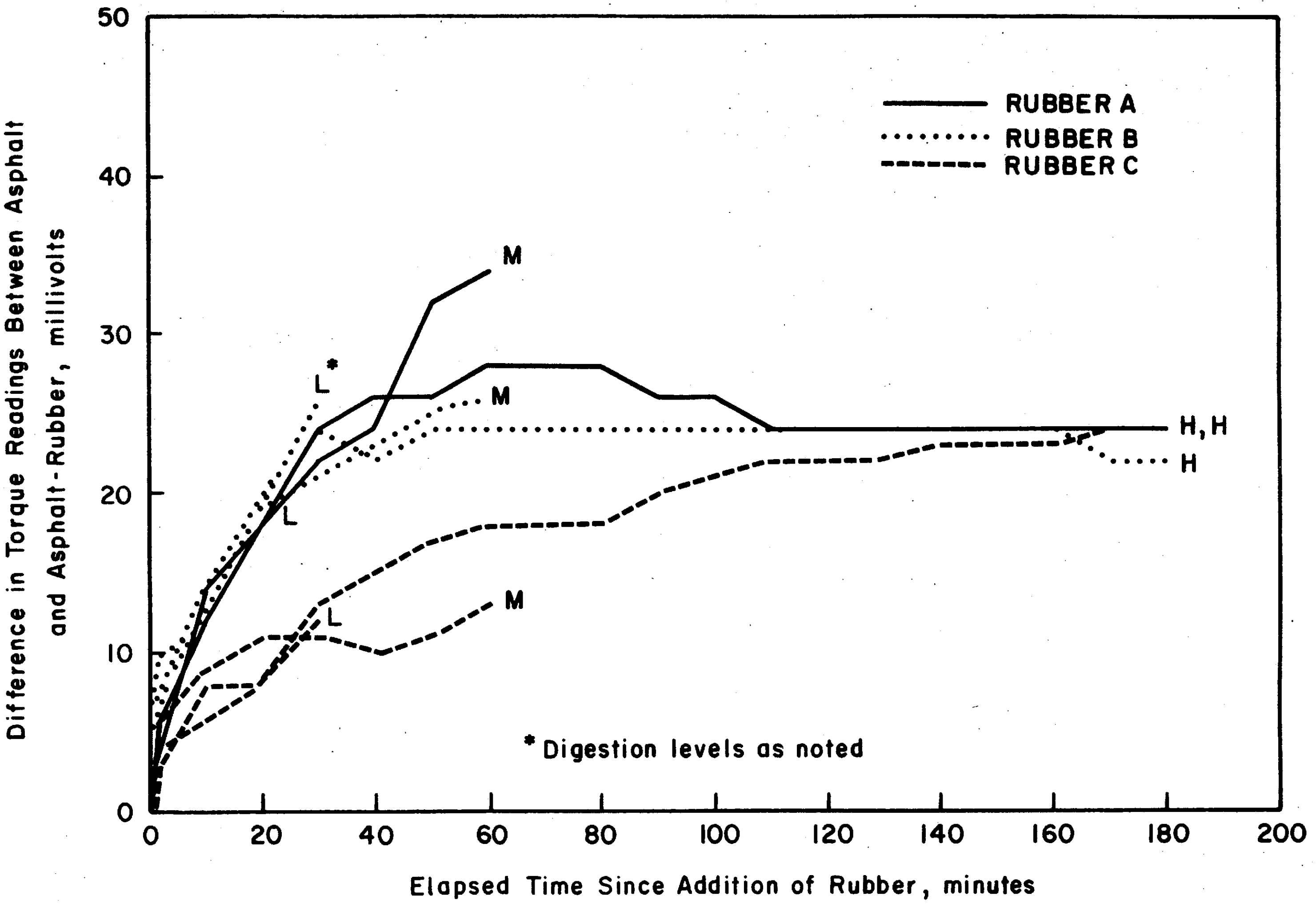


Figure 30. El Paso Torque Fork Output - 24 Percent Rubber

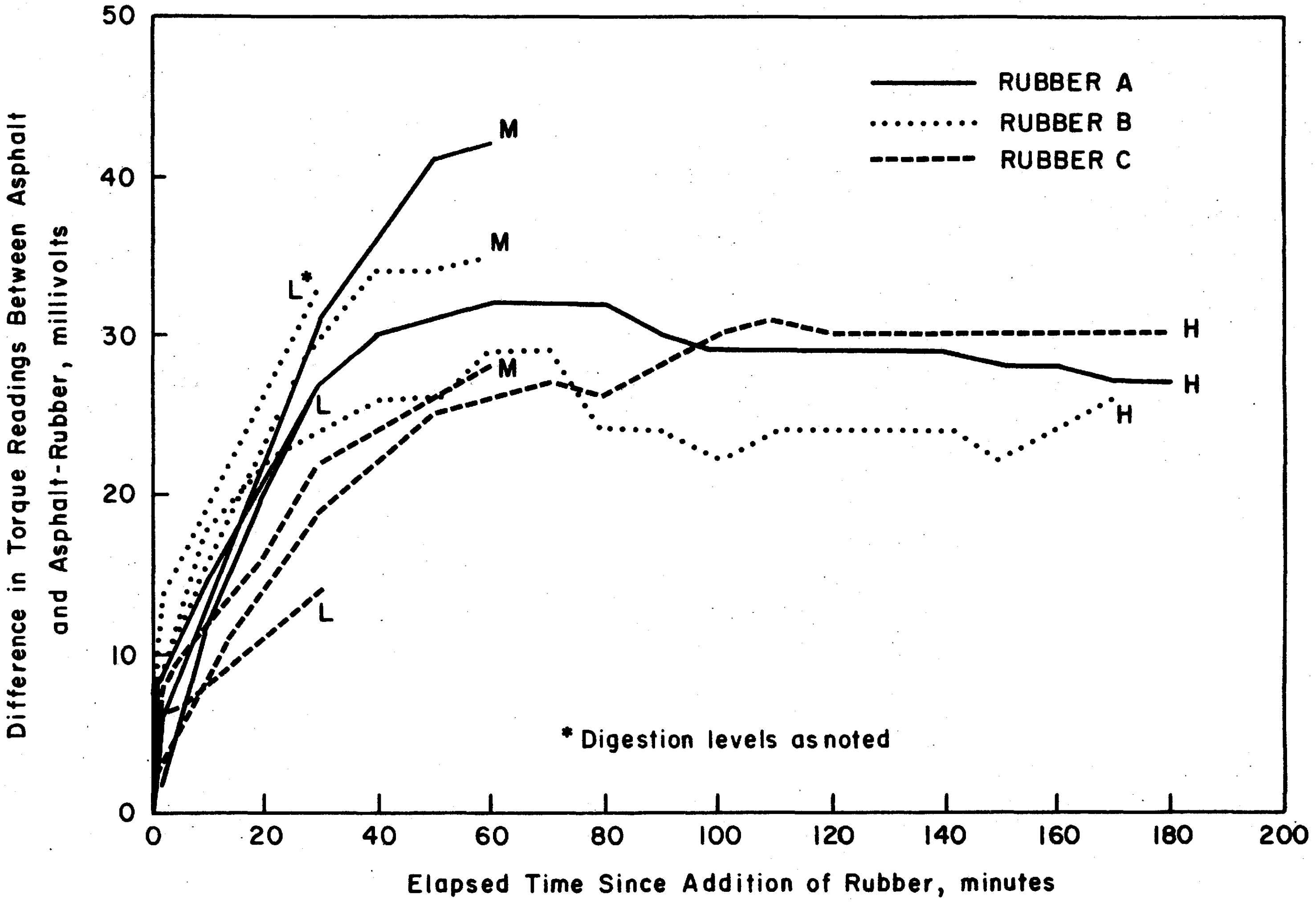


Figure 31. El Paso Torque Fork Output - 26 Percent Rubber

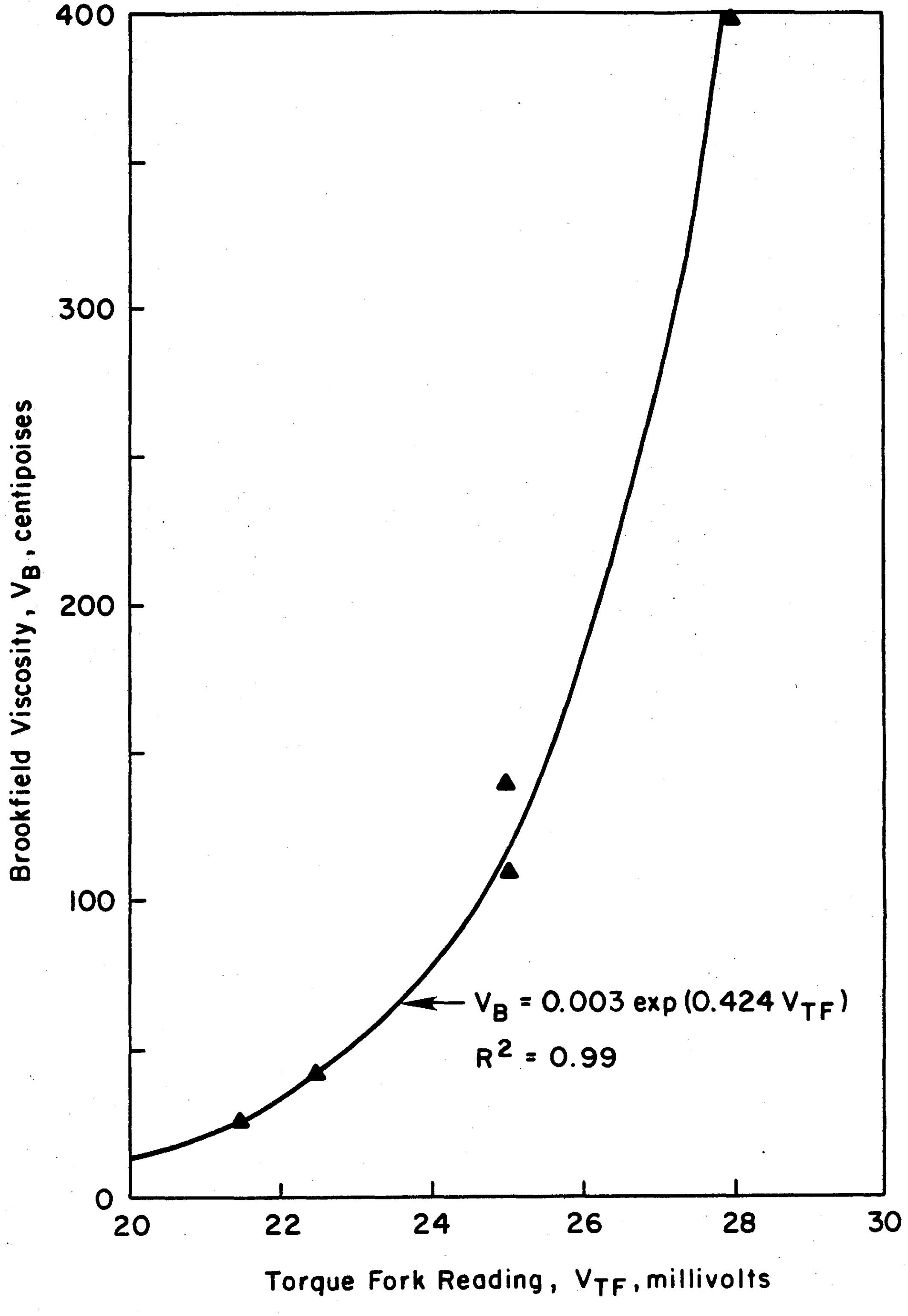


Figure 32. Relationship Between V_{TF} and V_B

asphalt-rubber can be determined using this relationship for millivolts and centipoises.

Data from Figures 29 to 31 were analyzed by regression techniques to yield the simplified results shown in Figure 33. All data from each of Figures 28 to 30 were used to generate curves representing mixtures containing 22 percent, 24 percent, and 26 percent rubber, respectively. Although the correlation coefficient for each curve is low, a trend to increased viscosity with increased rubber content is apparent. This is not an unexpected result since higher percentages of solids in liquid media have been shown theoretically to increase relative viscosity for mixtures of colloids in low concentrations (20). The viscosity of each blend follows a power function reaching approximately constant viscosity from 40 to 60 minutes after the addition of rubber to the hot asphalt. A simple mixture of solid particles in liquid would be expected to increase viscosity relative to the rate at which the solid was introduced (20). Therefore, the rapid rate which rubber was added to the blends should produce a corresponding rapid increase in viscosity. However, a relatively long period was required for the viscosity of the asphalt-rubber blends to increase and stabilize at relatively constant viscosity. This may suggest two things. First, approximately one hour may be required for the rubber to be wetted by the asphalt such that the relative viscosity of the blend can be measured by the torque fork. Second, some form of reaction may be occurring between the asphalt and rubber which raises viscosity beyond that explained by theory (7,20).

An attempt at explaining this phenomenon was made by calculating the relative viscosity for asphalt and rubber blends with 22 percent, 24 percent, and 26 percent rubber. Several models are available which predict the increase in viscosity of fluids with addition of solids. Available models which predict viscosity change are based on empirical adaptations of the Einstein relationship for relative viscosity, $\eta_{rel} = \eta/\eta_o$, where η is the mixture viscosity and $_o$ is the viscosity of the continuous phase. As concentration, particle shape and viscosity change, the original Einstein model becomes inapporopriate. Various adaptations of this original model have been proposed which better predict the actual

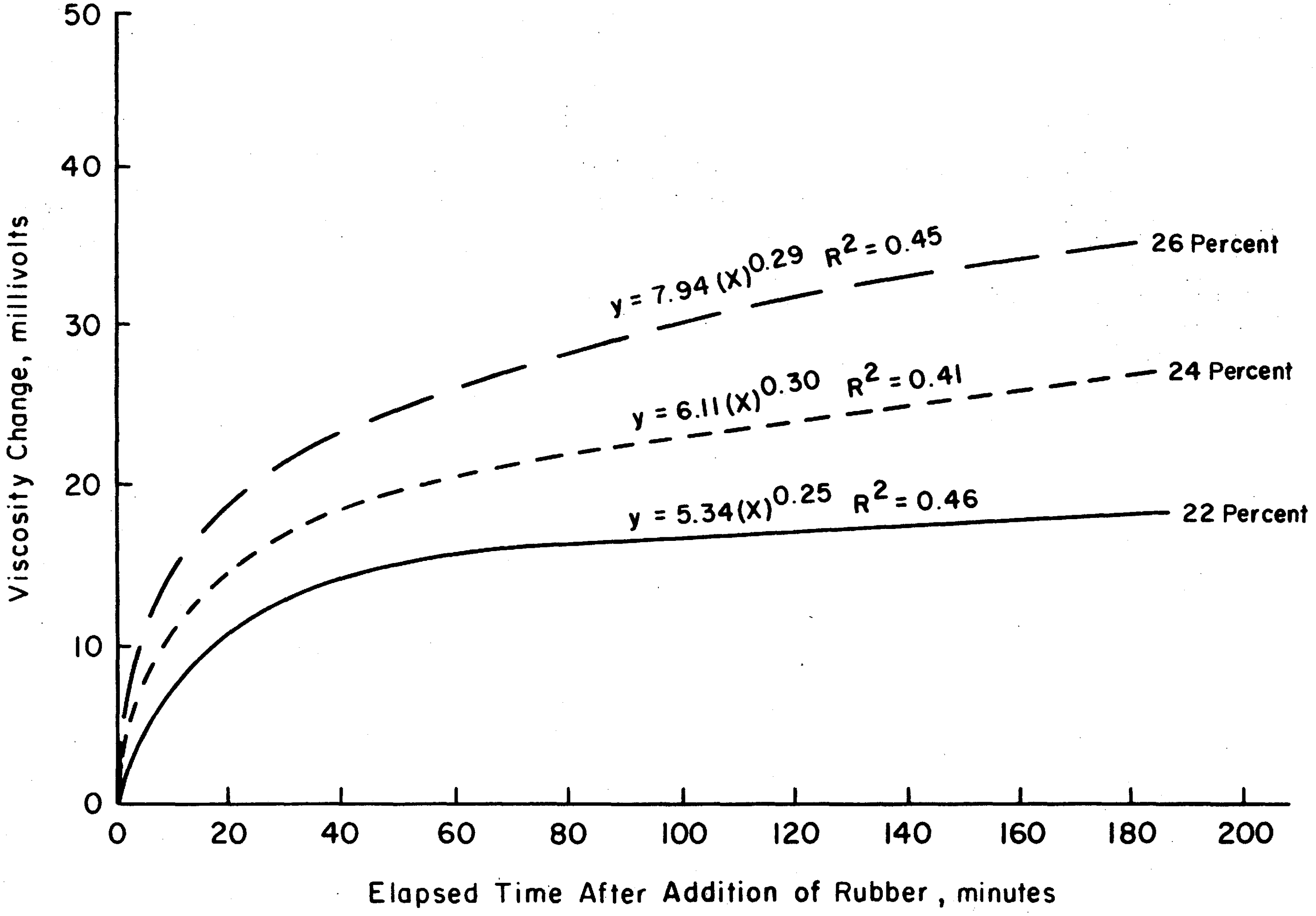


Figure 33. El Paso Torque Fork Viscosity

viscosity behavior of mixtures. Two such models as well as others are discussed by Frisch and Simka (20) and are included in Table 22 for comparison with values for relative viscosity obtained using the torque fork.

Relative viscosity is calculated based on rubber percent by volume in the blend. Specific gravity measurements of asphalt-rubber blends at various temperatures indicate that volume increases by asphalt-rubber blends at elevated temperatures can be explained by thermal coefficient of expansion calculations as shown in Figure 16. Rubber volume was, therefore, determined using a calculated increase in volume using constants of thermal coefficient of expansion.

Work by others (7) to determine rubber volume change in asphalt indicates that larger volume changes occur when rubber is immersed in heated oil than in asphalt. Such fluids as Califlux G. P., Dutrex 739 and Docal 166 have been used to produce rubber volume changes of 50 percent to 100 percent. Work in this project estimated similar results for tread and sidewall truck tire rubber when immersed in SAE 10W motor oil at 400 F. Rubber cubes initially measuring approximately one centimeter were measured with calipers after 0.25, 2, and 6 hours in the heated oil. Figure 34 depicts the increase in volume measured for the two types of rubber. Note from Figure 34 that after two hours a 30 to 38 percent increase in rubber volume over that expected from thermal expansion takes place. This has also been observed by others (7) however, this high volume increase seems to occur only for rubber in oil. Rubber in asphalt appears to increase in volume only slightly as shown in this experiment by specific gravity measurements, Figure 16, and the excellent agreement of theoretical and measured viscosity data, Table 22. The Brinkman equation appears to predict measured viscosity of asphalt-rubber best. This correspondence is apparently due to accounting by the model for addition of individual particles to the dilute suspension until a concentrated suspension is developed.

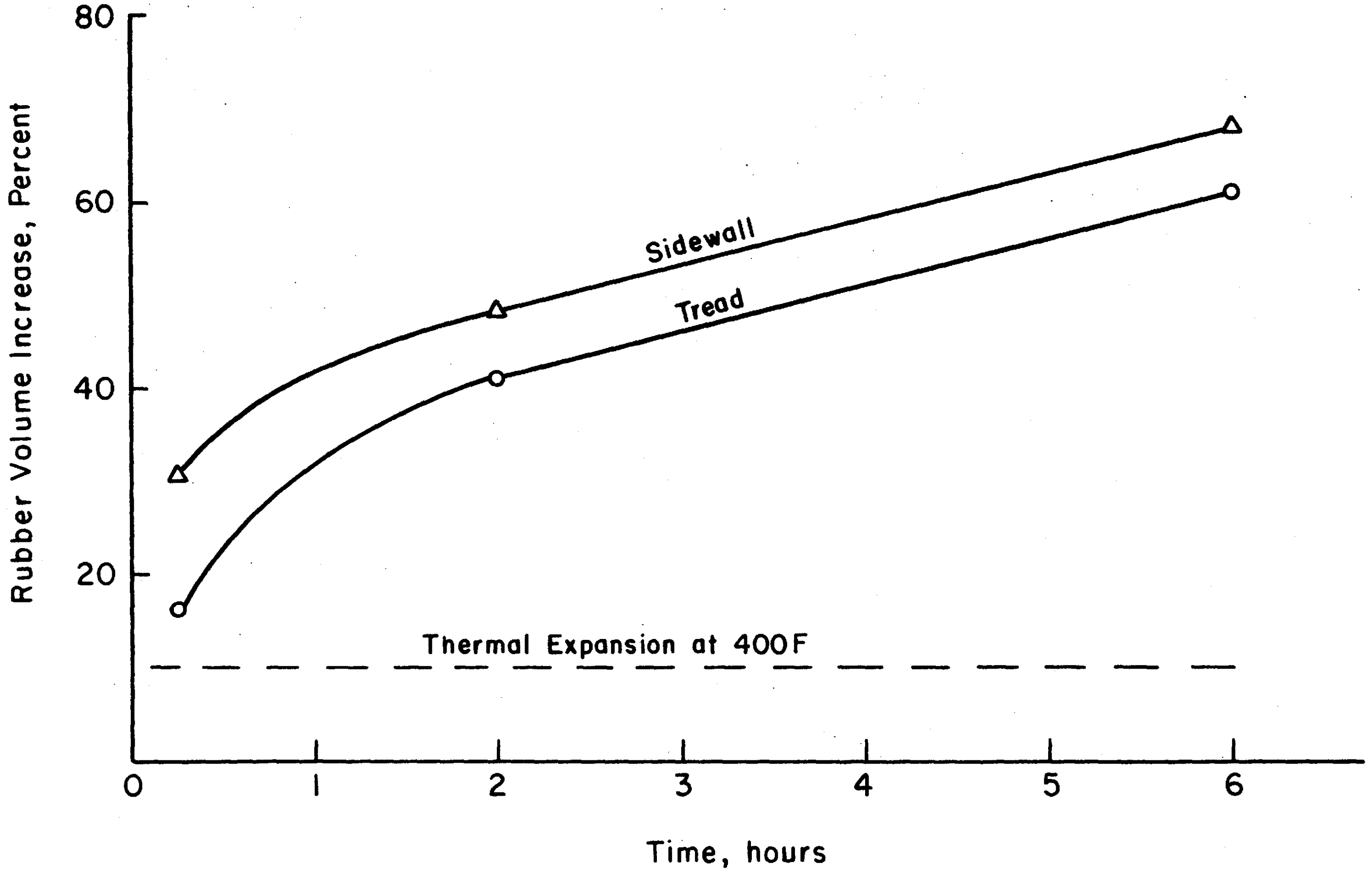


Figure 34. Rubber Volume Change in Oil at 400F

Force Ductility

Seven test responses appearing in Table 23 were measured from results of each force ductility test for both field prepared and laboratory prepared mixes. Multiple analysis of variance (ANOVA) techniques were employed to determine whether differences in material properties could be measured between the various factors investigated.

El Paso Mixes

Results of all tests appear in Appendix D, Tables D1 to D14. Values shown in Appendix D represent an average of two test results obtained during testing. A summary of ANOVA results from lab mixes appear in Table 23. Table 23 contains statistically significant test results at alpha $\leq$ 0.05 for test parameters and corresponding experimental factors. Table 24 provides similar information for results of field prepared asphalt-rubber mixes evaluated by force ductility.

After judging differences between control variables significant at alpha $\leq$ 0.05, the Newman-Keuls (21) multiple comparison procedure was used to judge which treatment means contributed to the significant ANOVA results. Newman-Keuls analysis was applied when ANOVA indicated significance as shown in Tables 23 and 24. The results of the Newman-Keuls analysis appear in Tables 25 and 26 for laboratory and field prepared mixes.

Buffalo Mixes

Analysis of variance results for seven response variables appear in Tables D15 to D21 for field mixed asphalt-rubber and Tables D22 to D28 for laboratory prepared asphalt-rubber mixes. These ANOVA results have been summarized as for the El Paso data in Tables 27 and 28. Entries in these tables are alpha values for alpha $\leq$ 0.05.

Note that for Buffalo field mixes, a significant difference between replicates is rejected at alpha $\leq$ 0.05. However, significance between

Table 23. Statistically Significant Results of ANOVA for Force Ductility Test Measurements of El Paso Lab Mixes.

	Alpha Level $F_{test} = F_{crit}$						
Source of Variation	Max. Engineering Stress	Max. True Stress	Max. Engineering Strain	Max. True Strain	Curve Area	Asphalt Modulus	Asphalt-Rubber Modulus
Rubber	0.05	0.01	0.0001	0.0001	0.001	0.02	0.01
Concentration	0.03	-	-	-	-	0.004	-
Digestion	-	-	0.0001	0.0001	-	0.0001	0.03

Table 24. Statistically Significant Results of ANOVA for Force Ductility Test Measurements of El Paso Field Mixes.

	Alpha Level $F_{test} = F_{crit}$						
Source of Variation	Max. Engineering Stress	Max. True Stress	Max. Engineering Strain	Max. True Strain	Curve Area	Asphalt Modulus	Asphalt-Rubber Modulus
Rubber	-	-	-	-	-	-	0.04
Concentration	-	-	0.002	0.003	-	-	-

Table 25. Results of Newman-Keuls Analysis of Force Ductility Test Measurements for El Paso Lab Mixes.

		Force-Ductility Parameters						
		Max. Engineering Stress, psi (MES)	Max. True Stress, psi (MTS)	Max. Engineering Strain in/in (ESF)	Max. True Strain, (TSF) in/in	Curve Area psi (CA)	Asphalt Modulus psi, (AM)	Asphalt-Rubber Modulus, psi (ARM)
Rubber	A	24.5(xy)	80.3(x)	3.67(x)	1.54(x)	73.6(x)	219.0(xy)	56.8(x)
	B	20.8(x)	87.9(x)	4.61(y)	1.72(y)	78.2(x)	186.7(x)	75.2(xy)
	C	24.2(y)	118.2(y)	4.92(z)	1.77(z)	105.4(y)	249.1(y)	101.1(y)
Concentration, %	22	27.8(y)					259.3(y)	
	24	23.8(xy)					213.1(x)	
	26	20.9(x)					181.4(x)	
ion	L			4.11(x)	1.62(x)		272.1(y)	61.5(x)
				4.24(x)	1.65(x)		210.5(x)	73.3(xy)
					[illegible]		171.1(x)	98.2(y)

Table 26. Results of Newman-Keuls Analysis of Force Ductility Test Measurements for El Paso Field Mixes.

		Force-Ductility Parameters						
		Max. Engineering Stress, psi (MES)	Max. True Stress, psi (MTS)	Max. Engineering Strain, in/in (ESF)	Max. True Strain in/in (TSF)	Curve Area, psi (CA)	Asphalt Modulus psi (AM)	Asphalt-Rubber Modulus, psi (ARM)
Rubber	A							43.6(x)
	B							74.8(y)
	C							65.7(xy)
Concentration, %	22			4.38(xy)	1.68(y)			
	24			3.72(x)	1.55(x)			
	26			3.71(x)				

Table 27. Statistically Significant Results of ANOVA for Force Ductility Test Measurements of Buffalo Lab Mixes.

	Alpha Level $F_{test} = F_{crit}$						
Source of Variation	Max. Engineering Stress	Max. True Stress	Max. Engineering Strain	Max. True Strain	Curve Area	Asphalt Modulus	Asphalt-Rubber Modulus
Concentration						0.001	0.01
Digestion	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.001
D x C	0.01	0.05			0.001	0.03	

Table 28. Statistically Significant Results of ANOVA for Force Ductility Test Measurements of Buffalo Field Mixes.

	Alpha Level $F_{test} = F_{crit}$						
Source of Variation	Max. Engineering Stress	Max. True Stress	Max. Engineering Strain	Max. True Strain	Curve Area	Asphalt Modulus	Asphalt-Rubber Modulus
Concentration	0.03		0.01	0.02			0.04
Digestion	0.005	0.02	0.0001	0.0002	0.02	0.01	0.01
Replicate							

digestion periods and between rubber concentrations is detected using parameters MES, MTS, and ARM.

Different digestion periods for laboratory mixed asphalt - rubber produces highly significant ANOVA results for each parameter tested as shown in Table 27.

Asphalt-rubber modulus (ARM) indicates significance for concentration and digestion. This is the only parameter which identifies significance for both of these factors in both field prepared and laboratory prepared mixes.

Newman-Keuls analysis was used for Buffalo mixes to determine which levels of factors were significantly different as described by ANOVA. This analysis is trivial for Buffalo field mixes since only two levels were measured for each factor. Results are shown in Table 29 such that trends present in the data can be more easily observed. The results of the Newman-Keuls analysis for laboratory prepared mixes appear in Table 30.

Double Ball Softening Point

Analysis of variance was used to judge the precision of the new double-ball softening point test. Results of these tests appear in Appendix D, Tables D29 and D30 for El Paso materials and Tables D31 and D32 for Buffalo materials.

El Paso Mixes

ANOVA results for laboratory mixes indicate no significant differences for main factors or interactions at an alpha level of 0.05. The test is sensitive to rubber type at an alpha level of 0.18 and to the rubber-digestion interaction at alpha = 0.14.

ANOVA results for field mixed material indicate sensitivity for differences in rubber concentartion at alpha = 0.18 and to rubber-concentration interaction at alpha = 0.06.

Table 29. Results of Newman-Keuls Analysis of Force Ductility Test Measurements for Buffalo Field Mixes.

		Force-Ductility Parameters						
		Max. Engineering Stress, psi (MES)	Max. True Stress, psi (MTS)	Max. Engineering Strain in/in (ESF)	Max. True Strain (TSF) in/in	Curve Area, psi (CA)	Asphalt Modulus psi (AM)	Asphalt-Rubber Modulus, psi (ARM)
Concentration, %	18	8.6(x)		6.3(y)	2.0(y)			33.7(x)
	22	18.7(y)		5.5(x)	1.8(x)			48.3(y)
Digestion	L	14.7(y)	63.4(y)	5.1(x)	1.8(x)	59.4(y)	113.8(y)	44.8(y)
	H	7.7(x)	42.7(x)	6.6(y)	2.0(y)	41.6(x)	51.8(x)	32.2(x)

Table 30. Results of Newman-Keuls Analysis of Force-Ductility Test Measurements for Buffalo Lab Mixes.

		Force-Ductility Parameters						
		Max. Engineering Stress (MES)	Max. True Stress, psi (MTS)	Max. Engineering Strain in/in (ESF)	Max. True Strain (TSF) in/in	Curve Area psi (CA)	Asphalt Modulus psi (AM)	Asphalt-Rubber Modulus, psi (ARM)
Concentration, %	18						94.0(y)	33.9(x)
	22						52.6(x)	44.9(y)
Digestion	L	19.5(z)	65.3(y)	4.32(x)	1.67(x)	67.9(y)	125.1(z)	37.5(x)
	M	12.8(y)	64.9(y)	5.73(y)	1.90(y)	62.7(y)	27.8(y)	52.2(y)
	H	6.5(x)	34.5(x)	6.46(y)	2.01(z)	35.3(x)	41.5(x)	28.7(x)

Buffalo Mixes

The double ball softening point test appears sensitive to changes in the Buffalo material. ANOVA results for field prepared mixes shown in Table D32 indicate that the test is sensitive to changes in rubber concentration and digestion conditions with highly significant test statistics. Asphalt-rubber mixes were replicated in the field and this factor was evaluated by ANOVA as shown in Table D32.

Replication appears significant at alpha = 0.07. This indicates that although care was taken to prepare identical replicate test sections in the field, differences exist between these replicates which cannot be explained purely by chance.

Similar results for lab prepared Buffalo mixes are shown in Table D31. ANOVA results indicate that the softening point is highly sensitive to rubber digestion and concentration conditions and less sensitive to the interaction of these factors. Newman-Keuls analysis indicates the softening point obtained from the high digestion mixes is significantly different from softening point results for materials fabricated at low and medium digestion levels. The trend appears to be toward a lower softening point as digestion level increases as seen in Table 31. The same trend appears for field prepared mixes as shown by Table 32. Softening point increases as rubber concentration increases, and the significant interaction of concentration and digestion suggests that softening point for low concentration-low digestion mixes may be similar to high concentration-high digestion mixes. This means that the optimum behavior of asphalt-rubber mixes may be obtained by adjusting rubber content and digestion conditions.

Brownsville Mixes

Force ductility and softening point data for field mixes appears in Table D33. Force ductility and softening point data for lab mixes is presented in Tables D34 and D41. ANOVA results for Brownsville lab mixes appear in Table 33. All parameters except engineering and true strain appear sensitive to changes in laboratory digestion. Newman-Keuls

Table 31. Results of Newman-Keuls Analysis of Softening Point Test Measurements for Buffalo Lab Mixes.

		Softening Point, F	
Concentration, %	18	113.7	(x)
	22	118.2	(y)
Digestion	Low	119.7	(y)
	Med	119.2	(y)
	High	109.1	(x)

Table 32. Results of Newman-Keuls Analysis of Softening Point Test Measurements for Buffalo Field Mixes.

		Softening Point, F	
Concentration, %	18	114.3	(x)
	22	119.3	(y)
Digestion	Low	118.9	(y)
	High	114.7	(x)

Table 33. ANOVA Force Ductility and Softening Point, Brownsville Lab Mixes

	Alpha Level F table = F critical							
Source of Variation	Max. Engineering Stress	Max. True Stress	Max. Engineering Strain	Max. True Strain	Curve Area	Asphalt Modulus	Asphalt-Rubber Modulus	Double Ball Softening Point
Digestion	0.01	0.0004	-	-	0.0004	0.003	0.001	0.0001

results appear in Table 34. Note the inverse relationship between each parameter and digestion condition.

Field and lab prepared data are shown in Tables D33 and D41. ANOVA results indicate digestion affects softening point as shown in Table 33 and Newman-Keuls analysis indicates softening point decreases as digestion increases as shown in Table 34.

Table 34. Newman-Keuls All Parameters, Brownsville Lab Mixes.

Digestion	Parameters							
	Max. Engineering Stress, psi (MES)	Max. True Stress, psi (MTS)	Max. Engineering Strain in/in (ESF)	Max. True Strain, (TSF) in/in	Curve Area psi (CA)	Asphalt Modulus psi (AM)	Asphalt-Rubber Modulus, psi (ARM)	Double Ball Softening Point (SP)
L	13.05 (y)	78.35 (y)	-	-	75.13 (y)	79.12 (y)	67.62 (y)	114.82 (y)
M	11.42 (y)	82.35 (y)	-	-	74.23 (y)	67.72 (y)	75.20 (y)	118.17 (y)
H	5.94 (x)	26.53 (x)	-	-	30.26 (x)	40.38 (x)	18.33 (x)	103.73 (x)

Note: Letters in parentheses of the same type indicate no significant difference by ANOVA at alpha$\leq$ .05.

CHAPTER VIII

ANALYSIS

Analysis of variance (ANOVA) results discussed previously have been used to measure sensitivity of force ductility and softening point parameters. Sensitivity is judged by the ability to identify differences in asphalt-rubber properties as rubber type, concentration, and digestion conditions are varied. Results of ANOVA indicate that not every force ductility parameter nor softening point result can detect differences in asphalt-rubber properties for all test conditions.

It is the purpose of this chapter to isolate those force- ductility parameters and softening point results which are sensitive to changes in asphalt-rubber formulation and present these changes as trends in materials properties.

Significant effects on test responses due to main factors are summarized in Table 35. Responses are noted in Table 35 which indicate statistical significance for lab and field data and lab data only between El Paso and Buffalo materials. Significant responses due to singular main effects are presented graphically in figures to follow. Multiple effects due to digestion level and rubber concentration for El Paso and Buffalo mixes prepared in the field and laboratory are also shown graphically by figures.

Rubber Concentration

The quantity of rubber in the mix affects the properties of failure strain, asphalt modulus, asphalt-rubber modulus and softening point as shown in Table 35.

Increasing rubber content of the asphalt-rubber mix causes a decrease in engineering and true failure strain for both Buffalo and El Paso mixtures prepared in the field. This relationship appears in Figure 35. Both engineering and true strain are presented in Figure 35, true strain

Table 35. Test Responses Judged Significant by ANOVA.

	Main Factor		
Test Road	Rubber Concentration	Digestion Level	Rubber Type
El Paso	Failure Strain (F)	Failure Strain (L)	Failure Strain (L)
			Failure Stress (L)
	Asphalt Modulus (L)	Asphalt Modulus (L)	Asphalt Modulus (L)
		Asphalt-Rubber Modulus (L)	Asphalt Rubber Modulus (L & F)
			Curve Area (L)
	Failure Strain (F)	Failure Strain (L & F)	
Buffalo		Failure Stress (L & F)	
	Asphalt Modulus (L)	Asphalt Modulus (L & F)	
	Asphalt-Rubber Modulus (L & F)	Asphalt-Rubber Modulus (L & F)	
		Curve Area (L & F)	
	Softening Point (L & F)	Softening Point (L & F)	
Brownsville		Failure Stress (L)	
		Curve Area (L)	
		Asphalt Modulus (L)	
		Asphalt-Rubber Modulus (L)	
		Softening Point (L)	

being a logarithmic transformation of engineering strain as discussed previously.

Figure 35 indicates El Paso mixes to have lower engineering strains at failure than corresponding Buffalo mixes. However, the difference between Buffalo and El Paso true failure strain for 22 percent mixtures does not appear practically significant. In fact, the true failure strain data appear to indicate a general decrease in strain as rubber content increases independent of project location.

Rubber content affects asphalt modulus inversely as shown in Figure 36 for El Paso and Buffalo laboratory mixes. Unlike true failure strain, asphalt modulus does not appear equivalent for Buffalo and El Paso mixes at 22 percent rubber. Rather, El Paso mixes have considerably higher asphalt modulus than corresponding Buffalo mixes.

Asphalt-rubber modulus is directly proportional to rubber content for Buffalo laboratory and field mixes as shown in Figure 37.

Asphalt-rubber stress-strain curves are composed of two slopes, i.e., asphalt modulus (early loading), and asphalt-rubber modulus (later loading). Because asphalt modulus and failure strain are decreasing and asphalt-rubber modulus is increasing with increases in rubber content, the Buffalo asphalt-rubber stress-strain curves are changing shape as shown in Figure 38. However, the asphalt-rubber modulus for El Paso mixtures is not significantly affected by rubber content, and therefore the shape of the stress-strain curve in Figure 38 changes differently as rubber content increases.

The asphalt-rubber modulus measured for laboratory prepared mixes compares closely with values measured for field prepared mixes. This indicates that the laboratory mixing procedure may simulate actual field mixing for the asphalt-rubber modulus parameter.

The Buffalo laboratory and field asphalt-rubber mixes demonstrate an increase in softening point as rubber content increases as shown in Figure 39. Note, as with asphalt-rubber modulus, there appears to be no subjective difference between softening point for laboratory and field

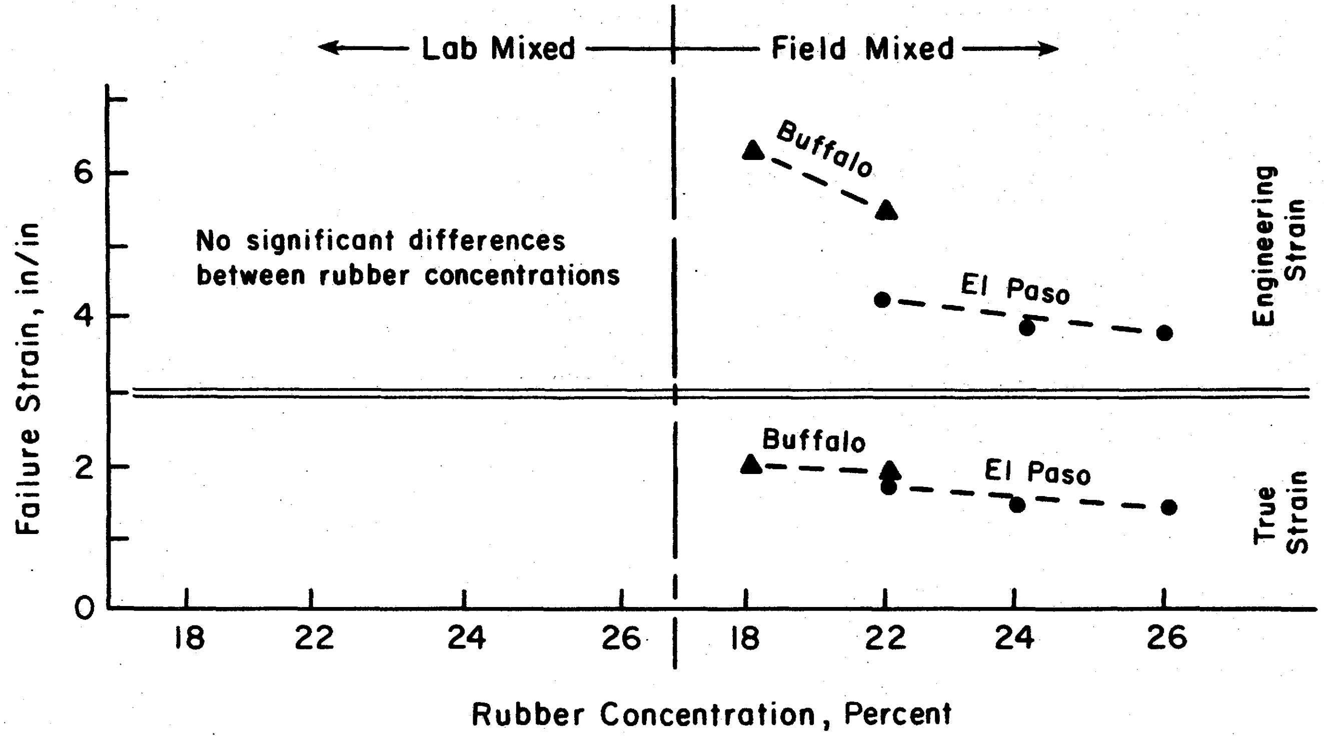


Figure 35. Effect of Rubber Concentration on Failure Strain

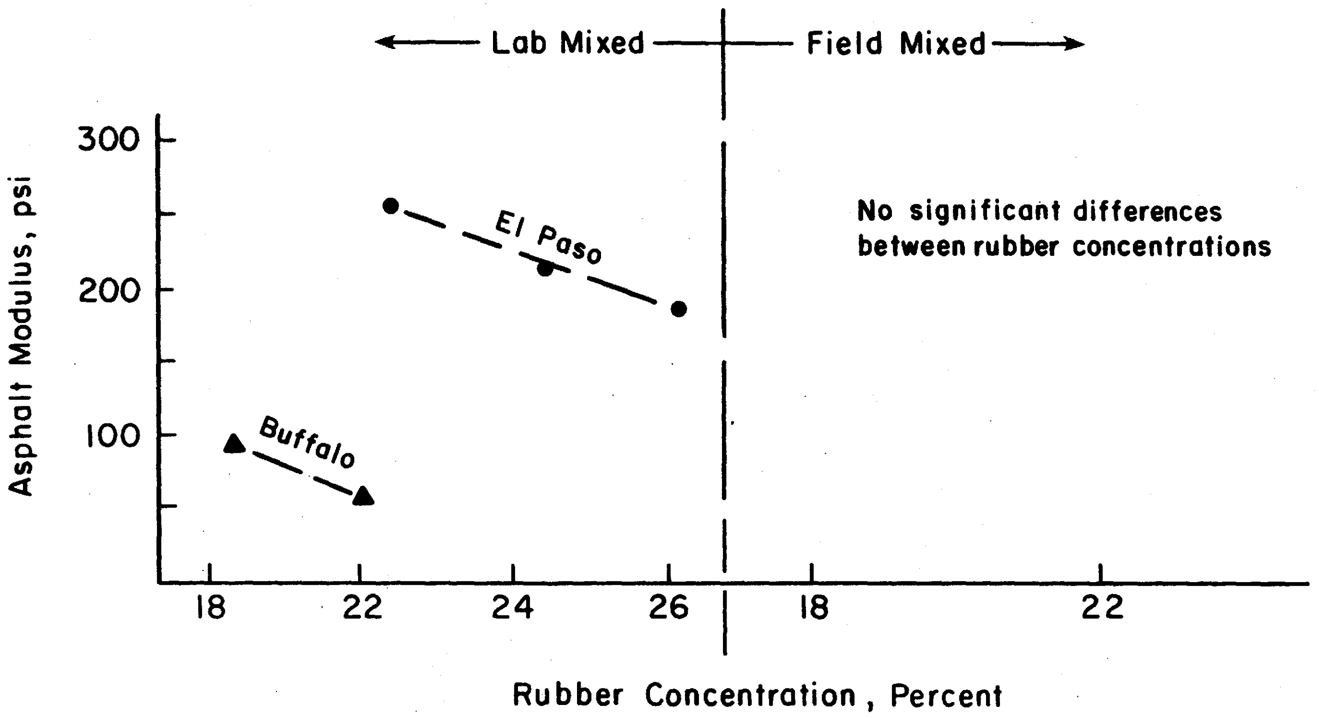


Figure 36. Effect of Rubber Concentration on Asphalt Modulus

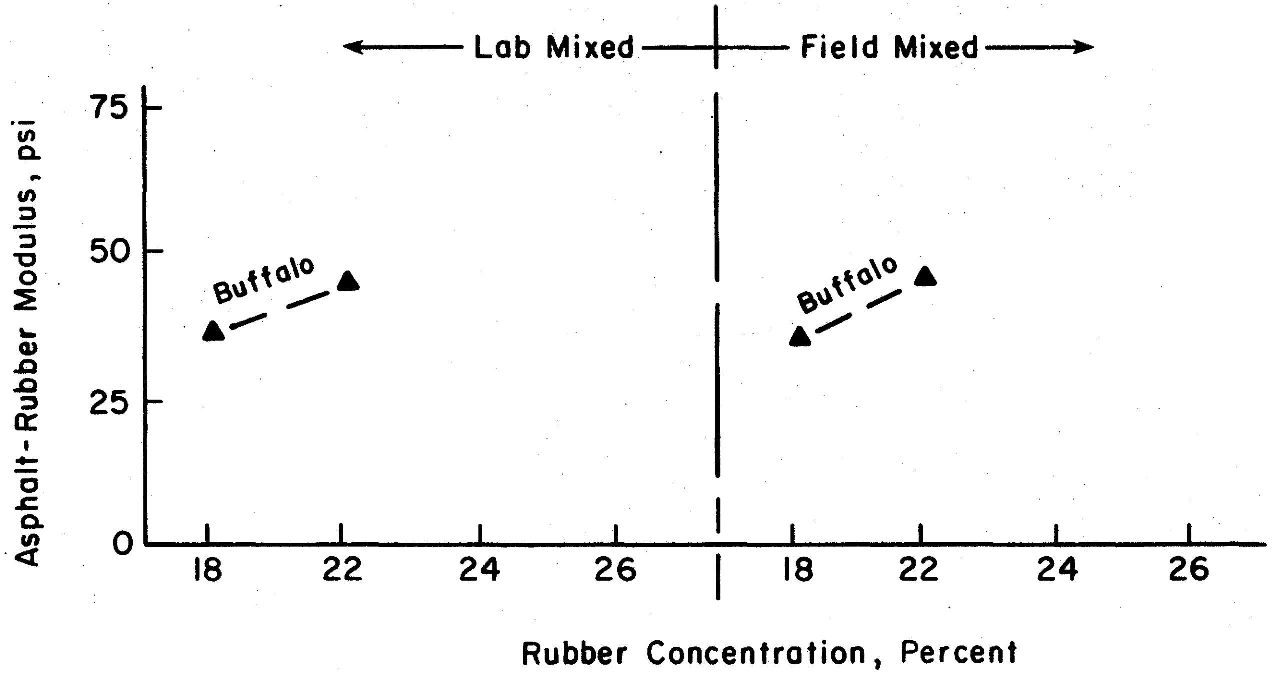


Figure 37. Effect of Rubber Concentration on Asphalt-Rubber Modulus

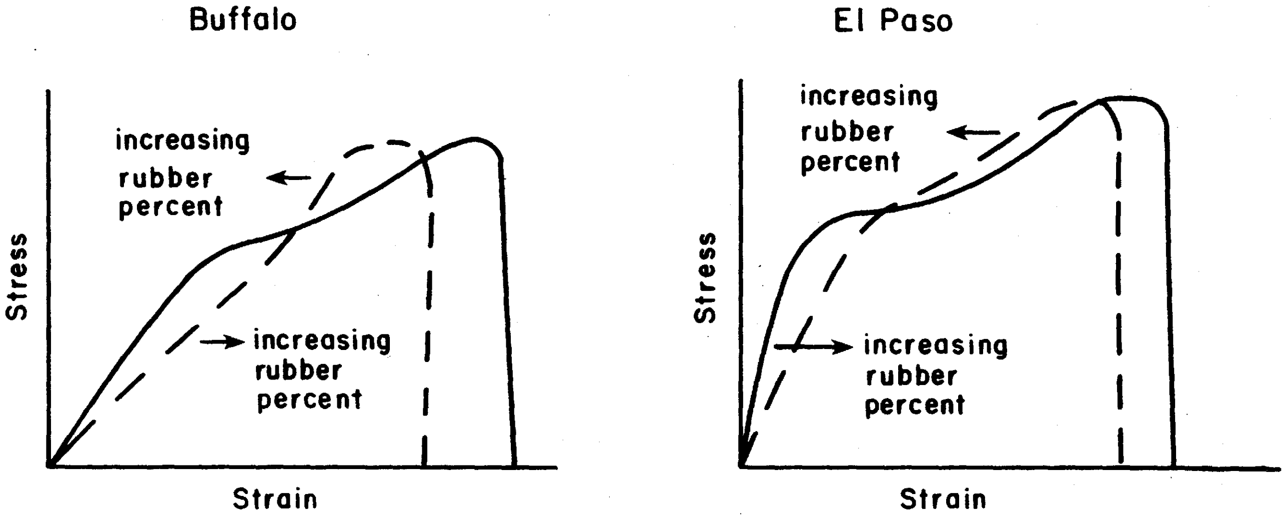


Figure 38. Change in Stress - Strain Curve Due to Increasing Rubber Content

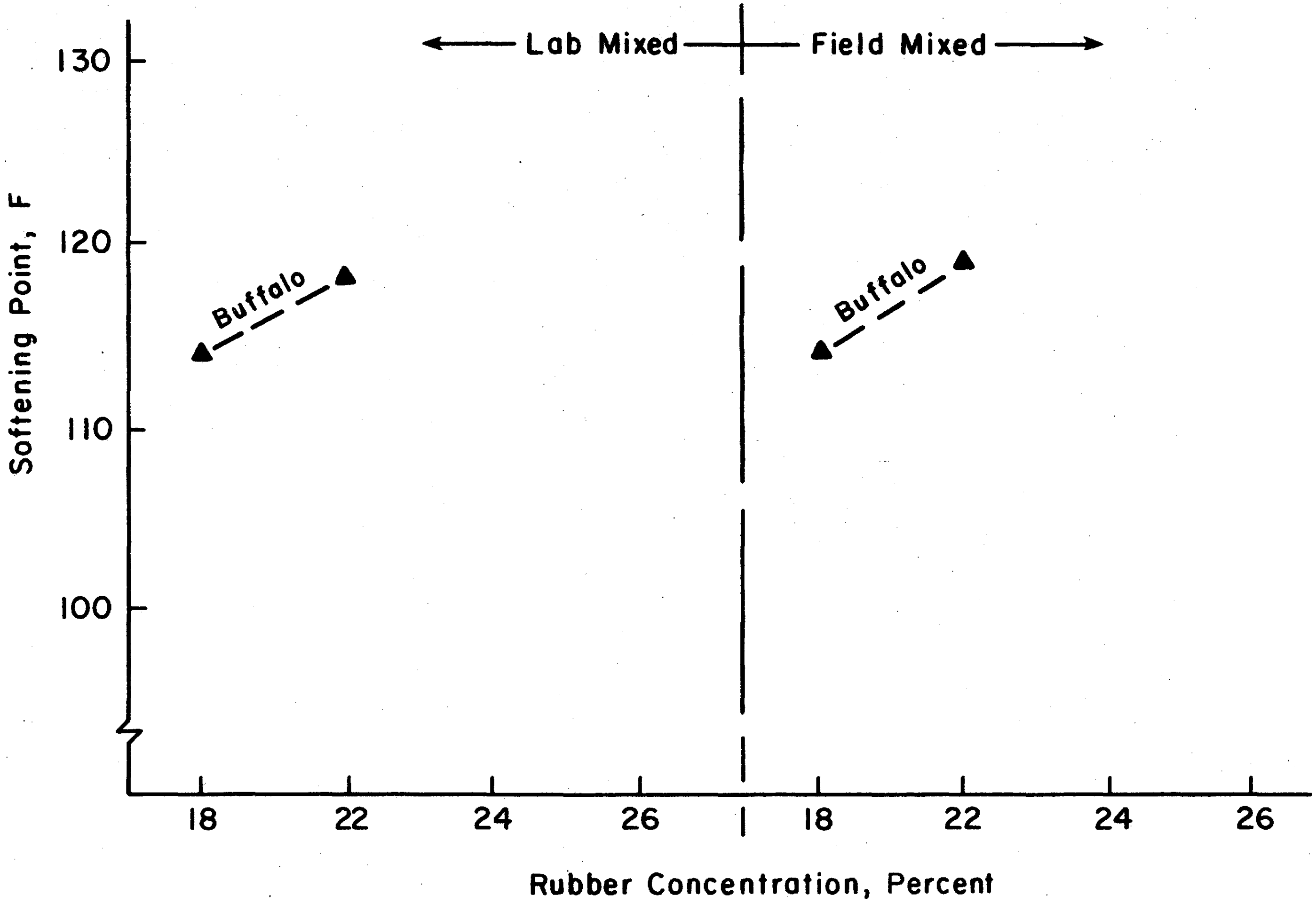


Figure 39. Effect of Rubber Concentration on Softening Point

prepared mixes. However, this test is less sensitive to changes in the El Paso lab prepared materials with insignificant F statistics for rubber content, but better sensitivity to rubber type at alpha = 0.18. Better sensitivity to rubber concentration in El Paso field mixed materials appears at alpha = 0.14 as shown in Table D30.

Digestion Level

Digestion level had no effect on failure stress for El Paso asphalt-rubber mixes but did affect Buffalo mixes prepared in the field and laboratory and Brownsville mixes. Failure stress decreases as digestion level increases as shown in Figure 40. True stress for Buffalo laboratory mixes does not change significantly for low or moderate digestion but rapidly decreases after high digestion. A good correlation appears again between laboratory and field mixes. Low field digestion results in failure stress slightly lower than low lab digestion and high field digestion results in failure stress slightly higher than high lab digestion.

Failure strain increases with increasing digestion level as shown in Figure 41. This is opposite to the effect shown for rubber concentration. This result coupled with that for rubber concentration indicates that high digestion may cause disintegration of rubber which acts to reduce the solid rubber content of the mix.

A test was devised to extract asphalt from asphalt-rubber mixes using a procedure described in ASTM D2172 Method B to determine if rubber disintegrates while digested at various levels with asphalt. The results are shown for Buffalo and El Paso asphalt-rubber blended in the laboratory with 22 percent Type A rubber under the conditions shown:

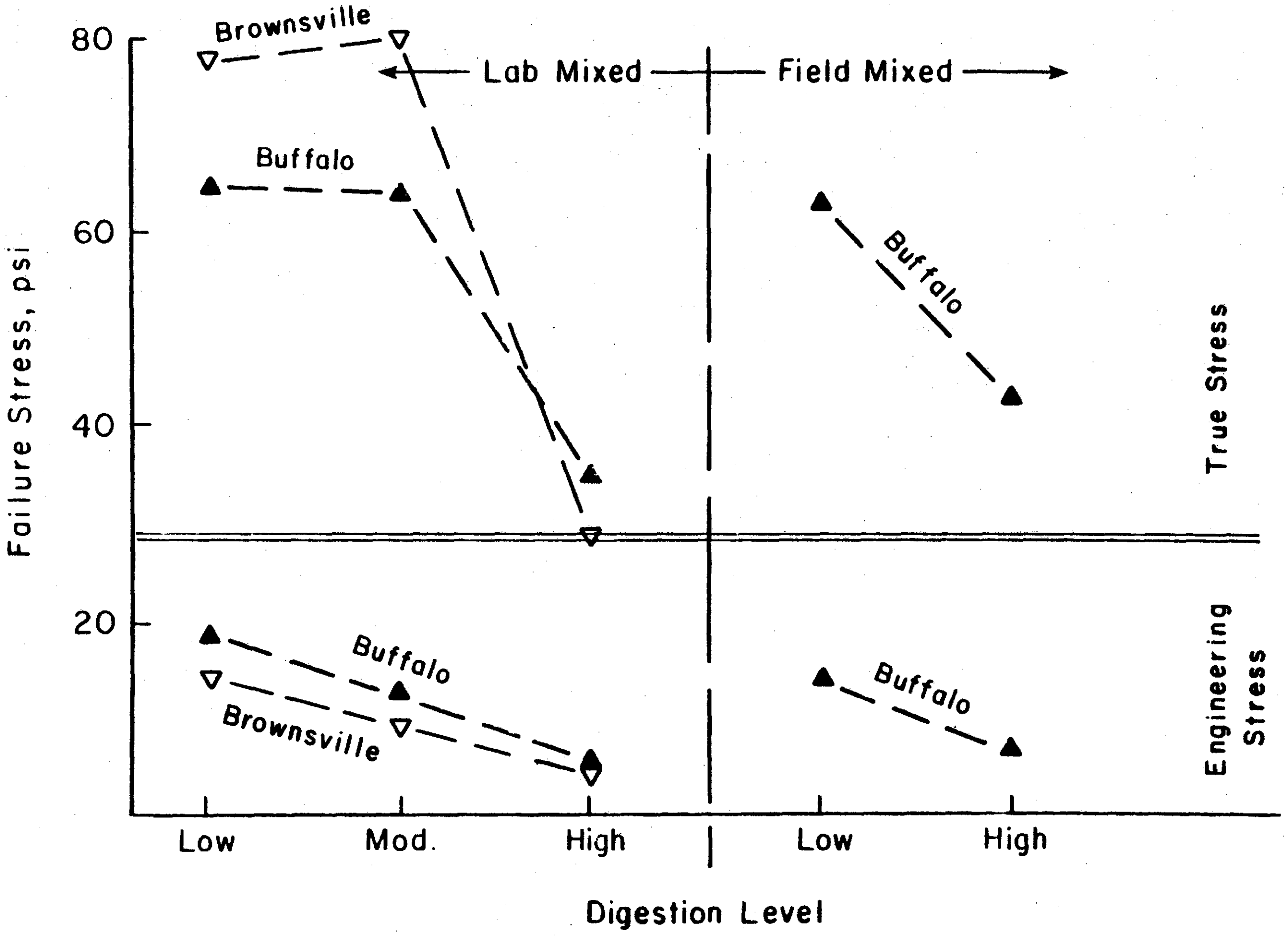


Figure 40. Effect of Digestion Level on Failure Stress.

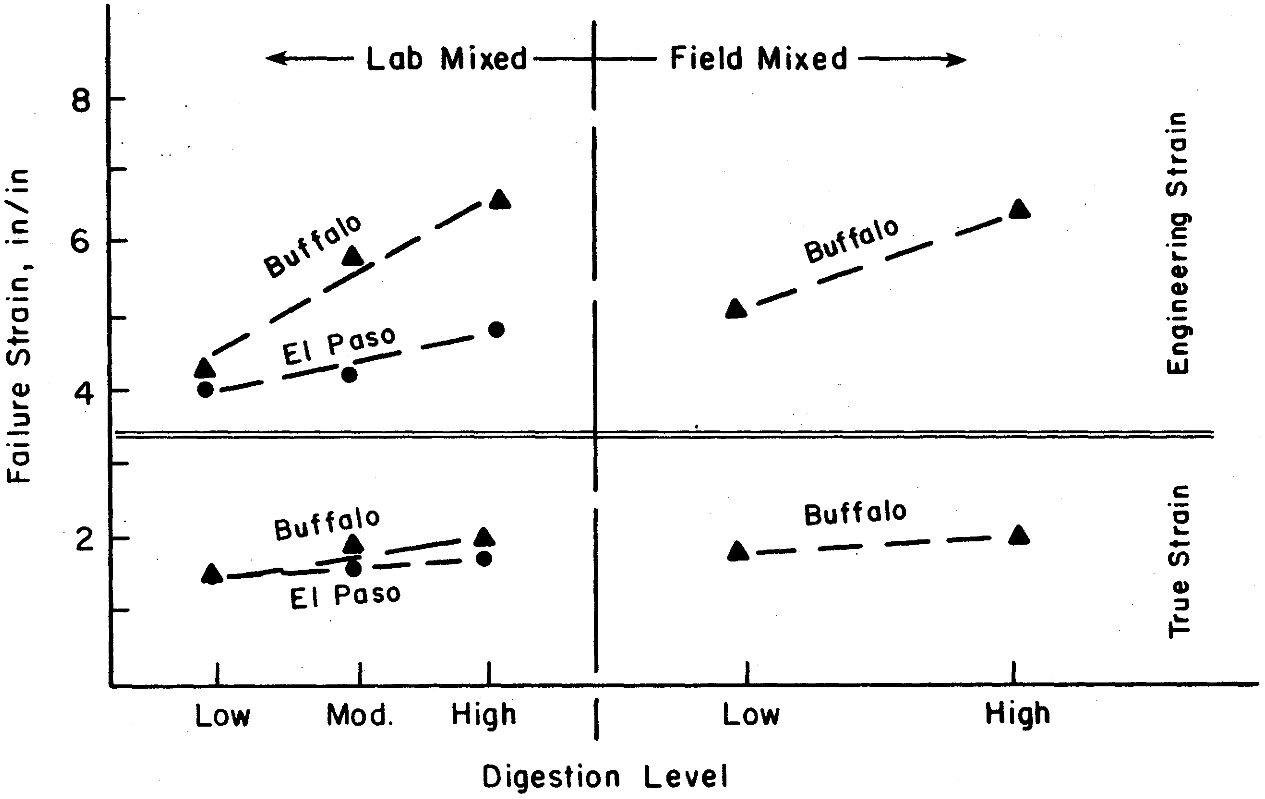


Figure 41. Effect of Digestion Level on Failure Strain

	Test Road			
	Buffalo		El Paso	
Digestion Conditions	Percent Rubber Extracted	Percent Rubber Loss	Percent Rubber Extracted	Percent Rubber Loss
2 hours @ 350F	18.0	18	18.6	15
4 hours @ 450F	15.1	31	15.2	31
24 hours @ 450F	14.6	34	15.1	31

These results support data previously presented which indicates that as digestion level increases, solid rubber disintegrates, leaving less rubber by weight in the mix. Favorable correspondence between lab and field mixed data occurs for failure strain of Buffalo mixes as shown in Figure 41.

Asphalt modulus decreases as digestion level increases for both El Paso and Buffalo lab mixes and Buffalo field mixes as shown in Figure 42. El Paso asphalt modulus is significantly higher than Buffalo and Brownsville lab mixed materials. Buffalo lab and field mixed asphalt modulus values are comparable as with other response variables. Again, low level field digestion produces a response corresponding to between low and moderate lab digestion.

Recall that increasing rubber content produced a decrease in asphalt modulus as presented in Figure 35. The result shown in Figure 42 is opposite that expected from Figure 35 since increasing digestion has been shown to reduce the total solid rubber content in the mixture. The high digestion (reduced rubber content) mixes would produce a higher asphalt modulus than low digestion mixes if reduced solid rubber content was the only result of high digestion. The apparent disagreement of Figures 36 and 42 indicates that a factor other than rubber content alone may affect asphalt modulus. Therefore, it is possible that during the process of digestion, other changes occur in the asphalt-rubber mixture besides a

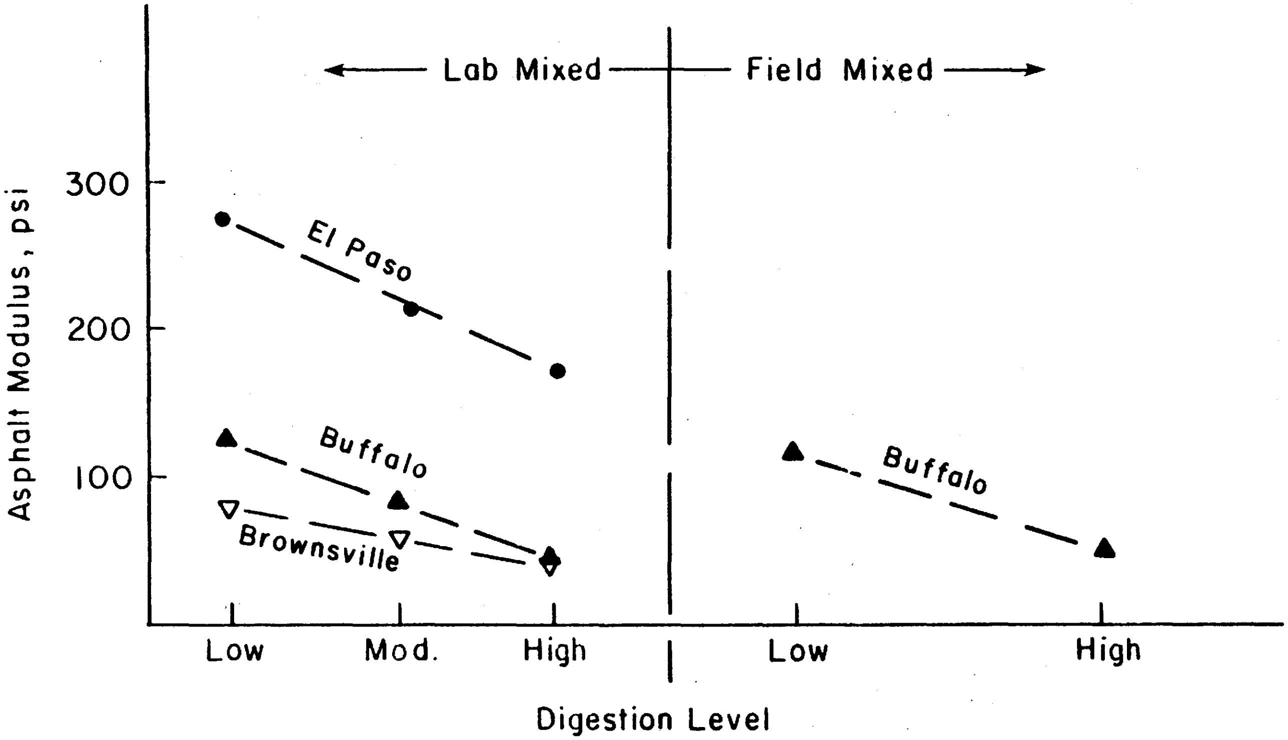


Figure 42. Effect of Digestion Level on Asphalt Modulus

reduction in solid rubber. These unknown changes may affect the behavior of asphalt modulus as well as the reduction in solid rubber.

To help identify such changes, asphalt was analyzed before and after mixing with rubber. The gel permeation chromatography (GPC) test (22) was used to identify changes between original asphalt and asphalt after mixing with rubber. The GPC test provided data regarding the molecular weight distribution of asphalt before and after digestion with rubber. The results are shown in Figure 43 and depict a shift in the molecular weight distribution after digestion. This shift in molecular weight of the asphalt after digestion indicates that alterations have occurred in the asphalt during the digestion process as noted by an increase in high and low molecular weight materials. This means that as digestion continues, some rubber may be lost to the asphalt fraction of the asphalt-rubber mixture. This has been shown by extraction results previously and by the increase in both high and low molecular weights as shown by GPC results in Figure 43. Asphalt modulus as measured by force-ductility is evidently sensitive to this change in the asphalt phase as shown in Figure 42. Therefore, asphalt-rubber evidently is simply not a mixture of solid rubber particles in a continuous asphalt phase, but a more complicated blend of modified asphalt and particulate rubber.

Asphalt-rubber modulus produces inconsistent results as digestion level increases and no general trends are apparent in the data between or within test road materials as shown in Figure 44. Asphalt-rubber modulus tends to increase with increasing digestion for El Paso lab mixed materials but Buffalo lab mixed materials do not demonstrate a clearly increasing or decreasing trend. Rather, the Buffalo laboratory mixed material displays an increase in asphalt-rubber modulus from low to medium digestion, and a decrease from medium to high digestion. From Table 28 we see that asphalt-rubber modulus at low and high digestion are not significantly different values. The Buffalo field mixed material tends to decrease in asphalt-rubber modulus as digestion level increases. This is consistent with Figure 37 which indicates a decrease in asphalt-rubber modulus as rubber content increases. However, general

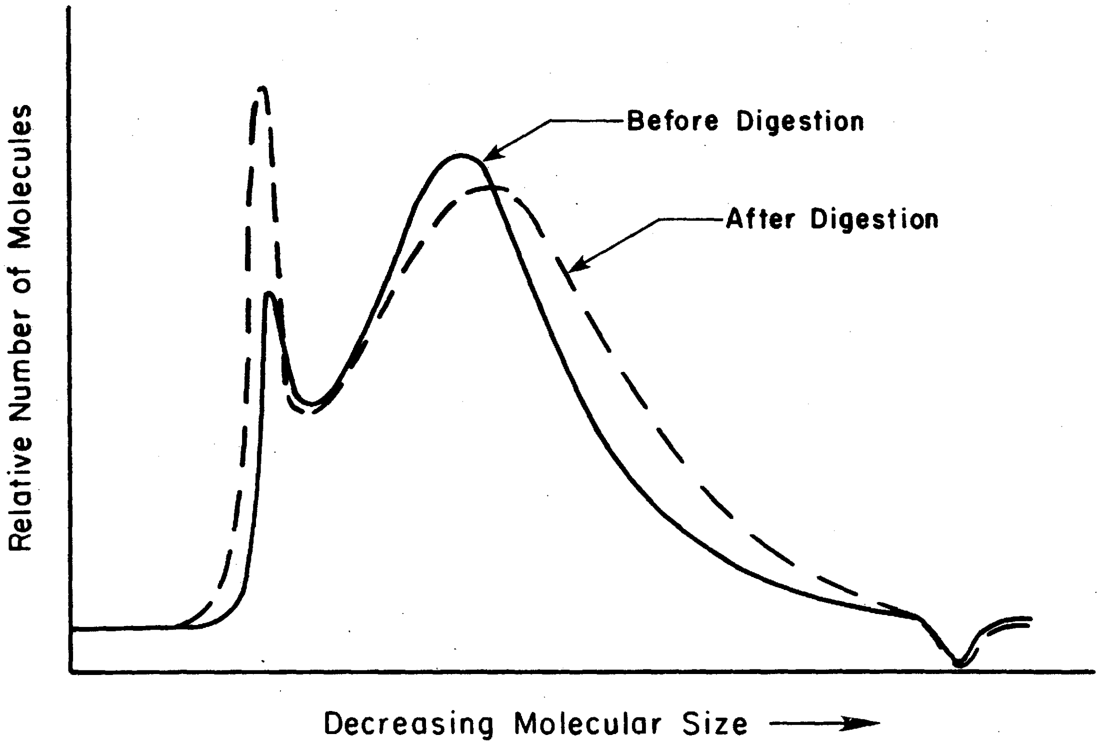


Figure 43. Gel Permeation Chromatography Results

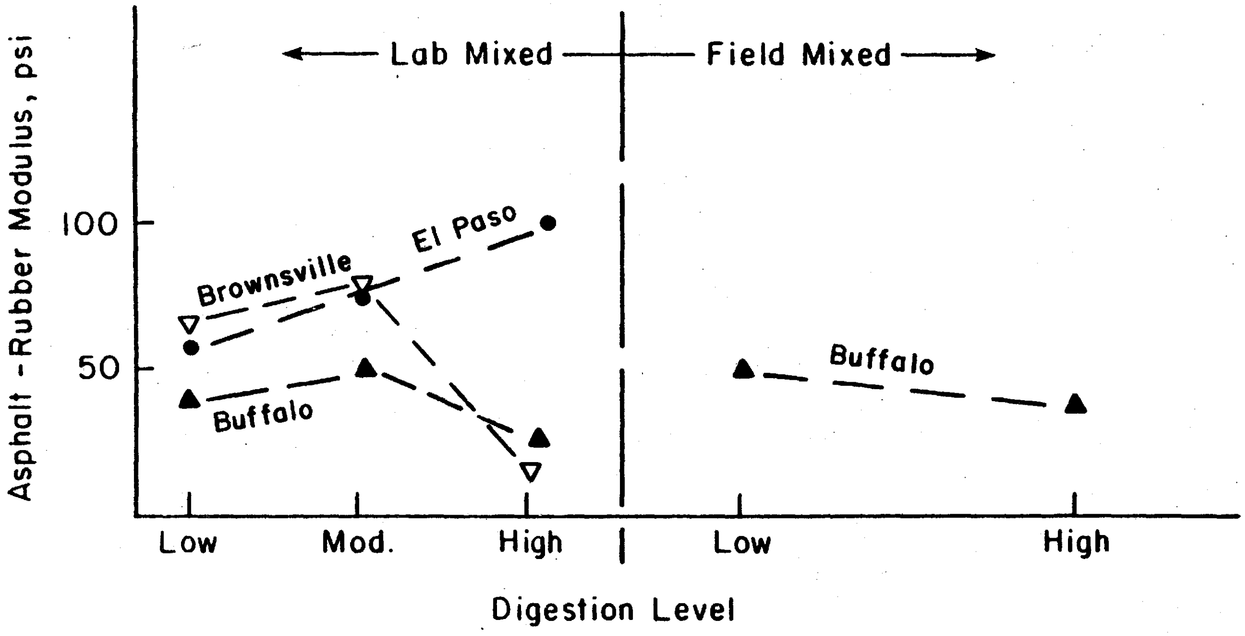


Figure 44. Effect of Digestion Level on Asphalt-Rubber Modulus

agreement between Figures 37 and 44 is not present. Therefore, an explanation of the effect on asphalt-rubber modulus due to a change in rubber content resulting from high digestion appears unwarranted. Therefore, reasons other than simple reduction of solid rubber content due to digestion seem to affect asphalt-rubber modulus similar to asphalt modulus.

The area under the stress-strain curve which is a measure of the toughness of the blend decreases for Buffalo asphalt-rubber as digestion level increases. However, the decrease in curve area does not occur until after moderate digestion has been reached. Curve areas for lab mixed material at low and moderate digestion are not significantly different as shown by Newman-Keuls results in Table 28 and graphically by Figure 45. Again, note the similarity between lab and field prepared mixtures. However, the curve area for low field digestion compares closer to values for moderate lab digestion than does low lab digestion.

Softening point is affected by digestion similar to curve area as shown in Figure 46. Again, as with curve area data, no significant difference occurs in softening point for low and moderate digestion laboratory mixes, but a significant decrease in softening point is shown for high digestion laboratory mixes. Newman-Keuls data in Table 26 verify this. Interestingly, failure stress, curve area, and softening point depict similar trends for low, moderate and high digestion levels for laboratory prepared Buffalo asphalt-rubber, and curve area and softening point for Brownsville asphalt-rubber. There was no significant difference between any factors at low and moderate digestion levels, but a significant decrease is observed for all factors between moderate and high levels of digestion.

Digestion appears to affect softening point at insignificant levels for El Paso lab and field prepared materials as shown in Table D29.

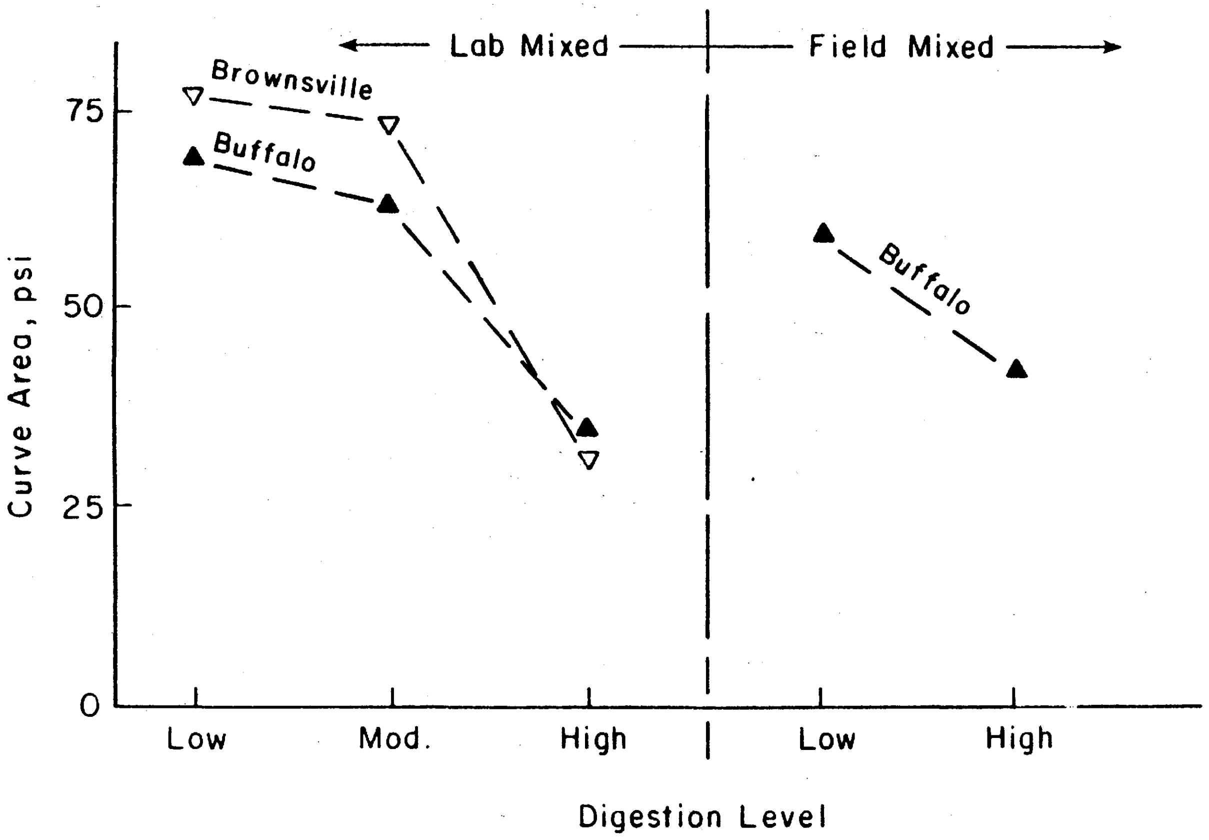


Figure 45. Effect of Digestion Level on Curve Area

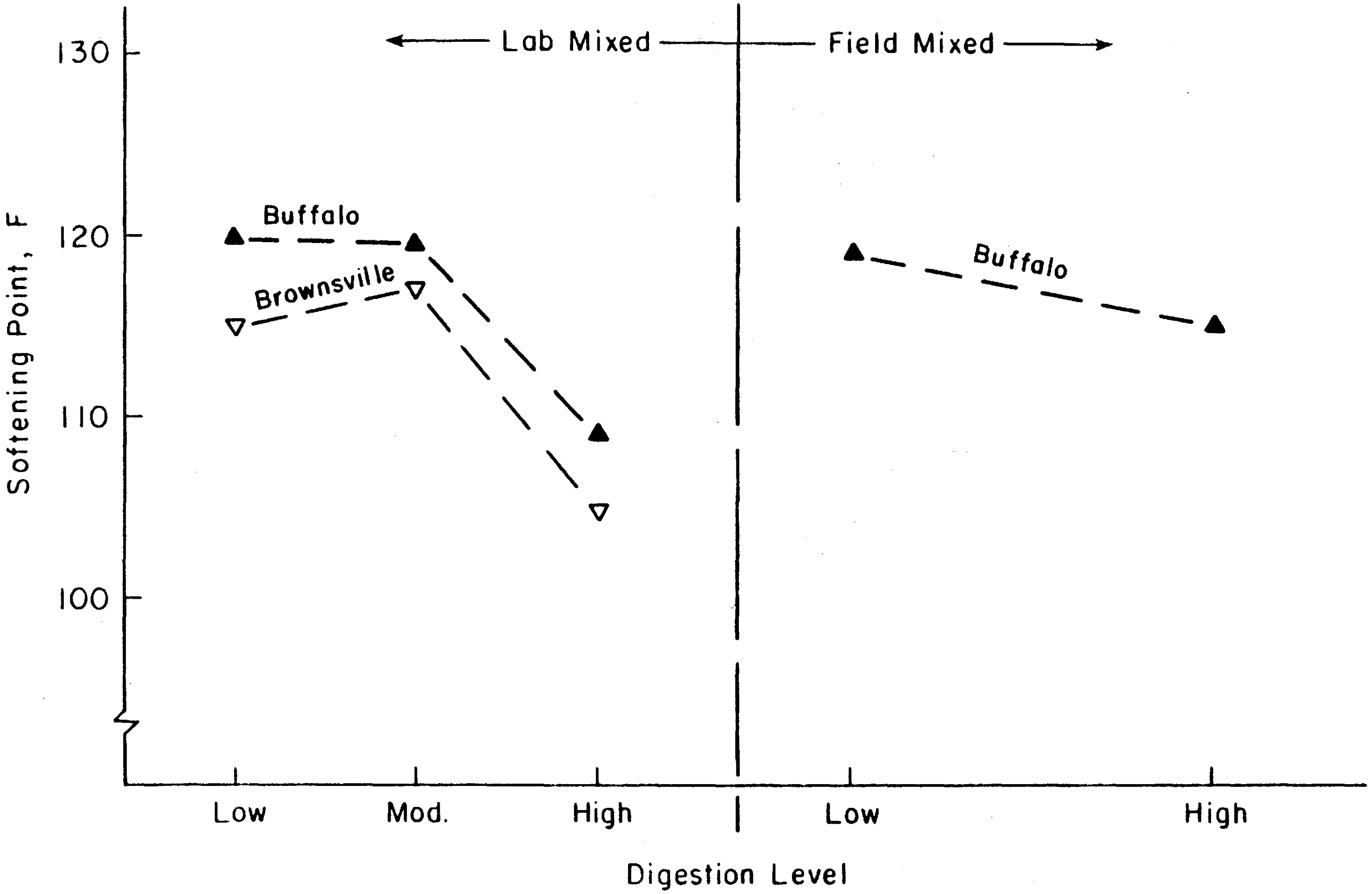


Figure 46. Effect of Digestion Level on Softening Point

Rubber Type

Rubber type affected the following factors for laboratory and/or field prepared mixtures as noted.

Factor	Effect for mixtures prepared in:
Failure Stress	Lab
Failure Strain	Lab
Curve Area	Lab
Asphalt Modulus	Lab
Asphalt-Rubber Modulus	Lab and Field

As noted above, significant differences in factors generally were measured for lab prepared mixes, asphalt-rubber modulus being the only factor affected by rubber type for both lab and field prepared mixes.

Rubber types A and B generally provide the same response from each factor noted above, the only factor showing a significant difference being failure strain. The difference measured for failure strain, although statistically significant at alpha ≤ 0.05, may not be of practical significance. Table 24 and Figure 48 indicate mean true failure strain for rubber types A, B and C to be 1.54, 1.72 and 1.77 in/in, respectively. All three values are judged statistically significant. Although 1.54 and 1.72 may have practical significance, 1.72 and 1.77, probably do not.

The difference in response between Rubber Types A and B and Rubber Type C, however, may be considered, not only of statistical significance, but practical significance as well. Figure 47 shows an increase in true failure stress for Type C over Types A and B. An increase in curve area is shown for Type C over Types A and B in Figure 49, and Type C demonstrates both higher asphalt and asphalt- rubber modulus than Type B and Type A rubber, respectively, in Figures 50 and 51.

Recall from Table 4 the most significant difference between Rubber Type C and Rubber Types A and B was the lack of natural rubber in Rubber C.

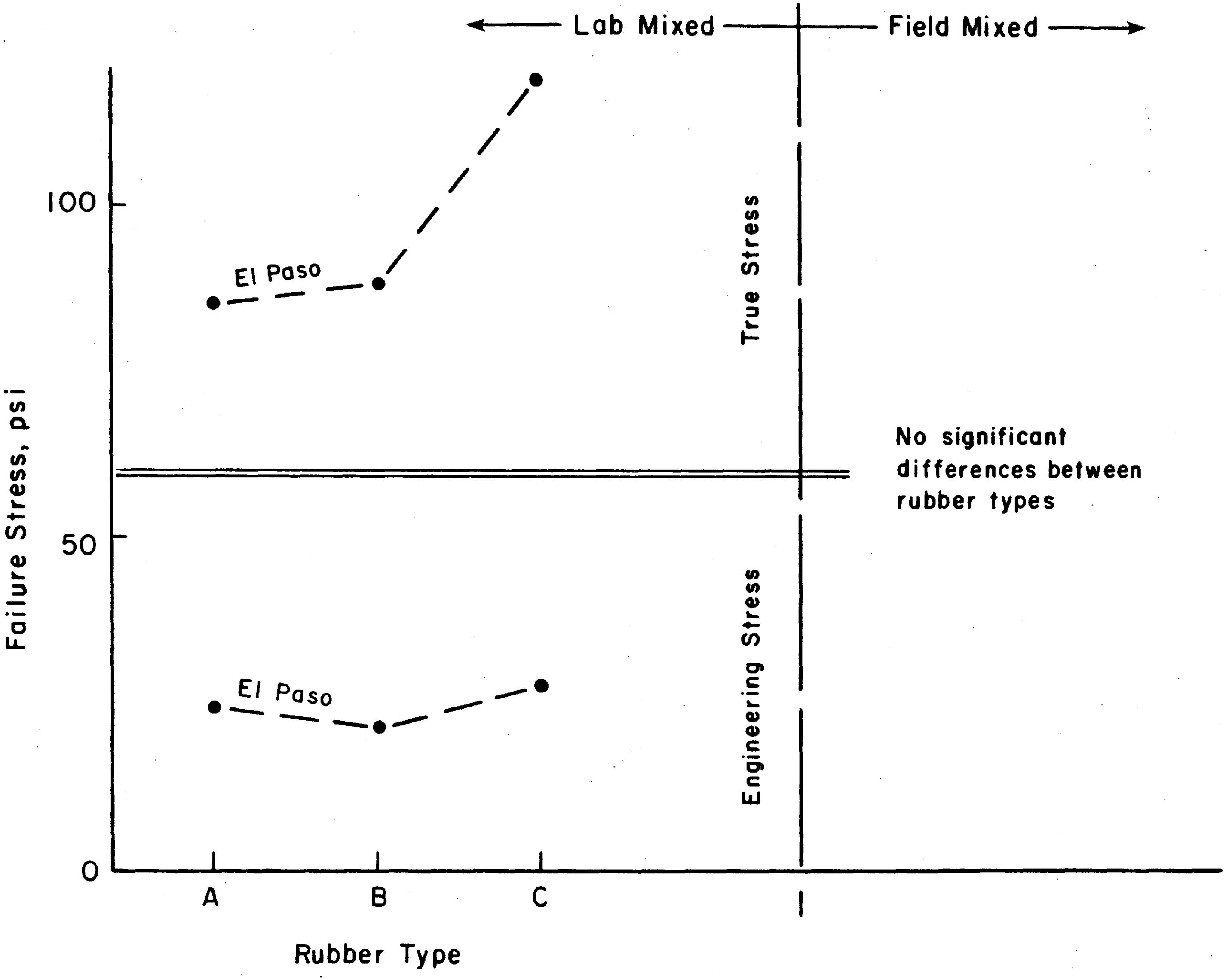


Figure 47. Effect of Rubber Type on Failure Stress.

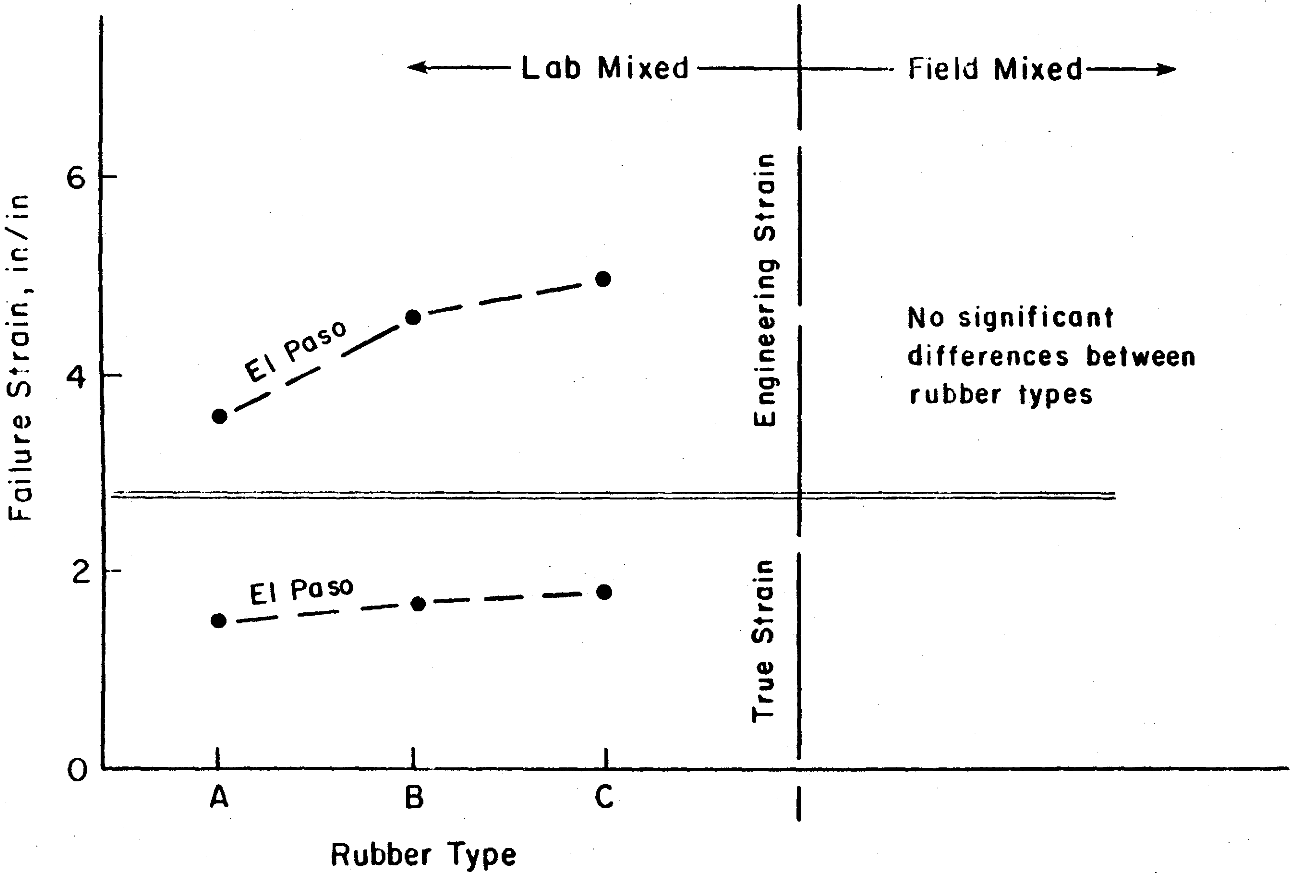


Figure 48. Effect of Rubber Type on Failure Strain

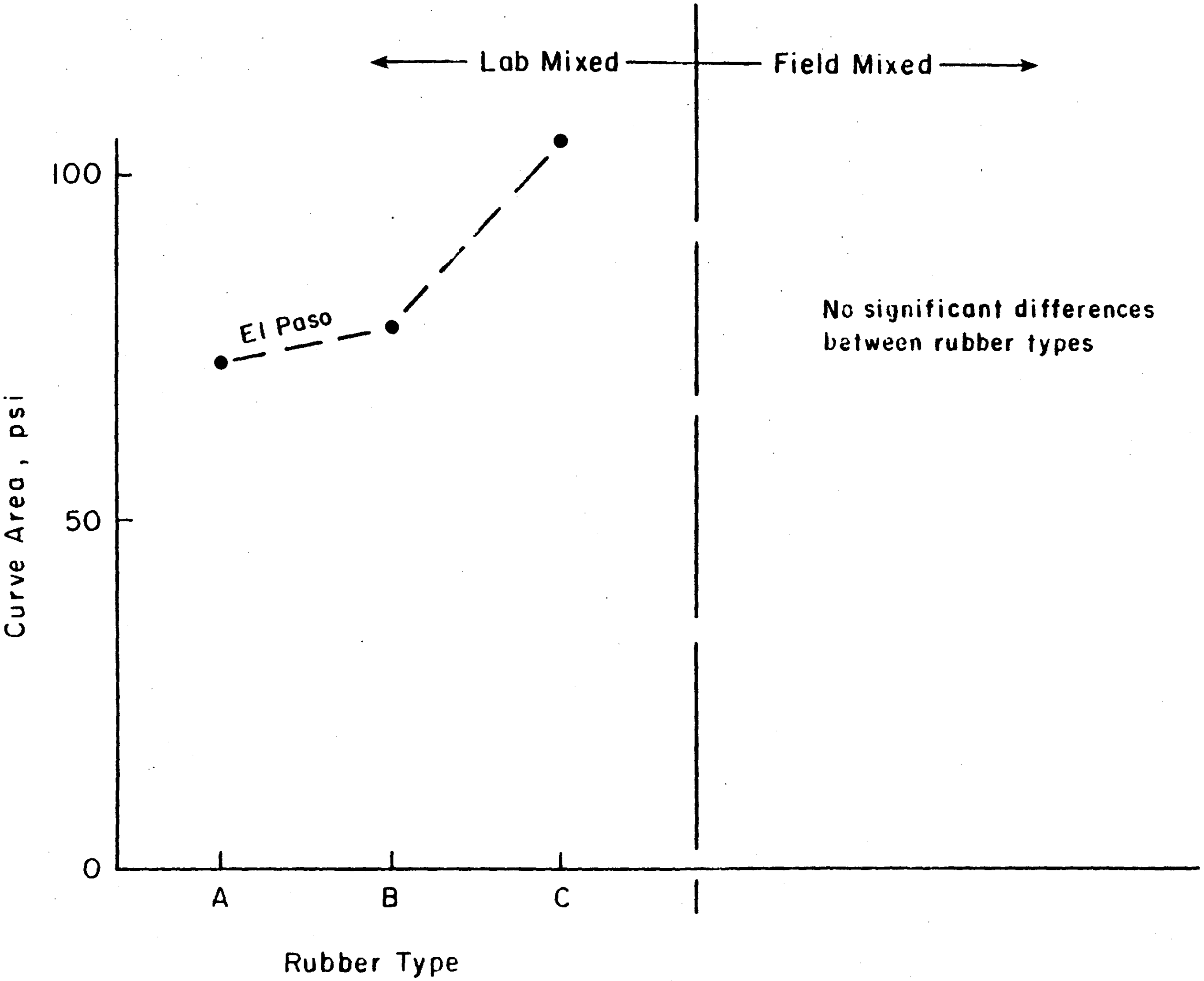


Figure 49. Effect of Rubber Type on Curve Area

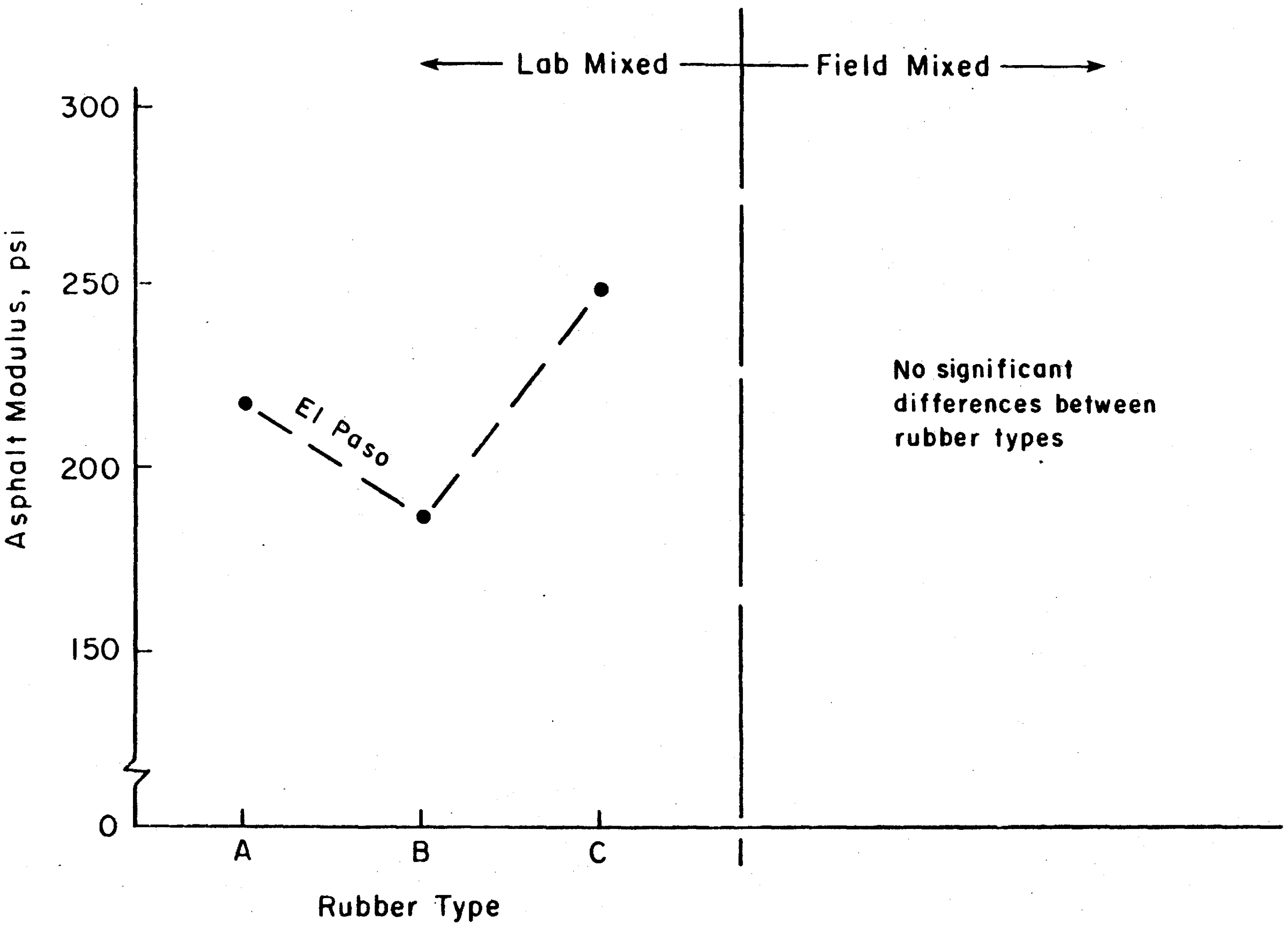


Figure 50. Effect of Rubber Type on Asphalt Modulus

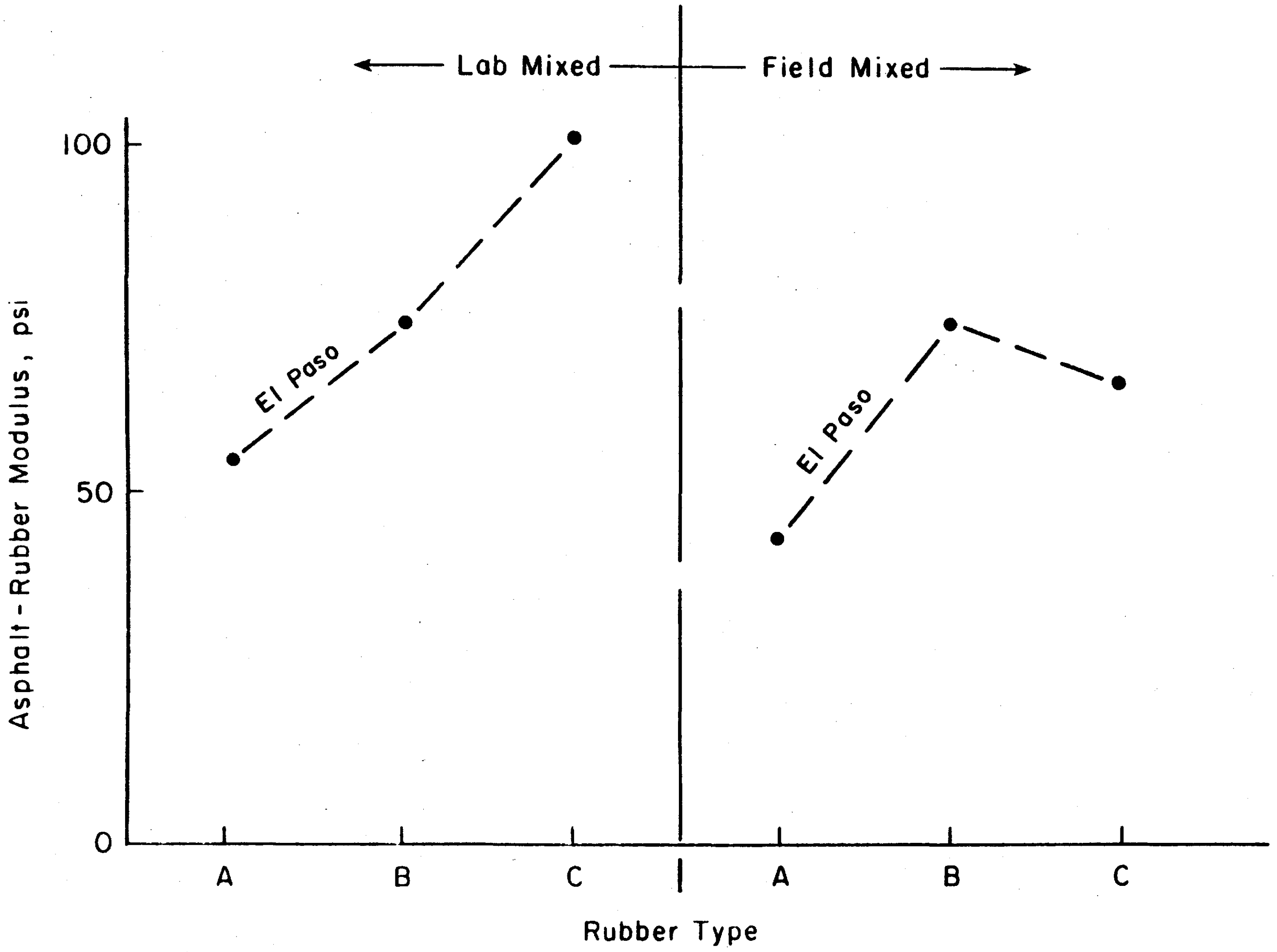


Figure 51. Effect of Rubber Type on Asphalt-Rubber Modulus.

Combined Effects: Concentration and Digestion

Asphalt modulus is affected significantly by both digestion level and rubber concentration as shown in Figure 52 for laboratory prepared mixes. Buffalo mixes show the most significant effects on asphalt modulus at low and moderate digestion levels. Asphalt modulus generally decreases with increases in rubber content and increases in digestion. Only a slight change in asphalt modulus occurs for high digestion mixes compared to low and moderate digestion at 18 and 22 percent rubber. This indicates that for Buffalo mixes the desired asphalt modulus might be achieved by changing either digestion or rubber content.

The effect of rubber content and digestion on El Paso laboratory mixes is less clear. At 22 percent rubber, the trend toward decreasing asphalt modulus with increasing digestion is present. However, as rubber content increases, this trend disappears as shown in Figure 52. Figure 52 shows the much higher asphalt modulus values for the El Paso mixes compared with Buffalo mixes.

The general trend in asphalt-rubber modulus data shown in Figure 53 appears to be toward lower modulus as digestion increases and rubber content decreases. This appears true for low and high digestion Buffalo mixes prepared both in the field and laboratory. Also, it appears from Figure 53 that the effect on asphalt-rubber modulus due to rubber content is less for high digestion mixes than low digestion mixes. The effect of rubber content on asphalt-rubber modulus at moderate digestion appears to be zero.

Softening point tends to increase with rubber content and decrease with digestion as shown in Figures 54 and 55 for Buffalo and El Paso mixes. The softening point values of the Buffalo and El Paso mixes do not appear to significantly differ at low and moderate digestion levels either for laboratory mixes or for field mixtures. Again, the effect of rubber content on softening point appears greatest at low digestion levels for both mixtures whether lab or field prepared.

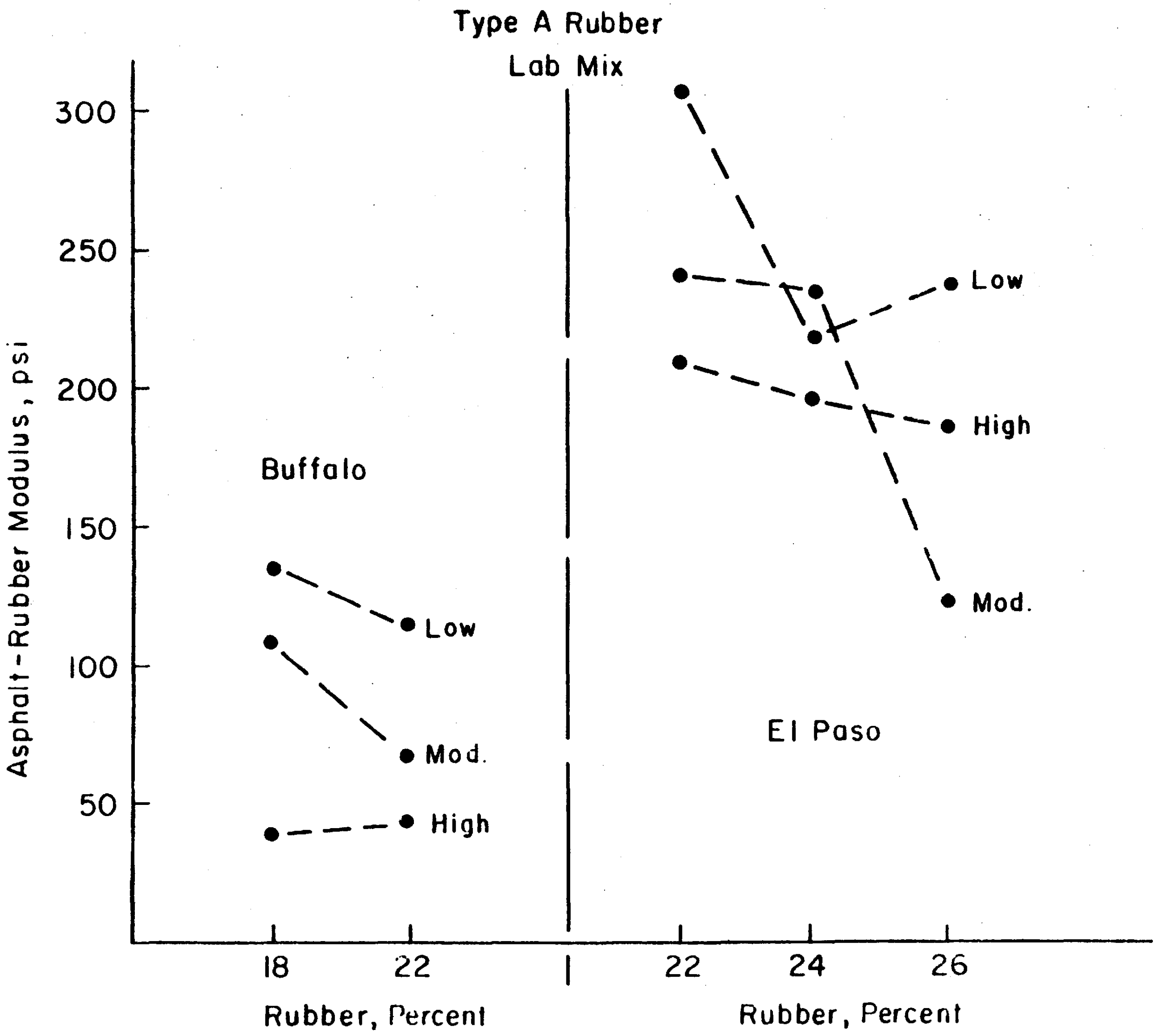


Figure 52. Effect of Rubber Concentration and Digestion Level on Asphalt Modulus.

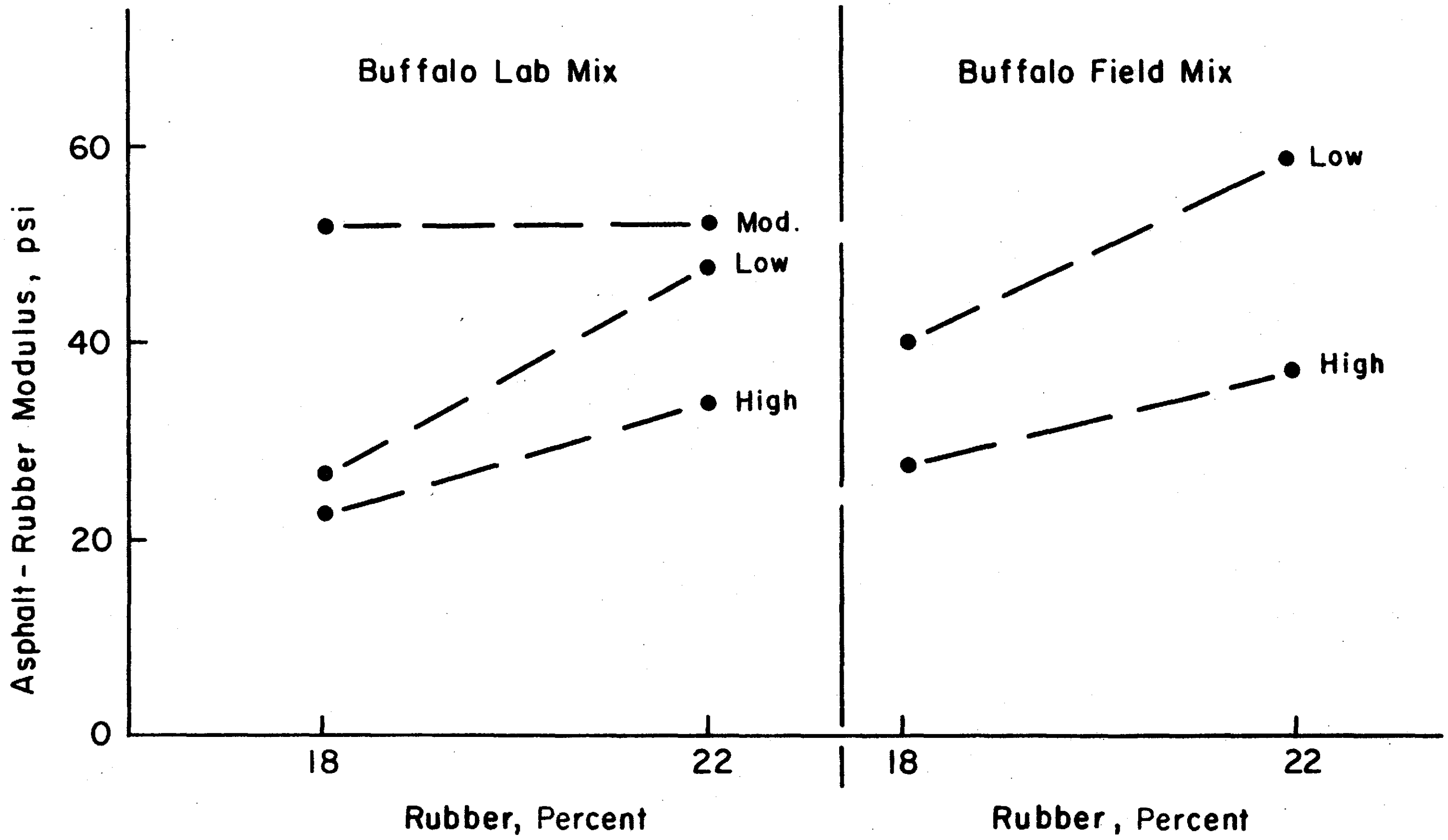


Figure 53. Effect of Rubber Concentration and Digestion Level on Asphalt-Rubber Modulus

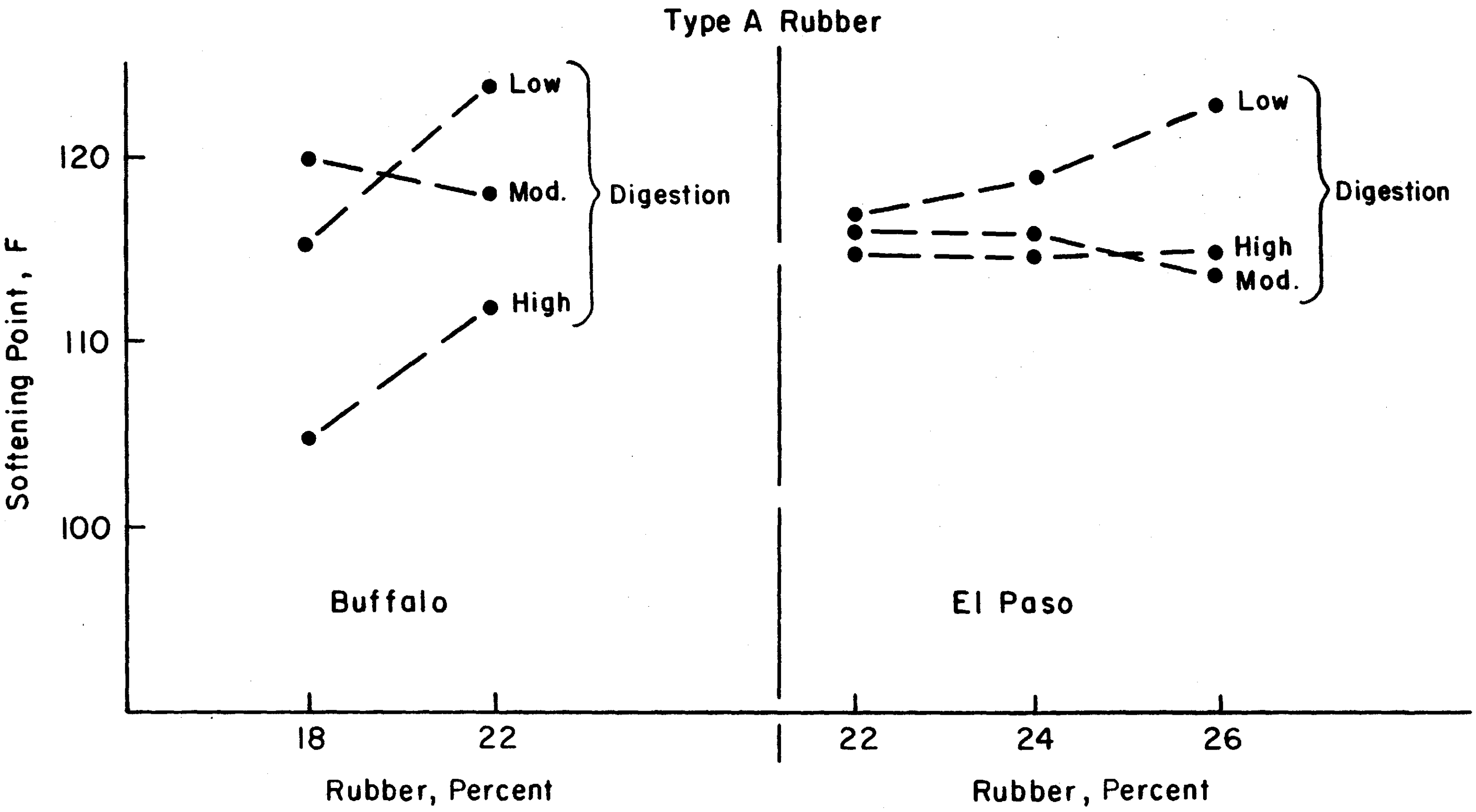


Figure 54. Effect of Rubber Concentration and Digestion Level on Softening Point of Lab Mixes

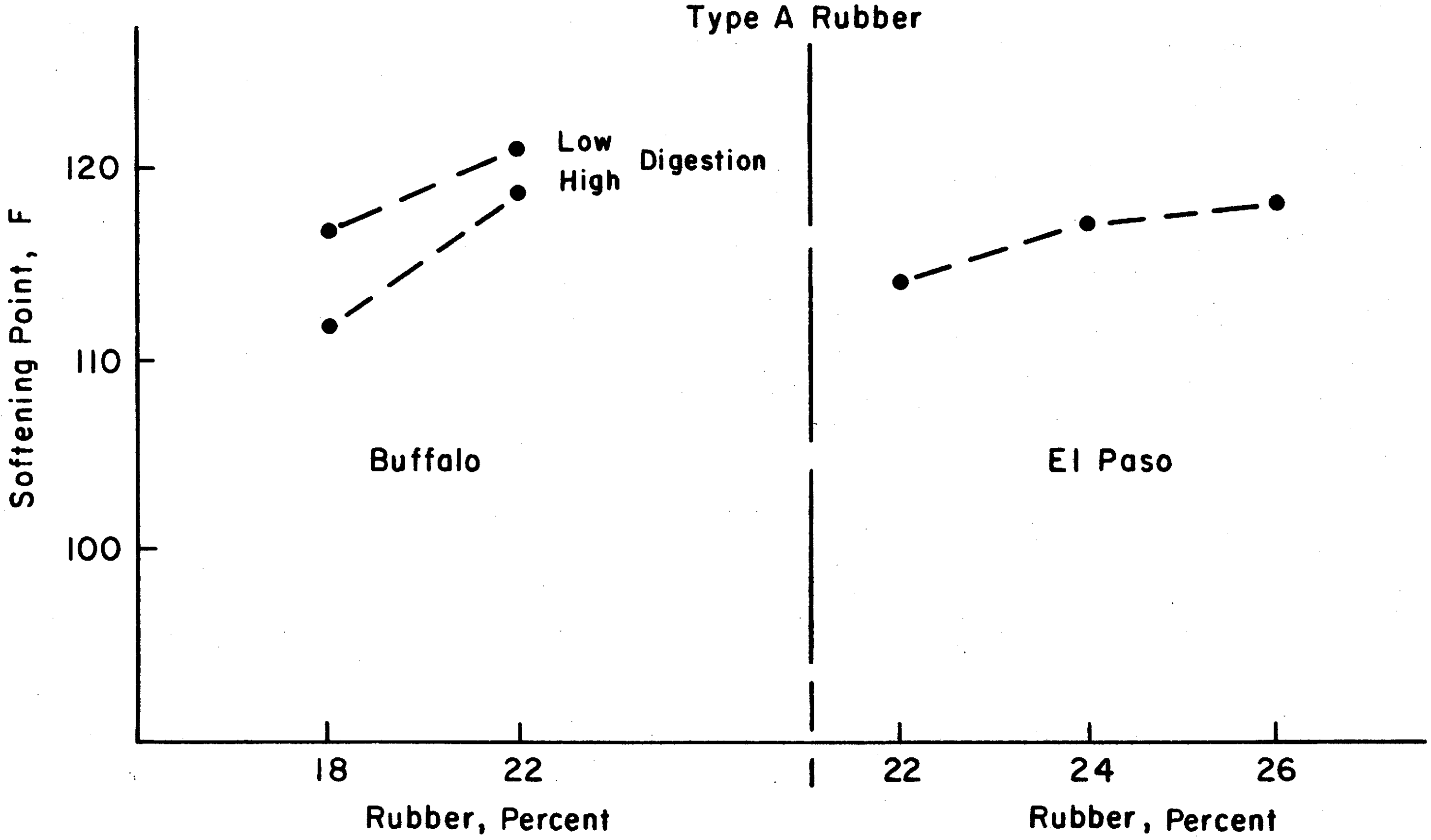


Figure 55. Effect of Rubber Concentration and Digestion Level on Softening Point of Field Mixes

Failure strain tends to decrease with increasing rubber content and increase with digestion for Buffalo field mixes as shown in Figure 56. This outcome supports the finding that as digestion proceeds, rubber disintegrates in the asphalt producing less solid rubber by weight in the mixture and a wider size distribution of molecules.

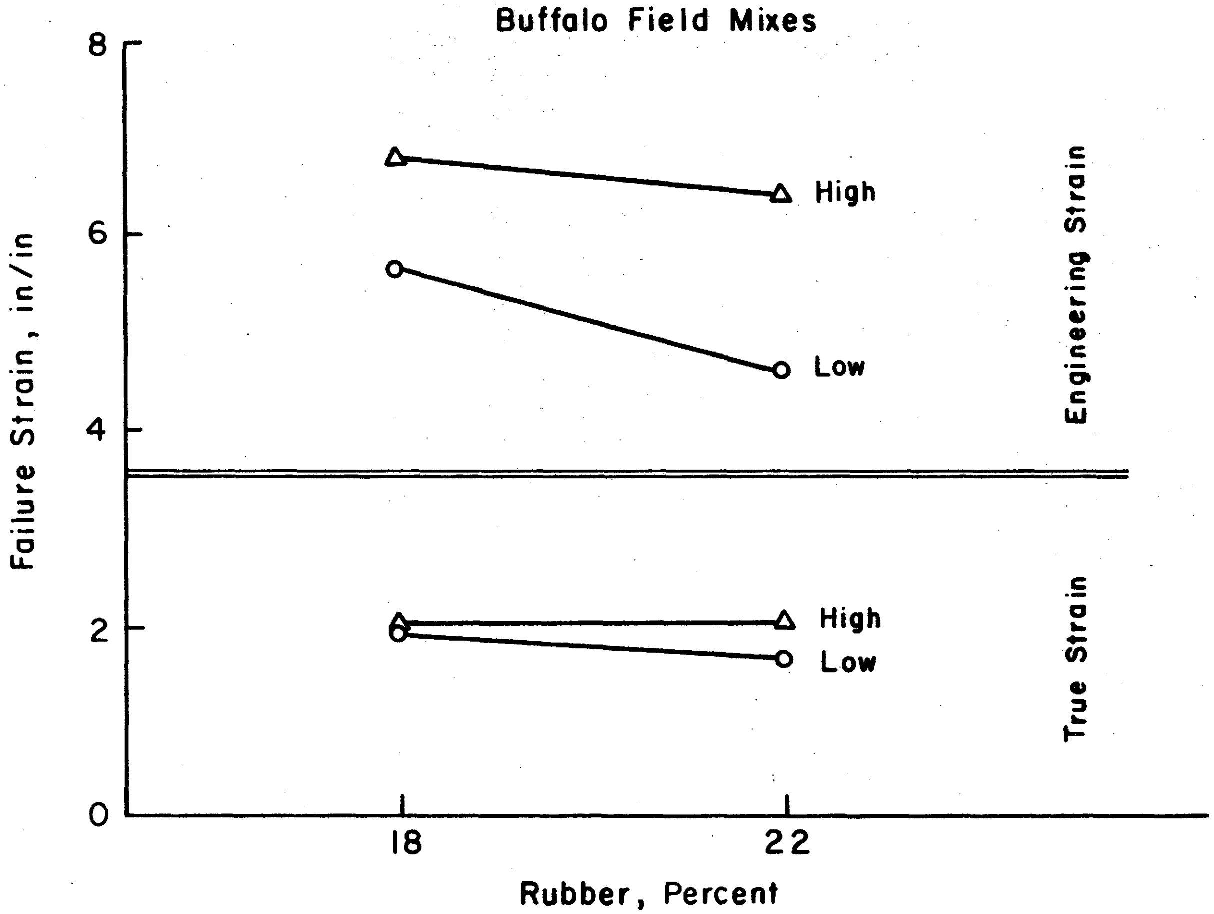


Figure 56. Effect of Rubber Concentration and Digestion Level on Failure Strain

CHAPTER IX

CONCLUSIONS

1. Two experimental full-scale test roads containing asphalt-rubber interlayers were constructed. The arrangement of test sections at both test roads is such that future correlation between field performance and laboratory properties of interlayer materials can be statistically analyzed.

2. Documentation on both test roads is extensive regarding initial pavement condition, construction procedures for asphalt-rubber fabrication and asphalt concrete overlay production. Material properties for both interlayer and overlay have been recorded such that future correlation between laboratory properties and field performance may be possible.

3. Further development of four new laboratory tests indicate test results are sentitive to changes in asphalt-rubber composition for certain asphalt-rubber mixtures.

4. Viscosity measured by the torque fork mixing apparatus compares closely with viscosity values calculated using theoretical models. This means future quality control procedures for determining rubber content may be possible by viscosity measurement.

5. Extraction of asphalt from asphalt-rubber mixtures indicates solid rubber disintegrates in the asphalt-rubber as digestion proceeds. Results of gel permeation chromatography tests indicate that the asphalt from asphalt-rubber mixtures contains more high molecular size and low molecular size molecules than the parent asphalt. This apparent addition of molecules to the asphalt in asphalt-rubber mixtures indicates the asphalt has been altered. Rubber is the only other constituent in the mix which could contribute additional molecules. Therefore, after digestion with rubber, asphalt in asphalt-rubber may contain some rubber components.

6. The force-ductility test yields seven parameters which may be used to predict changes in asphalt-rubber properties due to rubber type, rubber concentration, and digestion level.

7. The force-ductility test used in this study produces a true stress-strain curve for asphalt-rubber mixtures which has two characteristic linear portions. The slope of the linear portion of the curve during initial loading approximates the modulus of elasticity of asphalt cement tested under similar conditions and has, therefore, been labeled "asphalt modulus". The slope of the linear portion of the curve during later stages of loading is always less than that during initial loading and may measure a composite "asphalt-rubber modulus". The slopes of both portions of the stress-strain curve appear to be a function of rubber content and digestion level.

8. Strain at failure during force-ductility testing increases as digestion level increases. Strain at failure decreases as rubber content increases. Consistent with data are extraction tests which show solid rubber content is diminished as digestion proceeds. Therefore, it seems that an increase or decrease in tensile strain properties may be achieved with asphalt-rubber mixtures by varying digestion conditions and/or rubber content.

9. Similarly, asphalt-rubber modulus for some mixtures decreases with increasing digestion and decreasing rubber content. However, the effect of rubber content on asphalt-rubber modulus is diminished as digestion increases. This suggests that at some high level of digestion, rubber content could be increased with no effect on asphalt-rubber modulus.

10. Stress at failure for the force-ductility test decreases as digestion proceeds from moderate to high for some asphalt- rubber mixtures. These results are shown for the area under the stress-strain curve and the double-ball softening point for the same asphalt-rubber mixtures. Stress at failure, area under the stress-strain curve and double-ball softening point appear to measure similar properties for

these mixtures and may be useful tools for identifying optimum mixture properties.

11. Physical properties of some field prepared asphalt-rubber mixtures appear similar to mixtures prepared in the torque fork laboratory mixer/viscometer. However, low level field digestion does not produce mix properties corresponding to low level laboratory digestion. Rather, low level field digestion is better approximated by laboratory digestion conditions intermediate between low and moderate levels as defined in this report. Mixes which showed the best correlation were Buffalo materials tested using softening point at various rubber percentages and digestion levels. Buffalo materials showed good correlation at various digestion levels for force ductility parameters of failure stress and strain, asphalt modulus, and curve area. Asphalt-rubber modulus gave good correlation for Buffalo mixes prepared at high digestion levels, only. El Paso rubber types A and B produced similar results between lab and field mixes when evaluated by asphalt-rubber modulus.

12. The double-ball softening point test is sensitive to changes in asphalt-rubber similar to certain force-ductility parameters. However, although double-ball softening point was sensitive to Buffalo lab and field mixes, it was not sensitive to El Paso mixes from either lab or field. The reason for this discrimination is unknown, but may be related to the type of asphalt-rubber tested. The El Paso materials were visibly more heterogenous than the Buffalo materials, probably due to the larger rubber particles. The lumpy nature of these mixes may be the reason for a lack of sensitivity in the double-ball softening point test.

13. Asphalt-rubber prepared using Rubber Type C behaved unusually in the field, foaming resulted in overflow of the distributor. This asphalt-rubber also provided performance differences in the laboratory. Rubber C was processed cryogenically, and contained no natural rubber. These are the major known differences between Rubber C and Rubber A and B. It is unknown whether these differences caused

the observations noted herein. A relationship between asphalt-rubber rotational viscosity and rubber content has been shown. This relationship may provide a means of verifying rubber content and digestion conditions in the field by measuring rotational viscosity at the job site.

14. To test whether measurements of this type are practical and relay meaningful information, the Haake viscometer was used to measure viscosity of asphalt-rubber at various temperatures after three levels of digestion. Rubber content of the mixes was measured after low, moderate and high digestion, and viscosity taken at four temperatures. Asphalt-rubber tested consisted of 22 percent Type A rubber blends using El paso and Buffalo asphalt and rubber, respectively. Results are presented in Figure 57.

    The data indicates that extractble rubber content decreases as digestion level increases. This result is consistent with previous data presented. The data also show, not unexpectedly, that viscosity increases as temperature decreases. However, more significantly, it appears that rubber content may be predicted from Haake viscosity data at test temperatures below 250F. Figure 57 also indicates rubber-viscosity curves may be asphalt-rubber type related as shown by the difference in results at 200F for El Paso and Buffalo mixes.

    More testing would be required to produce impementable charts which could be used in the field, but data such as that shown may be derived for some typical types of asphalt-rubber mixes. This type information would be useful to field personnel responsible for quality control.

15. Based on observations and measurements made at the three test roads, certain modifications are recommended to the Texas SDHPT asphalt-rubber specification. The new recommended specification is included as Appendix E to this report.

16. A design and construction procedure for asphalt-rubber seal coats and interlayers should be adopted. This procedure uses fundamental concepts outlined by Epps, Gallaway and Hughes in TTI Research Report

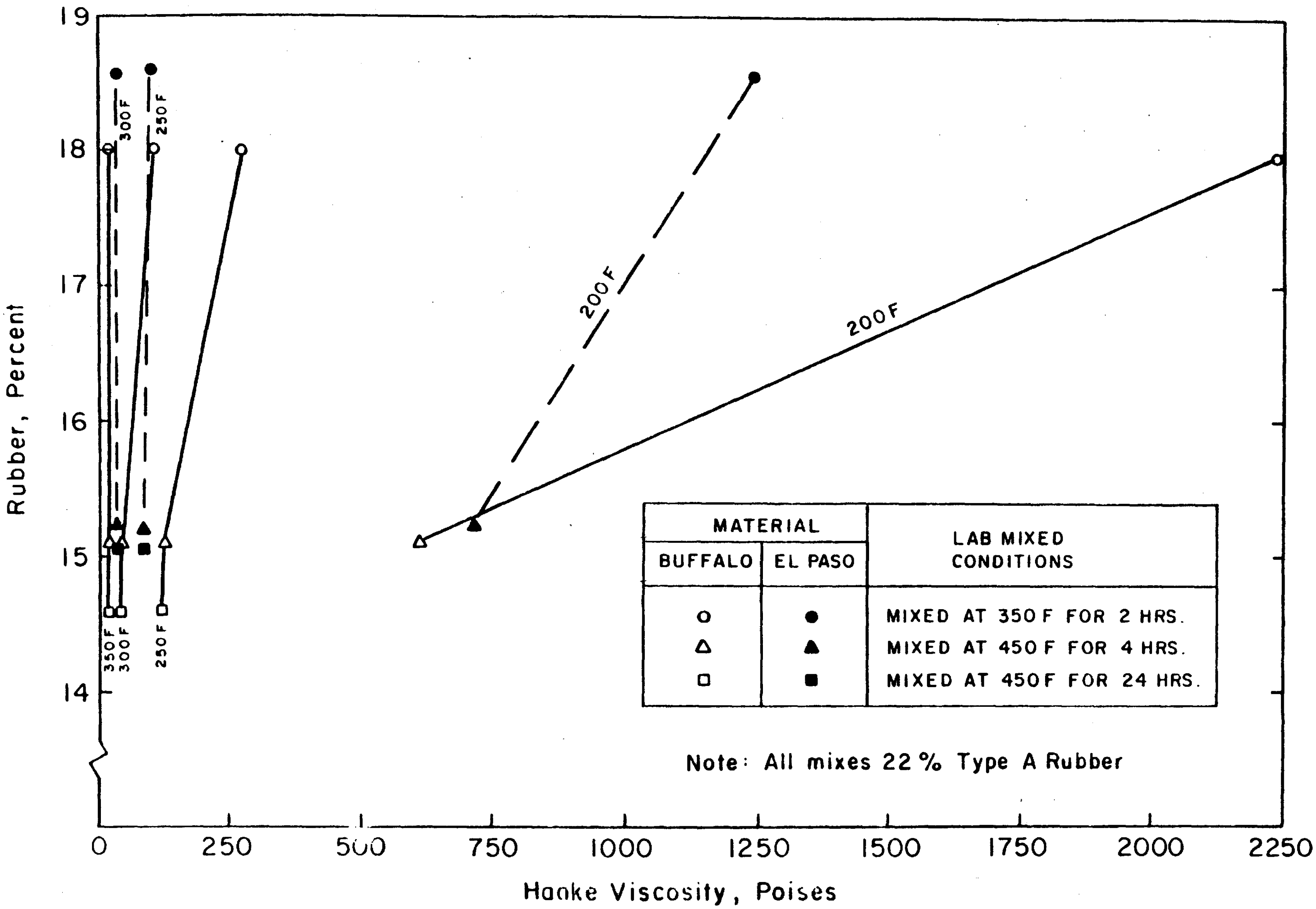


Figure 57. Relationship Between Viscosity and Rubber Content.

214-25 for design and construction of seal coats. However, asphalt-rubber seal coats and interlayers can tolerate higher initial embedment depths, and it is believed these higher embedment depths contribute largely to the reflective crack reduction possible when using these systems as surface treatments or interlayers. Figure 58 depicts a modified version of the embedment depth graph from Report 214-25. Initial embedment has been increased for seal coats and interlayers over that for conventional seal coats as shown. Allowable interlayer embedment is higher than seal coat, but judgement must be exercized for facilities which must carry traffic for extended periods prior to overlay construction to avoid excessive flushing.

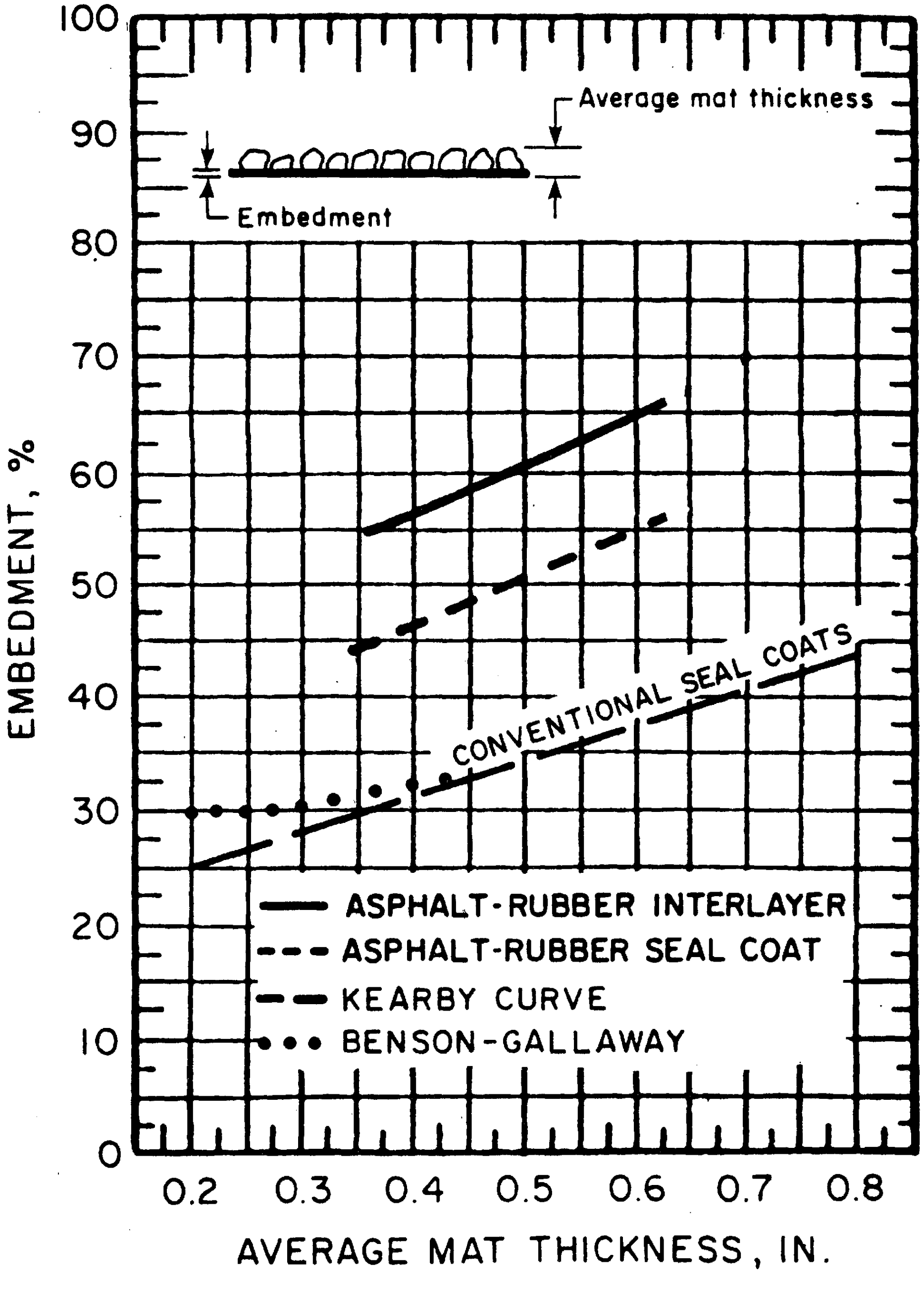


Figure 58. Percent Embedment Determined by Mat Thickness.

CHAPTER X

RECOMMENDATIONS

1. Monitor performance of El Paso, Buffalo and Brownsville Test Roads. As reflective cracking data becomes available meaningful correlations between laboratory data presented here and field performance should be established. These correlations will provide a datum for desirable laboratory properties of asphalt-rubber mixtures. Future mixtures can then be designed with appropriate laboratory properties based on this performance information.

2. Develop a correlation between torque fork rotational viscosity and portable rotational viscometers such as the Haake so that data can be generated relating rubber content, digestion level and rotational viscosity. Field verification of construction conditions should be possible after collection of sufficient data.

3. Develop a data base of force-ductility parameters for asphalt- rubber projects such that field performance can be compared with failure stress and strain and asphalt-rubber moduli. These correlation data can then be used with theoretical mechanical models to provide data regarding a desirable range of values for these parameters. In conjunction with the apparent relations between rubber content and digestion level, an asphalt-rubber mixture design method could be developed. This method would describe various means for producing a mixture with the desired material properties described by mechanical modeling. Production of the mixture could be accomplished by various means, by varying rubber content and type and digestion conditions.

4. Evaluate asphalt-rubber mixes by force ductility over a range of temperatures and strain rates. The successful establishment of seven force ductility parameters in this research should be extended to measure temperature and test rate effects on these parameters. Collection of these measurements at various temperatures and test rates would facilitate incorporation of such parameters in pavement

design models which require parameter description as a function of temperature and loading rate.

5. Expand the force ductility test to provide stress relaxation data. By halting the test after an initial load has been applied to the test specimen and monitoring the decrease in load corresponding to stress relaxation, two additional parameters can be measured; relaxation modulus, and relaxation time. These two parameters are of importance because they allow characterization of viscoelastic and fracture properties. Further use of these parameters should also be helpful in pavement structural analysis such that "application specific" materials can be formulated to solve specific design problems.

6. Adopt the specification included herein for construction of asphalt-rubber seal coats and interlayers.

7. Adopt an asphalt-rubber seal coat and interlayer design procedure based on that outlined in detail by TTI Research Report 214-25 with a modification to inital embedment depth as described previously.

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APPENDIX A

Photolog Summary - El Paso

Table A1. Photolog 1.

Severity	Slight		Moderate		Severe	
Filled, F; Not, N	F*	N**	F	N	F	N
Distress						
Transv., ft.	27	106	6	21		74
Long., ft.	9	59	33	11		10
Allig., ft.^{2}		358		322		56
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table A2. Photolog 2.

Severity	Slight		Moderate		Severe	
Filled, F; Not, N	F	N	F	N	F	N
Distress						
Transv., ft.	94	78	83		22	240
Long., ft.	134	23	4			
Allig., ft.^{2}		86		90		4
Flushing, ft.^{2}	362					
Patching, ft.^{2}						
Pumping, ft.						

*Filled cracks. **Not-filled cracks.

Table A3. Photolog 3.

Severity Filled, F; Not, N Distress	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.	155	130	90	3	4	196
Long., ft.	80	27				
Allig., ft.^{2}		8		10		

Distress	Slight	Moderate	Severe
Flushing, ft.^{2}	793		
Patching, ft.^{2}			
Pumping, ft.			

Table A4 . Photolog 4 .

Severity Filled, F; Not, N Distress	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.	112	16	332	41	72	194
Long., ft.	36	56	47		9	30
Allig., ft.^{2}		278		129		

Distress	Slight	Moderate	Severe
Flushing, ft.^{2}			
Patching, ft.^{2}	806		
Pumping, ft.			

Table A5. Photolog 5 .

Distress / Filled, F; Not, N / Severity	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.	265	8	52			11
Long., ft.	56	11				
Allig., ft.^{2}		15				

Distress	Slight	Moderate	Severe
Flushing, ft.^{2}	494		
Patching, ft.^{2}			
Pumping, ft.			

Table A6. Photolog 6 .

Distress / Filled, F; Not, N / Severity	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.	195	155				
Long., ft.	89	21				
Allig., ft.^{2}		31				

Distress	Slight	Moderate	Severe
Flushing, ft.^{2}	197		
Patching, ft.^{2}			
Pumping, ft.			

Table A7. Photolog 7.

Severity	Slight		Moderate		Severe	
Filled, F; Not, N / Distress	F	N	F	N	F	N
Transv., ft.	203	107	20			60
Long., ft.	61	31	2			
Allig., ft.^{2}		1149		232		
Flushing, ft.^{2}	1120					
Patching, ft.^{2}	378		318			
Pumping, ft.						

Table A8 . Photolog 8 .

Severity	Slight		Moderate		Severe	
Filled, F; Not, N / Distress	F	N	F	N	F	N
Transv., ft.	235	125	103			35
Long., ft.	29	52	2			
Allig., ft.^{2}		763		91		
Flushing, ft.^{2}	667		27			
Patching, ft.^{2}						
Pumping, ft.						

Table A9. Photolog 9.

Distress \ Severity / Filled, F; Not, N	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.	301	106	20			9
Long., ft.	49	35				
Allig., $ft.^2$		84				
Flushing, $ft.^2$	260					
Patching, $ft.^2$	378					
Pumping, ft.						

Table A10. Photolog 10.

Distress \ Severity / Filled, F; Not, N	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.	76	128	287	4	21	43
Long., ft.	109	69	84	8	31	
Allig., $ft.^2$		178		704		496
Flushing, $ft.^2$	422		46		35	
Patching, $ft.^2$	624					
Pumping, ft.						

Table A11. Photolog 11.

Distress / Severity	Slight		Moderate		Severe	
Filled, F; Not, N	F	N	F	N	F	N
Transv., ft.	137	174	61	79		
Long., ft.	37					
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table A12. Photolog 12.

Distress / Severity	Slight		Moderate		Severe	
Filled, F; Not, N	F	N	F	N	F	N
Transv., ft.	70	76	112	39	4	24
Long., ft.	35	10	68	4	2	
Allig., ft.^{2}		255		218		225
Flushing, ft.^{2}	584		202			
Patching, ft.^{2}			200			
Pumping, ft.						

Table A13. Photolog 13.

Distress / Filled, F; Not, N / Severity	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.	143	45	eo	19	31	
Long., ft.	102	13	11		4	
Allig., ft.^{2}		302		363		113
Flushing, ft.^{2}	333					
Patching, ft.^{2}	419		40			
Pumping, ft.						

Table A14. Photolog 14.

Distress / Filled, F; Not, N / Severity	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.	202	157	89			
Long., ft.	119	23	9	5		
Allig., ft.^{2}		213		403		25
Flushing, ft.^{2}	268					
Patching, ft.^{2}						
Pumping, ft.						

Table A15. Photolog 15.

Distress	Severity: Slight		Moderate		Severe	
Filled, F; Not, N	F	N	F	N	F	N
Transv., ft.	394	31	60			
Long., ft.	286	37	30			
Allig., ft.^{2}		744		136		
Flushing, ft.^{2}	342					
Patching, ft.^{2}	963					
Pumping, ft.						

Table A16. Photolog 16.

Distress	Severity: Slight		Moderate		Severe	
Filled, F; Not, N	F	N	F	N	F	N
Transv., ft.	112	93	110	6		
Long., ft.	67	14	38			
Allig., ft.^{2}		122		779		194
Flushing, ft.^{2}	260		14			
Patching, ft.^{2}	820		725			
Pumping, ft.						

Table A17. Photolog 17.

Distress \ Severity, Filled, F; Not, N	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.	153	187	37	6		
Long., ft.	134	17				
Allig., ft.^{2}		542		188		
Flushing, ft.^{2}	175					
Patching, ft.^{2}	428		212			
Pumping, ft.						

Table A18. Photolog 18.

Distress \ Severity, Filled, F; Not, N	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.	109	74	169	31		
Long., ft.	76	35	87			
Allig., ft.^{2}		331		149		
Flushing, ft.^{2}	1039					
Patching, ft.^{2}	127		134			
Pumping, ft.						

Table A19. Photolog 19.

Distress / Filled, F; Not, N / Severity	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.	86	179				8
Long., ft.	184	30	153	7		
Allig., ft.^{2}		71		38		
Flushing, ft.^{2}	1219		119			
Patching, ft.^{2}	335		109			
Pumping, ft.						

Table A20. Photolog 20.

Distress / Filled, F; Not, N / Severity	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.	200	26	25			
Long., ft.	283	11	8			
Allig., ft.^{2}		2				
Flushing, ft.^{2}	242					
Patching, ft.^{2}	155		265			
Pumping, ft.						

Table A21. Photolog 21.

Severity Filled, F; Not, N Distress	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.	191	155	13			
Long., ft.	103	18				
Allig., ft.^{2}		447				
Flushing, ft.^{2}	261					
Patching, ft.^{2}			683			
Pumping, ft.						

Table A22. Photolog 22.

Severity Filled, F; Not, N Distress	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.	274	71	14			
Long., ft.	80	5				
Allig., ft.^{2}		134				
Flushing, ft.^{2}	219					
Patching, ft.^{2}	70		72			
Pumping, ft.						

Table A23. Photolog 23.

Distress / Severity / Filled, F; Not, N	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.	131	68	57			4
Long., ft.	26	7				
Allig., ft.^{2}		130				
Flushing, ft.^{2}	1028					
Patching, ft.^{2}						
Pumping, ft.						

Table A24. Photolog 24.

Distress / Severity / Filled, F; Not, N	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.	145	2	4			
Long., ft.	32	11				
Allig., ft.^{2}		333				
Flushing, ft.^{2}	372					
Patching, ft.^{2}	178		140			
Pumping, ft.						

Table A25. Photolog 25.

Severity / Filled, F; Not, N / Distress	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.	81	49	117	17	14	
Long., ft.	38	30	10			
Allig., ft.^{2}		213		59		
Flushing, ft.^{2}	578					
Patching, ft.^{2}						
Pumping, ft.						

Table A26. Photolog 26.

Severity / Filled, F; Not, N / Distress	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.	224	16	5			
Long., ft.	326	10	129	18	14	
Allig., ft.^{2}		458		197		
Flushing, ft.^{2}	301					
Patching, ft.^{2}	11		680			
Pumping, ft.						

Table A27. Photolog 27.

Distress / Filled, F; Not, N / Severity	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.	302	78	64	4		51
Long., ft.	282	36	19			
Allig., ft.^{2}		314		57		
Flushing, ft.^{2}	1021		15			
Patching, ft.^{2}	323		385			
Pumping, ft.						

Table A28 Photolog 28.

Distress / Filled, F; Not, N / Severity	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.	24	18	54	12	12	
Long., ft.		304		128		
Allig., ft.^{2}		185		75		
Flushing, ft.^{2}	1274		540			
Patching, ft.^{2}	30		120			
Pumping, ft.						

APPENDIX B

Photolog Summary - Buffalo and Brownsville

Table B1. Photolog 1.

Severity Filled, F; Not, N Distress	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.		1912		192		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B2. Photolog 2 .

Severity Filled, F; Not, N Distress	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.		1954		63		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B3. Photolog 3.

Severity	Slight		Moderate		Severe	
Filled, F; Not, N Distress	F	N	F	N	F	N
Transv., ft.		1849		127		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B4. Photolog 4.

Severity	Slight		Moderate		Severe	
Filled, F; Not, N Distress	F	N	F	N	F	N
Transv., ft.		1819		41		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B5. Photolog 5.

Distress / Filled, F; Not, N / Severity	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.		793		5		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B6 . Photolog 6 .

Distress / Filled, F; Not, N / Severity	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.		775		17		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B7. Photolog 7.

Severity / Filled, F; Not, N / Distress	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.		1518		49		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B8. Photolog 8.

Severity / Filled, F; Not, N / Distress	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.		1452		58		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B9. Photolog 9.

Distress / Filled, F; Not, N / Severity	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.		575		37		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B10. Photolog 10.

Distress / Filled, F; Not, N / Severity	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.		592		51		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B11. Photolog 11.

Distress / Severity / Filled, F; Not, N	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.		1156		41		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B12. Photolog 12.

Distress / Severity / Filled, F; Not, N	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.		917		37		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B13. Photolog 13.

Distress	Severity Filled, F; Not, N	Slight		Moderate		Severe	
		F	N	F	N	F	N
Transv., ft.			997		95		
Long., ft.							
Allig., ft.^{2}							
Flushing, ft.^{2}							
Patching, ft.^{2}							
Pumping, ft.							

Table B14. Photolog 14.

Distress	Severity Filled, F; Not, N	Slight		Moderate		Severe	
		F	N	F	N	F	N
Transv., ft.			1192		99		
Long., ft.							
Allig., ft.^{2}							
Flushing, ft.^{2}							
Patching, ft.^{2}							
Pumping, ft.							

Table B15. Photolog 15.

Severity Filled, F; Not, N Distress	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.		1092		180		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B16. Photolog 16.

Severity Filled, F; Not, N Distress	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.		1232		144		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B17. Photolog 17.

Severity Filled, F; Not, N Distress	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.		1339		55		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B18. Photolog 18.

Severity Filled, F; Not, N Distress	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.		1257		33		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B19. Photolog 19.

Severity	Slight		Moderate		Severe	
Distress / Filled, F; Not, N	F	N	F	N	F	N
Transv., ft.		1279		54		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B20. Photolog 20.

Severity	Slight		Moderate		Severe	
Distress / Filled, F; Not, N	F	N	F	N	F	N
Transv., ft.		1540		53		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B21. Photolog 21.

Distress	Severity: Slight		Moderate		Severe	
Filled, F; Not, N	F	N	F	N	F	N
Transv., ft.		1181		47		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B22 Photolog 22.

Distress	Severity: Slight		Moderate		Severe	
Filled, F; Not, N	F	N	F	N	F	N
Transv., ft.		1158		22		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B23. Photolog 23.

Severity / Filled, F; Not, N / Distress	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.		1210		8		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B24 Photolog 24 .

Severity / Filled, F; Not, N / Distress	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.		943		62		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.	17					

Table B25. Photolog 25.

Severity	Slight		Moderate		Severe	
Filled, F; Not, N	F	N	F	N	F	N
Distress						
Transv., ft.		1223		19		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B26 Photolog 26 .

Severity	Slight		Moderate		Severe	
Filled, F; Not, N	F	N	F	N	F	N
Distress						
Transv., ft.		1159		62		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B27. Photolog 27.

Severity	Slight		Moderate		Severe	
Filled, F; Not, N	F	N	F	N	F	N
Distress						
Transv., ft.		1251		12		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B28. Photolog 28.

Severity	Slight		Moderate		Severe	
Filled, F; Not, N	F	N	F	N	F	N
Distress						
Transv., ft.		1063		5		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B29. Photolog 29.

Severity	Slight		Moderate		Severe	
Filled, F; Not, N	F	N	F	N	F	N
Distress						
Transv., ft.		1118		6		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}	5					
Pumping, ft.						

Table B30. Photolog 30.

Severity	Slight		Moderate		Severe	
Filled, F; Not, N	F	N	F	N	F	N
Distress						
Transv., ft.		1038		28		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

Table B31. Photolog 31.

Severity / Filled, F; Not, N / Distress	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.		1258		7		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.	2					

Table B32. Photolog 32.

Severity / Filled, F; Not, N / Distress	Slight		Moderate		Severe	
	F	N	F	N	F	N
Transv., ft.		780		5		
Long., ft.						
Allig., ft.^{2}						
Flushing, ft.^{2}						
Patching, ft.^{2}						
Pumping, ft.						

APPENDIX C

Force Ductility/Computer Program

The following computer program listing provides instructions for a Hewlett-Packard Model 86B microcomputer to obtain the digitized signal from a Bascom-Turner Model 8120T X-Y recorder via the HP-82939A Serial Interface Option 001. The Hewlett-Packard Model 86-B microcomputer system was equipped with parallel coupled HP-9121 disc drives, HP-82905B printer, HP-7470 A plotter, I/O ROM, and Plotter ROM. Two Schaevitz FTA-G-10000 force cells were coupled to the B-T 8120T by a Validyne MC1-3 chassis containing two CD-148 carrier demodulators and a PS-238 power supply.

Force-time information obtained during testing was reduced by this program to provide the seven force ductility parameters reported herein.

Steps involved in performing force ductility tests with the above system are as follows:

1. Signal conditioner 'on'
2. Power & plotter on B-T 'on' [Hello]
3. HP Plotter 'on'
4. HP 86B drives and monitor 'on'
5. Load "Data Acquisition/Reduction" program
6. Remove "DA/R" program disc, replace with 2 initialized data discs
7. HP plotter 'on', paper 'in'
8. B-T: 'Status 11 GO' [100]
9. B-T: 'ACQ 1 GO'
10. Check #1 load cell for response on B-T volt meter
11. B-T: 'CLEAR'
12. B-T: 'Status 12 GO' [100]
13. B-T: 'ACQ 2 GO'
14. Check #2 load cell for response
15. B-T: 'CLEAR'
16. B-T: 'Status 11 GO', '5000 GO', 'Status 12 GO', '5000 GO'
17. Turn on force ductility machine motor w/ clutch disengaged
18. B-T: 'ACQ 12 GO' (Starts data sampling)
19. Engage clutch
20. Sample data until failure or specimen reaches end of machine
21. B-T: 'ACQ 9 GO' (Stops data sampling)
22. HP: 'Run'
23. HP: Monitor should ask following questions:
24. HP: Voltage Setting? (B-T should be set to 10 but answer is '1'
25. HP: Time Setting? '5000'
26. HP: Filename for Data Set #1 'Appropriate Name'
27. Continue to answer questions on monitor until FINISHED message

DATA TRANSFER/REDUCTION PROGRAM

```
10 OPTION BASE 1
20 DISP "*****************CHANGE PAPER IN PLOTTER******************"
30 DISP
40 DISP
50 DISP "VOLTAGE SETTING ?"
60 INPUT V
70 DISP "TIME SETTING ?"
80 INPUT T
90 !
100 CONTROL 10,3 ; 8
110 CONTROL 10,4 ; 26
120 CONTROL 10,2 ; 2
130 CONTROL 10,5 ; 48
140 DIM HH$(119)[60],D$[100],B$[70],C$(15)[70]
150 DIM F(500),FT(2,500),ESS(2,500),TSS(2,500),ECON(4,3),TCON(4,3)
160 DIM FTS(500),POINTS(4,2),EPOINTS(4,2),TPOINTS(4,2)
170 FOR MM=1 TO 2
180 DISP "FILENAME FOR STORING DATA SET",MM
190 INPUT FILES$
200 A=4
210 MASS STORAGE IS ":D700"
220 IF MM=2 THEN 450
221 GOTO 250
230 DISP "LAB MIX NUMBER ?"
240 INPUT B$
250 C$(1)="EL PASO LAB MIX"
251 GOTO 270
260 C$(1)[22,23]=B$
270 C$(2)=" %             REP  "
280 DISP "RUBBER PERCENT BY WEIGHT ?"
290 INPUT B$
300 C$(2)[1,2]=B$
```

```
310 DISP "RUBBER TYPE ?"
320 INPUT B$
330 C$(2)[5,18]=B$
340 DISP "REPETITION NUMBER ?"
350 INPUT B$
360 C$(2)[24,24]=B$
370 DISP "TEST TEMPERATURE ?"
380 INPUT B$
390 C$(3)= "TEST TEMPERATURE ?"
400 C$(3)[19,21]=B$
410 DISP "TEST DATE ?"
420 INPUT B$
430 C$(4)= "DATE ?"
440 C$(4)[7,15]=B$
450 IF MM=1 THEN FILE1$=FILES$
460 IF MM=2 THEN FILE2$=FILES$
470 NP=0
480 FL=0
490 DISP "ENTER CAL 41 ON DATACENTER THEN PRESS CONT. WHEN SCREEN
CLEARS THEN PRESS GO ON DATACENTER"
500 PAUSE
510 CLEAR
520 DISP "DATA TRANSFER IN PROGRESS"
530 FOR I=1 TO 119
540 ENTER 10 ; D$
550 HH$(I)=D$
560 PC=POS (HH$(I),".")
570 IF PC>0 THEN 600
580 NEXT I
590 IF I>119 THEN I=119
600 K=I
610 FOR I=1 TO K
620 DP=POS (HH$(I),".")
630 IF DP=0 THEN 730
```

```
640 SP=DP-3
650 EP=SP+32
660 COOR=LEN (HH$(I))
670 IF COOR<47 THEN EP=EP-48+COOR+1
680 FOR J=SP TO EP STEP 8
690 NP=NP+1
700 B$=HH$(I)[J,J+7]
710 F(NP)=VAL (HH$(3)[33,35])
720 NEXT J
730 NEXT I
740 NP=VAL (HH$(3)[33,35]
750 CLEAR
760 DISP "INPUT COMPLETE: PROCESSING IN PROGRESS"
770 GOSUB 970
780 XMAX-ABS (F(1))
790 FOR I=2 TO NP
800 X1=ABS (F(1))
810 IF X1>XMAX THEN XMAX=X1
820 NEXT I
830 IF XMAX<91.97 THEN 910
840 SF=91.97 THEN 910
850 FOR I=1 TO NP
860 F(I)=SF*F(I)
870 NEXT I
880 DISP "THE SCALING FACTOR IS ";SF
890 IF MM=2 THEN 950
900 GOTO 915
910 SF=1 @ GOTO 880
915 BEEP 150,800
920 DISP "PRESS CAL 22 ON DATACENTER THEN PRESS CONT"
930 PAUSE
940 CLEAR
950 NEXT MM
960 GOTO 1190
```

```
970 NB=(2*NP+2)*8+A*60
980 FILE$=FILES$
990 ER=0
1000 ON ERROR GOSUB 5420
1010 CREATE FILE$,1,NB
1020 IF ER=1 THEN 990
1030 OFF ERROR
1040 FOR I=1 TO NP
1050 F(I)=F(I)*V/10
1060 FT(1,I)=F(I)&5
1070 FT(2,I)=I*T*10^-3/60
1080 NEXT I
1090 ASSIGN# 1 TO FILE$
1100 PRINT# 1 ; NP,A
1110 FOR I=1 TO A
1120 PRINT# 1 ; C$(I)
1130 NEXT I
1140 FOR I=1 TO NP
1150 PRINT# 1 ; FT (1,I),FT(2,I)
1160 NEXT I
1170 ASSIGN# 1 TO *
1180 RETURN
1190 GCLEAR
1200 DEG
1210 EFLAG=0
1220 FOR I=1 TO 15
1230 C$(I)=" "
1240 NEXT I
1250 DE=.2333333
1260 FOR MM=1 TO 2
1270 IF MM=1 THEN A$=FILE1$
1280 IF MM=2 THEN A$=FILE2$
1290 !
1300 ! READ FILE FROM DISC
```

```
1310 !
1320 DISP "OBTAINING FORCE-TIME DATA FROM TAPE"
1330 ASSIGN# 1 TO A$
1340 READ# 1 ; NP,NL
1350 FOR I=1 TO NL
1360 READ#1 ; B$
1370 C$(I)=B$
1380 NEXT I
1390 FOR I=1 TO NP
1400 READ# 1 ; FT(1,I),FT(2,I)
1410 NEXT I
1420 CLEAR
1430 !
1440 ! DISPLAY FILE INFORMATION
1450 !
1460 DISP "********************FILE INFORMATION*********************"
1470 DISP
1480 DISP
1490 FOR I=1 TO NL
1500 DISP C$(I)
1510 NEXT I
1520 DISP
1530 DISP
1540 DISP "*********************************************************"
1550 ASSIGN# 1 TO *
1560 TL=LEN (A$)
1570 FILE$=A$
1580 IF DE<.25 THEN FILE$[TL+1]="A"
1590 IF DE>.25 THEN FILE$[TL+1]="B"
1600 DISP
1610 DISP
1620 DISP
1630 DISP "DATA BEING PROCESSED"
1640 !
```

```
1650 ! ZERO OUT ARRAYS
1660 !
1670 FOR I=1 TO 500
1680 ESS(1,I)=0
1690 ESS(2,I)=0
1700 TSS(1,I)=0
1710 TSS(2,I)=0
1720 FTS(I)=0
1730 NEXT I
1740 FOR I=1 TO 4
1750 POINTS(I,1)=0
1760 POINTS(I,2)=0
1770 EPOINTS(I,1)=0
1780 EPOINTS(I,2)=0
1790 TPOINTS(I,1)=0
1800 TPOINTS(I,2)=0
1810 FOR J=1 TO 3
1820 ECON(I,J)=0
1830 TCON(I,J)=0
1840 NEXT J
1850 NEXT I
1860 !
1870 ! CONVERT, SMOOTH, AND CALCULATE STRESS-STRAIN VALUES.  ALSO
1880 ! DETERMINE MAXIMUM VALUES AND AREAS UNDER CURVES
1890 !
1900 TEMP=NP-2
1910 EAREA=0
1920 TAREA=0
1930 MESTRESS=0
1940 MTSTRESS=0
1950 MFORCE=0
1960 NUMPT=0
1970 FOR I=1 TO NP
1980 IF I<50 AND FT(1,I)<=0 THEN 2130
```

```
1990 IF I<3 THEN FTS(I)=FT(1,I) @ GOTO 2020
2000 IF I>TEMP THEN FTS(I)=FT(1,I) @ GOTO 2020
2010 FTS(I)=(FT(1,I-2)+FT(1,I-1)+FT(1,I)+FT(1,I+1)+FT(1,I+2))/5
2020 ESS(2,I)=DE*FT(2,I)
2030 ESS (1,I)=FTS(I)*2.54^2
2040 TSS(2,I)=LOG (1+ESS(2,I))
2050 TSS(1,I)=FTS(I)*(1+DE*FT(2,I))*2.54^2
2060 IF I=1 THEN 2090
2070 EAREA=EAREA+(ESS(1,I)+ESS(1,I-1))*(ESS*(2,I)-ESS(2,I-1))/2
2080 TAREA=TAREA+(TSS(1,I)+TSS(1,I-1))*(TSS*(2,I)-TSS(2,I-1))/2
2090 MESTRESS=MAX (MESTRESS,ESS(1,I))
2100 MTSTRESS-MAX (MTSTRESS,TSS(1,I))
2110 MFORCE=MAX (MFORCE,FTS(I))
2120 NUMPT=NUMPT+1
2130 NEXT I
2140 MESTRAIN=ESS(2,NP)
2150 MTSTRAIN=TSS(2,NP)
2160 YLIM=40
2170 XLIM=CEIL (MFORCE)
2180 PLOTTER IS 705
2190 LIMIT 10,250,10,190
2200 IF MM=1 THEN LOCATE 5,50,20,90
2210 IF MM=2 THEN LOCATE 70,115,20,90
2220 SCALE XLIM,0,0,YLIM
2230 IF XLIM<=2 THEN XTIC=.1 ELSE XTIC-.5
2240 XNUMM=XLIM+1
2250 AXES XTIC,5,0,0,1,1
2260 AXES XTIC,5,XLIM,40,1,1
2270 DEG
2280 LDIR 90
2290 LORG 5
2300 CSIZE 2
2310 YNUM$=" 0.0"
2320 YNUM=0
```

```
2330 FOR I=1 TO 9
2340 MOVE0,YNUM
2350 SETGU
2360 IMOVE 2,0
2370 LABEL YNUM$
2380 YNUM=YNUM+5
2390 YNUM$[1,2]=VAL$ (YNUM)
2400 SETUU
2410 NEXT I
2420 MOVE 0,17.5
2430 SETGU
2440 IMOVE 5,0
2450 LABEL "TIME - MINUTES"
2460 SETUU
2470 MOVE 0,0
2480 LORG 8
2490 XNUM=0
2500 XNUM$=" 0.0"
2510 FOR I=1 TO XNUMM
2520 MOVE XNUM,0
2530 SETGU
2540 IMOVE 0,-1
2550 LABEL XNUM$
2560 XNUM=XNUM+1
2570 XNUM$[1,2]=VAL$ (XNUM)
2580 SETUU
2590 NEXT I
2600 LORG 5
2610 LDIR 180
2620 XLIM=XLIM/2
2630 MOVE XLIM,0
2640 SETGU
2650 IMOVE 0,-8
2660 LABEL "FORCE - POUNDS"
```

```
2670 SETUU
2680 MOVE 0,0
2690 FOR I=1 TO NP
2700 PLOT FTS(I),FT(2,I),-1
2710 NEXT I
2720 PEN U
2730 SCALE 0,1,0,1
2740 MOVE .08,.65
2750 LORG 1
2760 LDIR  90
2770 FOR I=1 TO 4
2780 LABEL C$(I)
2790 NEXT I
2800 IF MM=1 THEN LABEL "LOAD CELL 1"
2810 IF MM=2 THEN LABEL "LOAD CELL 2"
2820 PEN UP
2830 LIMIT 0,10,0,10
2840 MOVE 0,0
2850 PEN 0
2860 ! PLOT STRESS-STRAIN CURVES AND DETERMINE REGIONS OF CONSTANT
COMPLIANCE
2870 !
2880 PLOTTER IS 1
2890 LOCATE 15,160,25,85
2900 FXD 1
2910 FOR K=1 TO 2
2920 DISP
2930 DISP
2940 IF K=1 THEN XLIM=CEIL (MESTRAIN)
2950 IF K=1 THEN YLIM=CEIL (MESTRESS)
2960 IF K=2 THEN XLIM=CEIL (MTSTRAIN)
2970 IF K=2 THEN YLIM=CEIL (MTSTRESS)
2980 XINC=.1 @ YINC=YLIM
2990 XTIC=10 @ YTIC=1
```

```
3000 SCALE 0,XLIM,0,YLIM
3010 LAXES -XINC,YINC,0,0,XTIC,YTIC
3020 AXES XINC,YINC,XLIM,YLIM,XTIC,YTIC
3030 MOVE XLIM/2,0
3040 SETGU
3050 IMOVE 0,-8
3060 LDIR 0
3070 LORG 5
3080 LABEL "STRAIN - IN/IN"
3090 SETUU
3100 MOVE 0,YLIM/2
3110 SETGU
3120 IMOVE -12,0
3130 LDIR 90
3140 LABEL "STRESS - PSI"
3150 SETUU
3160 LDIR 0
3170 IF K=2 THEN 3220
3180 FOR I=1 TO NP
3190 PLOT ESS(2,I),ESS(1,I),-1
3200 NEXT I
3210 GOTO 3250
3220 FOR I=1 TO NP
3230 PLOT TSS(2,I),TSS(1,I),-1
3240 NEXT I
3250 SETGU
3260 MOVE 3,6
3270 LORG 0
3280 LABEL "NUMBER OF REGIONS OF CONSTANT SLOPE ? - (1 NUMBER)"
3290 INPUT NUMREG
3300 IF K=1 THEN NUMEP=NUMREG
3310 IF K=2 THEN NUMTP=NUMREG
3320 GCLEAR 9
3330 NUMREG1=NUMREG+1
```

```
3340 STFLAG=0
3350 FOR I=1 TO NUMREG1
3360 IFLAG=0
3370 SETGU
3380 MOVE 3,6
3390 IF I=NUMREG1 THEN 3520
3400 LABEL "ENTER START AND END POINTS FOR REGION ";I;" (X1-X2)"
3410 INPUT POINTS (I,1),POINTS(I,2)
3420 GCLEAR 9
3430 SETUU
3440 CX=XLIM/346.305
3450 POINTS(I,1)=INT (POINTS(I,1)/DX)*DX
3460 PEN -2
3470 FOR J=POINTS(I,1) TO POINTS(I,2) STEP DX
3480 MOVE J.0
3490 DRAW J,YLIM
3500 NEXT J
3510 GOTO 3730
3520 SETGU
3530 MOVE 3,6
3540 LABEL "INPUT STRAIN AT FAILURE - (X1)"
3550 INPUT STRAINF
3560 PEN -2
3570 SETUU
3580 MOVE STRAINF,0
3590 DRAW STRAINF, YLIM
3600 SETGU
3610 PEN 1
3620 IF STFLAG=1 THEN STFLAG=0 @ GOTO 3520
3630 PEN 1
3640 GCLEAR 9
3650 MOVE 3,6
3660 LABEL "TO RE-SPECIFY STRAIN AT FAILURE ? - (Y/N)"
3670 INPUT D$
```

```
3680 GCLEAR 9
3690 IF D$="Y" THEN STFLAG=1 @ GOTO 3560
3700 IF K=1 THEN FESTRAIN=STRAINF
3710 IF K=2 THEN FTSTRAIN=STRAINF
3720 GOTO 3870
3730 MOVE 0,0
3740 IF IFLAG=1 THEN PEN 1 @ GOTO 3360
3750 SETGU
3760 MOVE 3,6
3770 PEN 1
3780 LABEL "TO RESPECIFY INTERVAL ? - (Y/N)"
3790 INPUT D$
3800 GCLEAR 9
3810 IF D$="N" THEN 3850
3820 IFLAG=1
3830 SETUU
3840 GOTO 3460
3850 IF K=1 THEN EPOINTS(I,1)=POINTS(I,1) @ EPOINTS(I,2)=POINTS(I,2)
3860 IF K=2 THEN TPOINTS(I,1)=POINTS(I,1) @ TPOINTS(I,2)=POINTS(I,2)
3870 NEXT I
3880 PEN 1
3890 GCLEAR
3900 !
3910 ! DETERMINE VALUES OF CONSTANT COMPLIANCE
3920 !
3930 NEXT K
3940 CLEAR
3950 DISP "DATA BEING PROCESSED"
3960 FOR K=1 TO 2
3970 IF K=2 THEN END1=NUMEP
3980 IF K=2 THEN END1=NUMTP
3990 TEMP=1
4000 FOR J=1 TO END1
4010 LBEG=TEMP
```

```
4020 SX=0
4030 SY=0
4040 SXY=0
4050 SX2=0
4060 NPOINT=0
4070 FOR I=LBEG TO NP
4080 IF K=2 THEN 4180
4090 IF ESS(2,I)<EPOINTS(J,1) THEN 4250
4100 IF ESS(2,I)>EPOINTS(J,2) THEN 4270
4110 SX=SX+ESS(2,I)
4120 SY=SY+ESS(1,I)
4130 SXY=SXY+ESS(2,I)*ESS(1,I)
4140 SX2=SX2+ESS(2,I)^2
4150 NPOINT=NPOINT+1
4160 TEMMP=TEMP+1
4170 GOTO 4260
4180 IF TSS(2,I)<TPOINTS(J,1) THEN 4250
4190 IF TSS(2,I)>TPOINTS(J,2) THEN 4270
4200 SX=SX+TSS(2,I)
4210 SY=SY+TSS(1,I)
4220 SXY=SXY+TSS(2,I)*TSS(1,I)
4230 SX2=SX2+TSS(2,I)^2
4240 NPOINT=NPOINT+1
4250 TEMP=TEMP+1
4260 NEXT I
4270 TEMP=TEMP+1
4280 XBAR=SX/NPOINT
4290 YBAR=SY/NPOINT
4300 SLOPE=(SXY-NPOINT*XBAR*YBAR)/(SX2-NPOINT*XBAR^2)
4310 IF K=2 THEN 4360
4320 ECON(J,1)=SLOPE
4330 ECON(J,2)=EPOINTS(J,1)/DE
4340 ECON(J,3)=EPOINTS(J,2)/DE
4350 GOTO 4390
```

```
4360 TCON(J,1)=SLOPE
4370 TCON(J,2)=(EXP (TPOINTS(J,1))-1)/DE
4380 TCON(J,3)=(EXP (TPOINTS(J,2))-1)/DE
4390 NEXT J
4400 NEXT K
4410 PRINTER IS 703
4420 PRINT "************************************************************"
4430 PRINT "************************************************************"
4440 PRINT
4450 PRINT
4460 FOR I=1 TO NL
4470 PRINT USING 4490 ; C$(I)
4480 NEXT I
4490 IMAGE 20X,50A
4500 LOC=POS (A$,"M")
4510 C$(NL+1)="LOAD CELL NUMBER:"
4520 C$(NL+1)[19]=A$[8,8] ! *********CHANGED FOR BUFFALO MIX********
4530 PRINT USING 4490 ; C$(NL+1)
4540 C$(NL+2)="STRAIN RATE:"
4550 C$(NL+2)[14,18]=VAL$ (DE)
4560 PRINT USING 4490 ; C$(NL+2)
4570 PRINT
4580 PRINT
4590 PRINT "MAXIMUM ENGINEERING STRESS:",TAB (60);INT
(100*MESTRESS)/100
4600 PRINT "MAXIMUM TRUE STRESS:",TAB (60);INT (100*MTSTRESS)/100
4610 PRINT
4620 PRINT "ENGINEERING STRAIN AT FAILURE:",TAB (60);FESTRAIN
4630 PRINT "TRUE STRAIN AT FAILURE:",TAB (60);FTSTRAIN
4640 PRINT
4650 PRINT "AREA UNDER ENGINEERING STRESS-STRAIN CURVE:",TAB (60);INT
(100*EAREA)/100
4660 PRINT "AREA UNDER TRUE STRESS-STRAIN CURVE:",TAB (60);INT
(100*TAREA)/100
```

```
4670 PRINT
4680 PRINT
4690 PRINT USING 4720
4700 PRINT USING 4730
4710 PRINT USING 4720
4720 IMAGE 23X,"********************************"
4730 IMAGE 23X,"*   CONSTANT VALUES OF SLOPE   *"
4740 PRINT
4750 PRINT
4760 PRINT USING 4800
4770 PRINT USING 4810
4780 PRINT USING 4820
4790 PRINT USING 4830
4800 IMAGE 15X,"LOWER LIMIT",10X,"UPPER LIMIT"
4810 IMAGE 15X,"OF TIME   ",10X,"OF TIME   ",10X,"   SLOPE  "
4820 IMAGE "CURVE",10X,"INTERVAL (MIN)",7X,"INTERVAL (MIN)",7X," PSI"
4830 IMAGE "-------------------------------------------------------------"
4840 FOR I=1 TO NUMEP
4850 PRINT USING 4870 ; ECON(I,2),ECON(I,3),ECON(I,1)
4860 NEXT I
4870 IMAGE "ENG.",11X,MD.DDDE,11X,MD.DDDE,11X,MD.DDDE
4880 IMAGE "TRUE",11XMD.DDDE,11X,MD.DDDE,11X,MD.DDDE
4890 FOR I=1 TO NUMTP
4900 PRINT USING 4880 ; TCON(I,2),TCON(I,3),TCON(I,1)
4910 NEXT I
4920 PRINT
4930 FOR I=1 TO 8
4940 PRINT
4950 NEXT I
4960 !
4970 ! STORE RESULTS ON TAPE
4980 !
4990 MASS STORAGE IS ":D701"
5000 ER=0
```

```
5010 ON ERROR GOSUB 5420
5020 CREATE FILE$,1,1140
5030 IF ER=1 THEN 5000
5040 OFF ERROR
5050 C$(NL+1)="ENG. STRAIN AT FAILURE:"
5060 C$(NL+2)="MAX. ENG. STRESS:"
5070 C$(NL+3)="TRUE STRAIN AT FAILURE:"
5080 C$(NL+4)="MAX. TRUE STRESS:"
5090 C$(NL+5)="AREA UNDER ENG. CURVE:"
5100 C$(NL+6)="AREA UNDER TRUE CURVE:"
5110 C$(NL+1)[24,29]=VAL$ (FESTRAIN)
5120 C$(NL+2)[19,24]=VAL$ (MESTRESS)
5130 C$(NL+3)[24.29]=VAL$ (FTSTRAIN)
5140 C$(NL+4)[19,24]=VAL$ (MTSTRESS)
5150 C$(NL+5)[24,29]=VAL$ (EAREA)
5160 C$(NL+6)[24,29]=VAL$ (TAREA)
5170 NSL=NL+6
5180 ASSIGN# 1 TO FILE$
5190 PRINT# 1,1 ; NSL,C$(),ECON(,)
5200 ASSIGN# 1 TO *
5210 MASS STORAGE IS ":D700"
5220 CLEAR
5230 GCLEAR
5240 NEXT MM
5250 PLOTTER IS 1
5260 SCALE 0,10,0,10
5270 LORG 5
5280 FOR ANG=1 TO 15
5290 CSIZE 30,.6,ANG
5300 MOVE 5,5
5310 LABEL "FINISHED"
5320 NEXT ANG
5330 FOR I=1 TO 30 @ NEXT I
5340 CLEAR
```

```
5350 FOR I=1 TO 6
5360 ALPHA
5370 FOR J=1 TO 150 @ NEXT J
5380 GRAPH
5390 FOR J=1 TO 150 @ NEXT J
5400 NEXT I
5410 END
5420 OFF ERROR
5430 ERNUM=ERRN
5440 IF ERNUM#63 THEN 5480
5450 DISP "FILE ";FILE$;" AREADY ON DISC. ENTER NEW FILENAME."
5460 INPUT FILE$
5470 GOTO 5510
5480 DISP "DISC FULL. PUT IN NEW DISC AND THEN PRESS CONT."
5490 PAUSE
5500 INITIALIZE "DRIVE1"
5510 ER=1
5520 RETURN
5530 END
 109207
```

APPENDIX D

Force Ductility/Double Ball Softening Point Data

Table D1. Maximum Engineering Stress, psi (MES) El Paso Lab Mix 39.2F.

Rubber	A			B			C		
Concentration, %	22	24	26	22	24	26	22	24	26
Digestion									
Low	35.6 32.9 23.3	36.1 17.8 17.2	30.2 22.9 23.0	37.1 30.5 20.1	39.9 24.9 15.5	37.1 10.8 23.0	34.8 35.4 28.0	33.8 29.2 20.0	34.3 18.5 23.5
Mod	41.4 23.3 26.6	42.6 19.2 19.6	10.5 19.7 14.3	41.6 20.3 12.1	27.1 10.3 16.2	11.8 11.0 18.3	35.2 41.5 20.1	31.7 24.8 17.0	32.6 35.1 13.0
High	28.3 18.0 20.5	16.7 32.0 18.4	39.3 14.5 18.o	15.2 20.3 21.4	20.9 12.0 19.5	14.8 18.0 11.8	40.4 14.1 34.1	45.0 20.8 13.9	16.4 20.2 22.6

Table D1, (continued). El Paso Lab Mix 39.2F (MES).

Source	df	SS	MS	F	Pr > F
Rubber	2	571.2	186.1	3.18	0.05
Concentration	2	646.4	323.2	3.59	0.03
Digestion	2	418.1	209.1	2.33	0.11
R x C	4	10.1	2.5	0.03	0.99
R x D	4	157.2	39.0	0.44	0.78
C x D	4	121.3	30.1	0.34	0.85
R x C x D	8	298.4	37.2	0.41	0.91
Error	54	4854.2	90.0		
Total	80	7077.7			

Table D2. Maximum True Stress, psi (MTS) El Paso Lab Mix 39.2F.

Rubber	A			B			C		
Concentration, %	22	24	26	22	24	26	22	24	26
Digestion									
Low	101.6 80.0 54.0	107.2 48.0 41.8	85.8 61.6 74.2	122.0 86.4 84.8	145.2 76.2 64.8	153.2 51.6 109.8	106.0 116.6 91.6	113.0 87.8 57.2	108.6 50.8 100.2
Mod	154.4 75.2 90.2	152.0 49.0 52.2	25.7 60.2 38.2	170.4 64.8 50.6	127.4 33.0 71.4	51.8 37.8 91.4	158.0 199.6 66.2	147.8 103.0 45.4	156.0 163.2 40.6
High	117.4 57.2 81.8	67.8 139.4 70.0	164.8 43.6 73.4	67.0 106.6 106.2	108.6 58.2 97.6	76.4 97.2 63.2	227.2 119.6 179.6	299.2 119.6 79.0	95.4 123.8 138.4

Table D2, (continued). El Paso Lab Mix 39.2F (MTS).

Source	df	SS	MS	F	Pr > F
Rubber	2	21802.1	10901.0	5.18	0.01
Concentration	2	5788.2	2894.1	1.38	0.26
Digestion	2	5162.2	2581.1	1.23	0.30
R x C	4	759.5	190.1	0.09	0.99
R x D	4	9777.4	2444.1	1.16	0.34
C x D	4	3667.4	917.1	0.44	0.78
R x C x D	8	4988.8	624.1	0.30	0.96
Error	54	113552.1	2102.0		
Total	80	165499.7			

Table D3. Maximum Engineering Strain, in/in (ESF) El Paso Lab Mixed 39.2F.

Rubber	A			B			C		
Concentration, %	22	24	26	22	24	26	22	24	26
Digestion									
Low	3.18 3.27 3.35	3.34 3.84 3.26	3.19 3.60 3.68	3.72 3.45 4.55	3.11 3.38 5.08	4.26 5.82 4.37	4.40 4.26 4.50	4.69 4.70 4.75	4.13 5.10 5.59
Mod	3.00 3.92 3.98	3.18 3.65 3.51	3.34 3.80 3.58	3.30 4.03 5.60	4.58 4.84 4.64	4.38 4.63 4.67	4.17 4.39 4.95	4.61 4.68 4.91	4.40 4.21 4.86
High	4.04 3.91 4.20	3.90 3.87 3.94	3.73 3.89 4.26	4.66 5.25 4.73	5.00 4.77 5.00	5.10 5.43 5.69	5.30 5.87 4.71	5.04 5.69 5.51	5.68 6.00 5.71

Table D3, (continued). El Paso Lab Mix 39.2F (ESF).

Source	df	SS	MS	F	Pr > F
Rubber	2	22.73	11.36	56.5	0.0001
Concentration	2	1.01	0.51	2.5	0.09
Digestion	2	8.18	4.09	20.4	0.0001
R x C	4	0.93	0.23	1.2	0.34
R x D	4	0.95	0.24	1.2	0.33
C x D	4	0.90	0.23	1.1	0.36
R x C x D	8	0.82	0.10	0.5	0.84
Error	54	10.86	0.20		
Total	80	46.39			

Table D4. Maximum True Strain, in/in (TSF) El Paso Lab Mix 39.2F.

Rubber / Concentration, % / Digestion	A			B			C		
	22	24	26	22	24	26	22	24	26
Low	1.43 1.45 1.41	1.48 1.57 1.45	1.43 1.52 1.54	1.54 1.60 1.71	1.41 1.48 1.80	1.44 1.92 1.68	1.69 1.67 1.69	1.93 1.75 1.75	1.63 1.81 1.88
Mod	1.57 1.59 1.59	1.43 1.53 1.51	1.47 1.57 1.53	1.47 1.64 1.89	1.73 1.75 1.73	1.70 1.73 1.74	1.64 1.69 1.78	1.72 1.74 1.77	1.69 1.64 1.77
High	1.61 1.59 1.65	1.58 1.59 1.59	1.55 1.57 1.66	1.73 1.84 1.74	1.78 1.75 1.80	1.81 1.86 1.89	1.85 1.96 1.76	1.80 1.91 1.87	1.91 1.95 1.90

Table D4, (continued). El Paso Lab Mix 39.2F (TSF).

Source	df	SS	MS	F	Pr > F
Rubber	2	0.835	0.418	61.38	0.0001
Concentration	2	0.030	0.015	2.24	0.11
Digestion	2	0.287	0.143	21.09	0.0001
R x C	4	0.033	0.008	1.20	0.32
R x D	4	0.029	0.007	1.05	0.39
C x D	4	0.024	0.006	0.89	0.47
R x C x D	8	0.036	0.005	0.66	0.72
Error	54	0.367	0.007		
Total	80	1.642			

Table D5. Curve Area, psi (CA) El Paso Lab Mix 39.2F.

Rubber	A			B			C		
Concentration, %	22	24	26	22	24	26	22	24	26
Digestion									
Low	89.4 81.4 56.8	44.2 52.2 42.2	78.4 63.4 69.8	111.2 86.6 77.6	112.2 67.8 64.4	139.2 50.6 89.8	112.0 115.4 94.6	118.8 97.2 66.6	110.2 64.4 105.0
Mod	139.0 74.6 87.6	123.2 52.0 52.8	26.3 60.2 39.3	123.2 66.0 53.6	113.8 36.0 65.6	45.2 38.5 65.6	129.6 163.6 73.0	134.2 99.6 55.6	129.2 133.2 46.6
High	101.2 56.4 75.0	59.2 107.8 63.8	123.6 43.8 69.4	63.0 83.8 90.8	90.0 52.4 85.8	59.4 86.6 59.6	173.2 66.6 133.2	173.4 101.8 70.0	81.4 97.2 105.2

Table D5, (continued). El Paso Lab Mix 39.2F (CA).

Source	df	SS	MS	F	Pr > F
Rubber	2	16124.0	8062.0	7.81	0.001
Concentration	2	4553.4	2277.2	2.21	0.12
Digestion	2	441.8	220.4	0.21	0.81
R x C	4	278.2	70.3	0.07	0.99
R x D	4	2431.4	608.1	0.59	0.67
C x D	4	2313.4	578.1	0.56	0.69
R x C x D	8	2604.0	326.0	0.32	0.96
Error	54	55757.5	1033.1		
Total	80	84507.7			

Table D6. Asphalt Modulus, psi (AM) El Paso Lab Mixed 39.2F.

Rubber	A			B			C		
Concentration, % Digestion	22	24	26	22	24	26	22	24	26
Low	378.2 312.3 242.4	356.6 160.3 141.6	308.0 210.0 207.1	417.1 351.1 173.7	294.4 159.6 140.6	408.4 118.1 159.2	410.2 420.5 271.1	375.4 305.3 197.7	352.3 169.4 253.7
Mod	312.1 208.8 205.9	358.4 200.4 154.1	75.1 191.0 111.8	322.7 193.6 107.1	250.6 96.5 154.1	106.3 117.5 136.1	410.2 332.3 209.4	336.7 239.0 157.1	321.7 269.3 115.4
High	266.8 180.6 189.2	161.2 241.3 187.7	256.7 124.6 178.2	94.5 167.5 193.0	168.0 108.1 157.0	138.0 123.0 103.1	233.3 135.2 271.1	259.4 213.2 119.1	106.2 118.0 135.3

Table D6, (continued). El Paso Lab Mix 39.2F (AM).

Source	df	SS	MS	F	Pr > F
Rubber	2	54349.0	27175.0	4.09	0.02
Concentration	2	82777.1	41388.0	6.23	0.003
Digestion	2	139914.2	69957.1	10.53	0.0001
R x C	4	2240.4	560.1	0.08	0.99
R x D	4	23995.5	5999.1	0.90	0.47
C x D	4	16176.7	4044.2	0.61	0.66
R x C x D	8	14214.1	1777.0	0.27	0.97
Error	54	358920.0	6647.0		
Total	80	692590.0			

Table D7. Asphalt-Rubber Modulus, psi (ARM) El Paso Lab Mixed 39.2F.

Rubber	A			B			C		
Concentration, % / Digestion	22	24	26	22	24	26	22	24	26
Low	60.1 42.4 23.3	68.4 24.3 21.0	51.1 33.3 50.4	95.1 64.1 66.0	131.1 58.3 48.4	133.1 40.0 106.2	74.0 84.0 65.2	77.1 52.2 32.4	72.2 26.1 75.0
Mod	124.3 48.2 62.1	128.5 25.4 29.4	11.0 35.4 13.0	174.1 46.3 36.5	114.5 20.4 59.1	45.1 26.3 75.5	141.1 186.3 41.5	119.4 80.3 24.0	143.0 153.1 23.1
High	104.0 38.0 65.4	53.4 132.3 52.0	164.4 27.3 58.2	51.2 100.2 101.3	103.3 49.3 92.1	66.4 86.1 50.0	226.6 53.4 186.8	278.3 116.2 66.6	85.2 119.3 134.4

Table D7, (continued). El Paso Lab Mix 39.2F (AFM).

Source	df	SS	MS	F	Pr > F
Rubber	2	26776.4	13388.2	5.51	0.007
Concentration	2	4078.3	2039.1	0.84	0.44
Digestion	2	18937.2	9464.1	3.90	0.03
R x C	4	1174.6	294.2	0.12	0.97
R x D	4	16186.6	4046.2	1.67	0.17
C x D	4	4761.4	1190.1	0.49	0.74
R x C x D	8	6714.3	839.1	0.35	0.94
Error	54	131091.0	2427.0		
Total	80	209720.8			

Table D8. Maximum Engineering Stress, psi (MES) El Paso Field Mix 39.2F.

		Rubber		
		A	B	C
Concentration, %	22	19.5 22.0 19.6	17.2 10.8 28.9	28.1 21.0 30.4
	24	27.2 24.0 29.9	26.4 24.2 38.3	25.7 22.3 21.3
	26	11.6 24.0 20.8	21.1 20.8 22.7	21.3 28.2 23.4

Source	df	SS	MS	F	Pr > F
Rubber	2	29.2	14.6	0.55	0.59
Concentration	2	141.4	70.7	2.67	0.09
R x C	4	175.1	43.8	1.66	0.20
Error	18	475.6	26.4		
Total	26	821.3			

Table D9. Maximum True Stress, psi El Paso Field Mix 39.2F.

		Rubber		
		A	B	C
Concentration, %	22	55.4 77.8 68.0	56.4 36.4 118.2	111.6 80.4 123.4
	24	86.2 64.2 92.2	93.4 91.4 161.8	90.0 64.4 65.4
	26	33.2 78.0 60.8	80.2 80.4 92.4	75.6 131.4 96.6

Source	df	SS	MS	F	Pr > F
Rubber	2	3271.3	1635.7	2.53	0.11
Concentration	2	487.7	243.9	0.38	0.69
R x C	4	5382.4	1345.6	2.08	0.13
Error	18	11650.1	647.2		
Total	26	20791.5			

Table D10. Maximum Engineering Strain, in/in El Paso Field Mix 39.2F.

		Rubber		
		A	B	C
Concentration, %	22	3.98 4.19 4.89	4.05 4.85 4.40	4.21 4.40 4.47
	24	3.04 3.29 3.39	3.34 4.30 4.11	4.05 4.20 3.84
	26	3.81 3.46 3.06	3.83 4.06 3.68	3.10 4.38 4.00

Source	df	SS	MS	F	Pr > F
Rubber	2	0.906	0.453	3.07	0.071
Concentration	2	2.665	1.333	9.03	0.002
R x C	4	0.484	0.121	0.82	0.529
Error	18	2.656	0.148		
Total	26	6.712			

Table D11. Maximum True Strain, in/in El Paso Field Mix 39.2F.

		Rubber		
		A	B	C
Concentration, %	22	1.60 1.64 1.77	1.62 1.77 1.79	1.66 1.70 1.70
	24	1.42 1.46 1.47	1.47 1.67 1.63	1.62 1.64 1.57
	26	1.56 1.49 1.40	1.57 1.63 1.55	1.39 1.69 1.61

Source	df	SS	MS	F	Pr > F
Rubber	2	0.042	0.021	3.21	0.064
Concentration	2	0.1100	0.055	8.47	0.003
R x C	4	0.019	0.005	0.72	0.587
Error	18	0.117	0.007		
Total	26	0.289			

Table D12. Curve Area, psi (CA) El Paso Field Mix 39.2F.

		Rubber		
		A	B	C
Concentration, %	22	58.6 77.4 74.6	56.4 41.4 111.0	102.0 76.6 114.0
	24	71.8 63.8 84.0	80.4 87.2 140.5	86.2 69.6 66.2
	26	35.0 70.6 52.6	71.0 73.2 76.0	58.8 110.0 83.8

Source	df	SS	MS	F	Pr > F
Rubber	2	2017.4	1008.7	2.22	0.14
Concentration	2	831.5	415.8	0.92	0.42
R x C	4	2696.3	674.1	1.49	0.25
Error	18	8161.4	453.4		
Total	26	13706.7			

Table D13. Asphalt Modulus, psi (AM) El Paso Field Mix 39.2F.

		Rubber		
		A	B	C
Concentration, %	22	193.7 170.0 169.5	143.6 196.6 259.8	233.1 211.3 330.1
	24	250.6 175.6 294.4	228.4 247.0 370.9	241.6 188.8 201.0
	26	87.5 218.4 161.4	189.0 171.6 163.8	157.7 194.5 250.2

Source	df	SS	MS	F	Pr > F
Rubber	2	4741.4	2371.2	0.76	0.48
Concentration	2	20826.3	10413.1	3.32	0.06
R x C	4	21730.5	5433.1	1.73	0.19
Error	18	56479.7	3137.8		
Total	26	103777.9			

Table D14. Asphalt-Rubber Modulus, psi (ARM) El Paso Field Mix 39.2F.

		Rubber		
		A	B	C
Concentration, %	22	30.7 56.0 45.1	36.2 43.2 95.8	34.3 55.8 98.6
	24	61.2 36.3 57.3	82.4 68.1 142.2	60.7 34.8 38.8
	26	16.7 54.6 35.1	63.4 63.1 79.0	69.4 120.1 79.0

Source	df	SS	MS	F	Pr > F
Rubber	2	4627.4	2314.2	3.87	0.04
Concentration	2	541.2	271.1	0.45	0.64
R x C	4	5382.1	1346.3	2.25	0.10
Error	18	10762.0	598.0		
Total	26	21313.7			

Table D15. Maximum Engineering Stress (MES), psi Buffalo Field Mix.

Replication		1		2	
Concentration, %		18	22	18	22
Digestion	Low	14.1 11.3 6.2	27.2 27.5 6.9	9.6 11.6 10.3	19.8 20.4 11.2
	High	7.5 7.4 6.0	12.6 7.9 5.2	8.9 8.3 2.5	9.7 10.4 5.6

Source	df	SS	MS	F	Pr > F
Replication	1	5.29	5.29	0.20	0.66
Concentration	1	152.89	152.89	5.68	0.03
Digestion	1	292.57	292.57	0.12	0.73
R x C	1	3.15	3.15	10.86	0.005
R x D	1	3.84	3.84	0.14	0.71
C x D	1	63.68	63.68	2.36	0.14
R x C x D	1	5.30	5.30	0.20	0.66
Error	16	431.00	26.94		
Total	23	957.72			

Table D16. Maximum True Stress (MTS), psi Buffalo Field Mix.

Replication	1		2	
Concentration, %	18	22	18	22
Digestion				
Low	72.9	85.4	48.0	102.8
	54.1	71.9	57.9	96.4
	29.8	33.2	51.3	57.1
High	45.8	71.3	50.5	55.0
	42.0	44.4	47.7	58.3
	30.9	28.5	10.2	27.5

Source	df	SS	MS	F	Pr > F
Replication	1	115.9	115.9	0.29	0.59
Concentration	1	1514.6	1514.6	3.83	0.06
Digestion	1	2572.2	2572.2	0.55	0.46
R x C	1	218.2	218.2	6.51	0.02
R x D	1	266.4	266.4	0.67	0.43
C x D	1	234.6	234.6	0.59	0.45
R x C x D	1	142.8	142.8	0.36	0.55
Error	16	6322.3	395.1		
Total	23	11387.0			

Table D17. Maximum Engineering Strain (MES) in/in Buffalo Field Mix.

Replication	1		2	
Concentration, %	18	22	18	22
Digestion				
Low	5.75 5.44 5.64	2.95 2.95 5.69	5.72 6.05 5.50	5.38 5.05 5.68
High	7.03 7.28 7.50	5.80 6.40 6.10	6.83 6.19 6.13	5.90 7.16 6.83

Source	df	SS	MS	F	Pr > F
Replication	1	0.627	0.627	1.46	0.24
Concentration	1	3.496	3.496	8.16	0.01
Digestion	1	12.514	12.514	29.21	0.0001
R x C	1	2.884	2.884	6.73	0.01
R x D	1	1.515	1.515	3.54	0.07
C x D	1	0.549	0.549	1.28	0.27
R x C x D	1	0.001	0.001	0.00	0.95
Error	16	6.854	0.428		
Total	23	21.578			

Table D18. Maximum True Strain (TSF), in/in Buffalo Field Mix.

Replication	1		2	
Concentration, %	18	22	18	22
Digestion				
Low	1.91 1.86 1.89	1.37 1.37 1.90	1.91 1.95 1.86	1.85 1.80 1.89
High	2.09 2.11 2.14	1.93 2.00 1.96	2.05 1.97 1.96	1.93 2.10 2.05

Source	df	SS	MS	F	Pr > F
Replication	1	0.0254	0.0254	1.82	0.19
Concentration	1	0.1001	0.1001	7.21	0.01
Digestion	1	0.3128	0.3128	22.52	0.0002
R x C	1	0.0828	0.0828	5.96	0.02
R x D	1	0.0523	0.0523	3.76	0.07
C x D	1	0.0301	0.0301	2.17	0.16
R x C x D	1	0.0035	0.0035	0.25	0.62
Error	16	0.2223	0.0139		
Total	23	0.8292			

Table D19. Curve Area (CA), PSI -- Buffalo Field Mix.

Replication	1		2	
Concentration, %	18	22	18	22
Digestion				
Low	72.5 52.2 29.8	69.9 65.8 31.9	48.1 59.6 50.1	91.9 84.3 56.7
High	44.4 42.9 36.6	63.9 45.4 25.9	54.1 41.1 10.1	52.5 52.7 29.4

Source	df	SS	MS	F	Pr > F
Replication	1	102.1	102.1	0.35	0.56
Concentration	1	689.0	689.0	2.35	0.14
Digestion	1	1902.6	1902.6	6.50	0.02
R x C	1	266.6	266.6	0.91	0.35
R x D	1	320.4	320.4	1.10	0.31
C x D	1	94.4	94.4	0.32	0.57
R x C x D	1	80.7	80.7	0.28	0.60
Error	16	4681.3	292.6		
Total	23	8137.1			

Table D20. Asphalt Modulus, (AM), psi Buffalo Field Mix.

Replication		1		2	
Concentration, %		18	22	18	22
Digestion	Low	81.9 94.6 43.1	209.7 286.2 40.4	105.3 67.1 79.5	132.4 145.4 80.5
	High	66.8 38.9 47.0	52.1 54.6 31.7	66.0 51.2 18.7	77.8 71.9 45.0

Source	df	SS	MS	F	Pr > F
Replication	1	470.2	470.2	0.19	0.66
Concentration	1	9104.0	9104.1	3.76	0.07
Digestion	1	23087.3	23087.3	9.54	0.01
R x C	1	786.3	786.3	0.32	0.57
R x D	1	1426.6	1426.6	0.59	0.45
C x D	1	5965.3	5965.3	2.47	0.13
R x C x D	1	3348.3	3348.3	1.38	0.25
Error	16	38716.8	2419.8		
Total	23	82904.7			

Table D21. Asphalt-Rubber Modulus, (ARM), psi Buffalo Field Mix.

Replication	1		2	
Concentration, %	18	22	18	22
Digestion				
Low	58.0 43.3 26.2	64.4 39.5 32.4	34.5 41.9 38.1	91.4 83.7 44.5
High	30.0 30.1 22.3	61.0 32.8 26.6	39.2 32.6 7.76	46.3 35.3 22.2

Source	df	SS	MS	F	Pr > F
Replication	1	106.4	106.4	0.43	0.51
Concentration	1	1292.4	1292.4	5.28	0.03
Digestion	1	1865.9	1865.9	7.62	0.01
R x C	1	284.7	284.7	1.16	0.29
R x D	1	335.5	335.5	1.37	0.25
C x D	1	111.6	111.6	0.46	0.50
R x C x D	1	503.1	503.1	2.06	0.17
Error	16	3915.6	244.7		
Total	23	8415.2			

Table D22. Maximum Engineering Stress (MES), PSI -- Buffalo Lab Mix.

		Concentration, %	
		18	22
Digestion	Low	17.3 19.6 21.2	19.6 21.6 18.0
	Mod	13.4 16.0 15.7	11.3 10.8 9.2
	High	5.59 5.02 6.99	5.21 7.71 8.56

Source	df	SS	MS	F	Pr > F
Digestion	2	508.0	254.0	111.9	0.0001
Concentration	1	3.8	3.8	1.7	0.22
D x C	2	28.4	14.2	6.3	0.01
Error	12	27.2	2.3		
Total	17	567.4			

Table D23. Maximum True Stress (MTS), PSI -- Buffalo Lab Mix

		Concentration, %	
		18	22
Digestion	Low	50.2 58.2 63.4	80.0 73.5 66.9
	Mod	56.9 74.3 75.2	66.5 61.5 55.0
	High	28.5 24.5 36.4	28.4 41.8 47.4

Source	df	SS	MS	F	Pr > F
Digestion	2	3758.3	1879.2	31.5	0.0001
Concentration	1	157.2	157.2	2.6	0.13
D x C	2	458.9	229.5	3.8	0.05
Error	12	716.4	59.7		
Total	17	5090.8			

Table D24. Maximum Engineering Strain (MES), in/in Buffalo Lab Mix.

		Concentration, %	
		18	22
Digestion	Low	4.77 4.14 4.10	4.48 3.75 4.70
	Mod	5.70 5.07 4.93	5.91 6.48 6.27
	High	6.23 7.80 5.58	6.75 6.03 6.40

Source	df	SS	MS	F	Pr > F
Digestion	2	14.24	7.12	20.50	0.0001
Concentration	1	0.35	0.35	0.97	0.34
D x C	2	1.22	0.61	1.67	0.22
Error	12	4.24	0.35		
Total	17	20.05			

Table D25. Maximum True Strain (TSF), in./in. Buffalo Lab Mix.

		Concentration, %	
		18	22
Digestion	Low	1.75 1.63 1.63	1.70 1.56 1.73
	Mod	1.89 1.80 1.78	1.92 2.01 1.98
	High	1.98 2.17 1.89	2.04 1.96 2.00

Source	df	SS	MS	F	Pr > F
Digestion	2	0.360	0.180	25.9	0.0001
Concentration	1	0.008	0.008	1.16	0.30
D x C	2	0.024	0.012	1.72	0.22
Error	12	0.083	0.007		
Total	17	0.475			

Table D26. Curve Area (CA), PSI Buffalo Lab Mix.

		Concentration, %	
		18	22
Digestion	Low	60.1 67.8 68.7	77.3 69.0 69.7
	Mod	62.2 73.0 70.8	58.7 58.4 63.3
	High	29.7 80.5 34.2	30.9 40.4 46.0

Source	df	SS	MS	F	Pr > F
Digestion	2	3691.6	1845.8	75.7	0.0001
Concentration	1	7.6	3.8	0.3	0.58
D x C	2	392.2	196.1	8.0	0.01
Error	12	292.8	24.4		
Total	17	4384.2			

Table D27. Asphalt Modulus (AM), PSI Buffalo Lab Mix.

		Concentration, %	
		18	22
Digestion	Low	130.7 138.7 133.9	123.6 129.2 94.6
	Mod	121.9 118.3 84.5	76.6 61.2 64.6
	High	45.8 36.1 36.1	34.1 49.7 47.1

Source	df	SS	MS	F	Pr > F
Digestion	2	21036.0	10518.0	66.30	0.0001
Concentration	1	1514.9	1514.9	9.55	0.01
D x C	2	1521.8	760.9	4.80	0.02
Error	12	1903.6	158.6		
Total	17	25976.3			

Table D28. Asphalt-Rubber Modulus (ARM), PSI. Buffalo Lab Mix.

		Concentration, %	
		18	22
Digestion	Low	20.4 28.5 31.2	55.4 46.2 43.2
	Mod	39.0 57.1 59.3	55.7 54.4 47.4
	High	22.5 16.7 30.7	22.6 35.8 43.7

Source	df	SS	MS	F	Pr > F
Digestion	2	1691.7	845.9	13.4	0.001
Concentration	1	545.5	545.5	8.7	0.01
D x C	2	325.7	162.9	2.6	0.11
Error	12	755.3	62.9		
Total	17	3318.3			

Table D29. Softening Point, F, El Paso Lab Mix.

Rubber	A			B			C		
Concentration, %	22	24	26	22	24	26	22	24	26
Digestion									
Low	116.9 117.0 116.5	122.6 117.5 116.0	123.8 123.1 122.9	118.5 117.8 114.1	123.4 119.8 112.5	123.5 118.3 120.1	118.0 121.3 118.3	120.6 114.3 115.5	117.8 112.8 116.4
Mod	124.3 113.4 110.4	121.9 108.9 116.9	112.3 110.1 118.0	124.3 116.4 119.0	123.5 112.4 116.0	113.6 116.6 115.0	123.9 122.9 116.1	126.5 118.1 114.4	120.4 125.9 109.5
High	111.6 116.3 116.8	116.3 111.9 117.5	116.5 116.6 113.4	123.5 114.1 119.3	116.8 124.1 116.3	118.8 112.5 119.1	124.8 111.6 121.5	129.4 118.9 116.1	115.5 120.0 119.5

Table D29, (continued). Softening Point, El Paso Lab Mix.

Source	df	SS	MS	F	Pr > F
Rubber	2	70.40	35.20	1.74	0.18
Concentration	2	6.91	3.50	0.17	0.84
Digestion	2	15.42	7.71	0.38	0.68
R x C	4	34.33	8.61	0.43	0.79
R x D	4	144.45	36.11	1.80	0.14
C x D	4	78.99	19.72	0.98	0.42
R x C x D	8	65.90	8.20	0.41	0.91
Error	54	1084.41	20.10		
Total	80	1500.91			

Table D30. Softening Point, F (SP), El Paso Field Mix.

		Rubber		
		A	B	C
Concentration, %	22	113.1 110.3 117.6	113.3 115.2 115.1	118.0 116.1 120.5
	24	118.4 114.3 119.2	116.1 116.0 120.6	111.0 112.0 116.0
	26	118.0 117.1 118.0	113.0 114.5 119.5	120.0 120.0 118.0

Source	df	SS	MS	F	Pr > F
Rubber	2	10.31	5.16	0.58	0.57
Concentration	2	39.53	19.76	2.21	0.14
R x C	4	97.30	24.33	2.71	0.06
Error	18	161.28	8.96		
Total	26	308.43			

Table D31. Softening Point, F, Buffalo Field Mix.

Replication	1		2	
Concentration, %	18	22	18	22
Digestion				
Low	116.6 116.0 118.0	116.5 117.3 119.3	114.9 116.4 118.3	126.0 126.5 121.0
High	111.0 110.4 109.8	117.9 118.0 121.4	111.5 116.8 112.0	114.8 117.1 115.3

Source	df	SS	MS	F	Pr > F
Replication (e)	1	13.88	13.08	3.73	0.07
Concentration (c)	1	147.51	147.51	39.65	0.0001
Digestion (d)	1	107.32	107.32	28.84	0.0001
R x C	1	0.21	0.21	0.06	0.81
R x D	1	17.51	17.51	4.71	0.05
C x D	1	1.90	1.90	0.51	0.49
R x C x D	1	70.04	70.04	18.82	0.001
Error	16	59.53	3.72		
Total	23	417.90			

Table D32. Softening Point, F, Buffalo Lab Mix.

		Concentration, %	
		18	22
Digestion	Low	115.3 116.8 114.8	124.0 124.4 123.0
	Mod	116.6 123.4 120.1	118.3 118.4 118.1
	High	103.3 101.1 112.4	108.6 116.8 112.1

Source	df	SS	MS	F	Pr > F
Digestion	2	432.22	216.11	19.65	0.0001
Concentration	1	88.45	88.45	8.04	0.02
D x C	2	87.69	43.85	3.99	0.05
Error	12	132.02	11.00		
Total	17	740.38			

APPENDIX E

Specification for Asphalt-Rubber Seal Coats and Interlayers

1. DESCRIPTION

This work involves placement of an asphalt-rubber treatment on a prepared pavement surface in accordance with the plans and other specifications.

This specification describes two known proprietary processes for production of the treatment hereinafter known as Method A and Method B. Method A uses ground vulcanized rubber and an extender oil, whereas Method B uses ground vulcanized rubber and a kerosene diluent. Either method is acceptable based on proper compliance with the specification and certification of material.

2. MATERIALS

2.01 ASPHALT CEMENT. Asphalt cement shall meet the requirements of AASHTO M 20-70 (Table 1.), M226-80 (Table 1), or M226-80 (Table 3). Acceptable grades for the respective materials will depend on location and circumstances and may require approval of the supplier of the Asphalt-Rubber. In addition, it shall be fully compatible with the ground rubber proposed for the work as determined by the supplier.

2.02 RUBBER EXTENDER OIL (METHOD A). Extender oil shall be a resinous, high flash point aromatic hydrocarbon meeting the following test requirements:

Viscosity, SSU, at 100 F (ASTM D 88)	2500 min.
Flash Point, COC, degrees F (ASTM D 92)	390 min.
Molecular Analysis (ASTM D 2007):	
Asphalteness, Wt. percent	0.1 max.
Aromatics, Wt. percent	55.0 min.

2.03 KEROSENE-TYPE DILUENT (METHOD B). The kerosene-type diluent used shall be compatible with all materials used and shall have a flash point (ASTM D92) of not less than 80F. The initial boiling point shall not be less than 300 F with total distillation (dry point) before 450 F (ASTMD 850). The Contractor is cautioned that a normal kerosene or range oil cut may not be suitable.

2.04 GROUND RUBBER COMPONENTS.

A. FOR METHOD A. The rubber shall meet the following physical and chemical requirements.

Two types of ground rubber shall be blended. Rubber Types 1 and 2 shall meet the following test requirements as described by ASTM D297: The rubber shall be blended such that the resulting material conforms to test requirements as indicated below:

Specific Gravity	1.15	1.17	1.12	1.14	1.14	1.16
Total Extract, w percent	14	21	8	12	12	15
Ash, w percent	3.0	6.3	3.8	4.2	4.5	5.5
Free Carbon, w percent	28	32	27	29	27.5	29.5
Total Sulfur, w percent	1.0	1.2	1.0	1.2	1.0	1.2
Rubber Polymer:						
Natural Rubber, w percent	18	32	85	95	50	60
Styrene Butadiene, w percent	58	82	5	15	35	45
Polybutadiene, w percent	0	12	0	0	4	8
Rubber Hydrocarbon, w percent	50	65	50	60	55	65

The rubber blend shall be dry and free flowing, free of wire, fabric, or other contaminants except up to 4 Wt. percent of mineral powder may be included to prevent sticking of particles. Rubber constituents and moisture content shall be such that when mixed with asphalt, foaming of the resulting blend does not occur.

SIEVE ANALYSIS (ASTM C-136)

Sieve Number	Percent Passing
8	100
30	30-50
50	5-30
100	0-5

B. FOR METHOD B. The rubber shall be a ground tire rubber, 100 percent vulcanized, recommended by the Contractor for this use with the approval of the Engineer, meeting the following requirements:

COMPOSITION. The rubber shall be ground tire rubber, dry and free flowing, free from fabric, wire, or other contaminating materials except that up to 4 Wt. percent of calcium carbonate shall be included to prevent sticking together of the particles. Properties of the rubber shall conform to requirements shown below for tests described by ASTM D297.

	Min	Max
Specific Gravity	1.15	1.17
Total Extract, w percent	1	21
Ash, w percent	3	6.3
Free Carbon, w percent	28	32
Total Sulfur, w percent	1.0	1.2
Rubber Polymer:		
Natural Rubber, w percent	18	32
Styrene Butadieve, w percent	58	82

Polybutadiene, w percent	0	12
Rubber Hydrocarbon, w percent	50	65

Rubber constituents and moisture content shall be such that when mixed with asphalt, foaming of the resulting blend does not occur.

SIEVE ANALYSIS (ASTM C-136).

Sieve Number	Percent Passing
8	100
10	98-100
30	0-10
50	0-2

2.05 AGGREGATES. Cover aggregates shall be a dry, clean material meeting the requirements of AASHTO M 283-81 and the additional requirements listed below:

A. Only crushed stone or slag will be acceptable (hot or precoated aggregates, if used, will be by special provisions in the documents).

B. The aggregate shall not contain more than 5 Wt. percent chart or other known stripping material.

C. Gradation shall be according to ASTM C 448-80, Size 7 with the addition that no more than 1 Wt. percent shall pass the Number 50 sieve.

D. The aggregate shall be essentially free of deleterious material such as thin, elongated pieces, dirt, dust, and shall contain not more than 1 Wt. percent water when tested in accordance with ASTM C 566.

2.06 TACK COAT (METHODS A AND B). The tack coat shall be as shown on the plans or as directed by the Engineer.

2.07 CERTIFICATION AND QUALITY ASSURANCE. Prior to application, the Contractor shall submit certification of specification compliance for all materials to be used in the work. Also certification shall be submitted concerning the design of the asphalt-rubber blend as follows:

A. METHOD A. The Contractor shall submit certification that the asphalt cement is compatible with the rubber and has been tested to determine the quantity of extender oil (usually 1 to 7 Wt. percent) required and that the proposed percentage will produce an absolute viscosity of the blended materials of 600 to 2000 poises at 140F when tested in accordance with the requirements of AASHTO T 202-80. New certifications will be required if the asphalt cement grade or source is changed.

B. METHOD B. The Contractor shall submit certifications that the asphalt cement is compatible with the rubber. New certifications will be required if the asphalt cement grade is changed.

C. FOR EITHER METHOD. The Contractor shall submit information (that will vary with the location) that shows, to the satisfaction of the Engineer, that the asphalt-rubber and aggregate combination proposed for the project will not be subject to water stripping in the environmental exposure of the project.

3. EQUIPMENT

3.01 PREBLENDING. Rubber and a portion of the asphalt for the asphalt-rubber blend shall be preblended in a master batch prior to introduction of the master batch to the distributor. The master batch can be diluted with additional asphalt and additives in the distributor to the formulation recommended by the Supplier.

3.02 DISTRIBUTOR. At least one pressure-type bituminous distributor in good condition will be required. The distributor shall be equipped so as to be capable of even heating of the material up to 425F, have adequate pump capacity to maintain a high rate of circulation in the tank; have adequate pressure devices and suitable manifolds to provide constant positive cutoff to prevent dripping from the nozzles. The distributor bar shall be fully circulating with nipples and valves so constructed that they are in such intimate contact with the circulating asphalt that the nipples will not become partially plugged with congealing asphalt upon standing, thereby causing streaked or irregular distribution of the asphalt. Any distributor that produces a streaked or irregular distribution of the material shall be promptly removed from the project. Distributor equipment shall include a tachometer, pressure gages, volume measuring devices, and a thermometer for reading temperature of tank contents. The asphalt-rubber sections shall be so constructed that uniform applications may be made at the specified rate per square yard within a tolerance of plus or minus 0.03 gallons per square yard. It is suggested that the distributors used for Method B be equipped with mechanical mixing devices.

3.03 CHIP SPREADER. A self propelled chip spreader in good condition and of sufficient capacity to apply the aggregate within the time period specified is required. The spreader shall be so constructed that it can be accurately gauged and set to uniformily distribute the required amount of aggregate at regulated speed.

3.04 BROOMS. Revolving brooms shall be so constructed as to sweep clean or redistribute aggregate without damage to the surface.

3.05 PNEUMATIC TIRE ROLLERS. There shall be at least three multiple-wheel pneumatic-tired self-propelled rollers with provisions for loading to at least eight tons and at a tire inflation pressure as required by the Engineer with a minimum 3,000 pounds per wheel.

3.06 TRUCKS. Trucks of sufficient number and size to adequately supply the material will be required and shall be properly equipped for use with the chip spreader.

3.07 MUNICIPAL TYPE STREET SWEEPER. If the Contractor intends to put traffic on the asphalt-rubber surface treatment or interlayer, it may be necessary to sweep the surface with a Municipal Type Street Sweeper in urban areas and revolving broom in rural areas to pick up and/or remove stone and dust lodged in the surface.

4. CONSTRUCTION DETAILS.

4.01 PREPARATION OF BINDER FOR METHOD A.

A. PREPARATION OF ASPHALT-EXTENDER OIL MIX BLEND. Blend the preheated asphalt cement (250 to 400F), and sufficient rubber extender oil (1 to 7 Wt. percent) to reduce the viscosity of the asphalt cement-extender oil blend to within the specified viscosity range. Mixing shall be thorough by recirculation, mechanical stirring, air agitation, or other appropriate means. A minimum of 400 gallons of the asphalt cement-extender oil blend shall be prepared before introduction of the rubber.

B. PREPARATION OF ASPHALT-RUBBER BINDER. The asphalt-extender oil blend shall be heated to within the range of 350 to 425F. The asphalt-rubber blend for the master batch shall preblended in appropriate preblending equipment as specified by the supplier prior to introduction of the master batch into the distributor. Addition of asphalt cement into the distributor to provide the specified formula shall be as directed by the supplier. The percentage of rubber shall be 20 to 24 Wt. percent of the total blend as specified by the supplier. Recirculation shall continue for a minimum of 30 minutes after all the rubber is incorporated to insure proper mixing and dispersion. Sufficient heat should be applied to maintain the temperature of the blend between 375 and 425F while mixing. Viscosity of the asphalt-rubber shall be less than 4,000 centipoises at the time of application (ASTM D 2994 with the use of a Haake type viscometer in lieu of a Brookfield Model LVF or LVT if desired).

4.02 PREPARATION OF BINDER FOR METHOD B.

A. PREPARATION OF THE ASPHALT-RUBBER BLEND-MIXING.

The asphalt cement shall be preheated to within the range of 350 to 450F. The asphalt-rubber blend for the master batch shall be preblended in appropriate preblending equipment as specified by the supplier prior to introduction of the master batch into the distributor. Addition of asphalt cement and diluent into the distributor to provide the specified formula shall be as directed by the supplier. The percentage of rubber shall be 20 to 24 Wt. percent of the total asphalt-rubber mixture (including diluent). Mixing and recirculation shall continue until the consistency of the mixture approaches that of a semi-fluid material (i.e., reaction is complete). At the lower temperature, it will require approximately 30 minutes for the reaction to take place after the start of the addition of rubber. At the higher temperature, the reaction will take place within approximately five minutes; therefore, the temperature used will depend on the type of application and the methods used by the Contractor. Viscosity of the asphalt-rubber shall be less than 4,000 centipoises at the time of application (ASTMD 2994 with the use of a Haake type viscometer in lieu of a Brookfield Model LVF or LVT if desired). After reaching the proper consistency, application shall proceed immediately.

B. ADJUSTMENT TO SPRAYING VISCOSITY WITH DILUENT. After the full reaction described in MIXING (4.02) above has occurred, the mix can be diluted with a kerosene type diluent. The amount of diluent used shall be less than 7.5 percent by volume of the hot asphalt-rubber composition as required for adjusting viscosity for spraying or better wetting of the cover aggregate. Temperature of the hot composition shall not exceed the kerosene initial boiling point at the time of adding the diluent.

4.03 JOB DELAYS. Prior to preparation or use of asphalt-rubber (prepared by either Method A or B), maximum holdover times due to job delays (time of application after completion of reaction) to be allowed will be agreed upon between the Contractor, Supplier, and Engineer. However, holdover times in excess of 16 hours will not be allowed at temperatures above 290F. Retempering by additional heating and/or addition of asphalt rubber, or diluent (kerosene/extender oil) will be allowed with approval of the Engineer.

4.04 SEASONAL AND WEATHER LIMITATIONS. Placement of the asphalt-rubber surface treatment or interlayer shall be made only under the following conditions:

A. Ambient air temperature is above 60F and rising.
B. The pavement surface for application is absolutely dry.
C. The wind conditions are such that a satisfactory membrane application can be achieved.

4.05 PREPARATION OF SURFACE. Prior to the hot asphalt-rubber treatment, the entire surface to be treated shall be cleaned as required by sweeping, blowing, and other methods until all dust, mud, clay lumps, and foreign material are removed entirely from the area. Patching may be required. No moisture should be present on the surface. After cleaning and patching, the surface shall receive a tack coat if directed by the Engineer.

4.06 APPLICATION OF BINDER. The material shall be applied at a temperature of 375 to 425F for Method A and 290 to 350F for Method B. The rate shall be specified by the Engineer, but should generally be 0.35 to 0.65 gallons per square yard. No shot shall be in excess of a length which can be immediately covered with aggregate. The Contractor is reminded that the traffic in the adjacent lane must be protected from asphalt-rubber aggregate, and sweepings. Application width may have to be adjusted to protect this traffic.

The application from the distributor shall be stopped when the tank contains less than 300 gallons of blended asphalt-rubber. At all startings, which shall include joints with preceeding application, intersections, and at junctions with all pavements, etc., a property junction shall be made to insure that the distributor nozzles are operating at full force when the application begins. Building paper or other suitable devices shall be used to receive the initial application from the nozzles before any material reaches the road surface at the joint.

The paper or other suitable device shall be removed immediately after use without spilling surplus material on the road surface. During the application of binder, the Contractor shall provide adequate protection to prevent marring or discoloration of pavement, structures, curbs, trees, etc., adjacent to the area being treated.

Longitudinal joints shall be reasonably true to line and parallel to the centerline. The overlap in the application of the binder shall be the minimum to assure complete coverage.

Where any construction joint occurs, the treatment of the edges shall be blended so there are no gaps and the elevations are the same and free from ridges and depressions.

When the application of binder is on less than the full width of treatment, the aggregate shall be spread only to within eight inches of the edge of the next application until the binder is applied to the adjacent width.

Between shots no substantial quantity of binder shall remain in the spray bars or nozzles.

4.07 APPLICATION OF COVER AGGREGATE. The application of aggregate shall follow immediately after the application of binder. The hot application of binder shall not be made further in advance of the spreading of the cover aggregate than can be covered immediately. The distributor and the aggregate spreader shall not be separated by more than 150 feet.

Spreading of the aggregate shall be done directly from approved spreaders. Trucks and spreaders shall not drive on the uncovered binder.

The dry aggregate shall be spread uniformly to cover the binder with an amount of mineral aggregate such that no more than one layer of mineral aggregate is applied, this quantity is generally 25 to 40 pounds per square yard but will be as directed by the Engineer. Any deficient areas shall be covered by additional material.

The entire application of cover material shall be rolled as soon as possible after application. Rolling shall continue to be repeated as often as necessary to key the cover material thoroughly into the binder over the entire surface.

Pneumatic tire rollers shall be used in the sequence and combination which will provide the rolling pattern that results in the best adhesion of the aggregate to the binder and the best surface qualities.

Any loose cover aggregate not embedded after initial rolling shall be removed by sweeping. Deficient areas where loose aggregate has been removed may have blotter sand applied to prevent traffic from removing embedded coarse aggregates.

All such rolling shall be performed while the temperature is favorable for seating the aggregate into the binder.

In no case shall there be less than three complete coverages with pneumatic tire rollers of the entire surface of the treatment after initial placement. Additional coverage, may be necessary if directed by the Engineer.

When the Engineer has determined that the maximum amount of cover aggregate has been embedded, the Contractor shall sweep or otherwise remove all loose material from the entire surface at such time and in such manner as will not displace any embedded aggregate.

The completed asphalt-rubber surface treatment or interlayer shall be allowed to cure for a minimum period as directly by the Engineer prior to placing any final overlays. Traffic will not be permitted on the asphalt-rubber surface treatment or interlayer until it has cured and the embedded cover aggregates are tightly bound to the surface such that they will not be dislodged by traffic.

The Engineer may require the surface to be swept with a municipal type street sweeper should power brooming fail to remove all stone and dust particles from the surface which would in his opinion be detrimental to traffic.

5. METHOD OF MEASUREMENT.

The asphalt-rubber surface treatment or interlayer will be measured by the number of square yards of compacted material in place.

6. BASIS OF PAYMENT.

The unit price bid per square yard shall include the cost of furnishing all material, all labor and equipment necessary to complete the work. Payment for patching material and tack coat will be made under the appropriate items.

7. ALTERNATE METHOD OF MEASUREMENT AND BASIS OF PAYMENT.

An alternate method of measurement and basis of payment is based on actual quantities used for the asphalt-rubber application. Asphalt-rubber (including diluent and/or extender oil) and cover aggregate will be measured by the ton of materials actually used for the project. All materials will be weighed in the vehicle at the time and place of unloading or at such other points as may be directed by the Engineer.

The amount of completed and accepted work, measured as provided above, will be paid for at the contract price per ton for "Asphalt-Rubber" and at the contract price for "Cover Aggregate".