EVALUATION OF ASPHALT-RUBBER INTERLAYERS

by

Cindy K. Estakhri
Engineering Research Associate
Texas Transportation Institute

Olga Pendleton
Research Scientist
Texas Transportation Institute

and

Robert L. Lytton
Research Engineer
Texas Transportation Institute

Research Report 187-20F
Research Study Number 1-10-77-187.4
Study Title: Monitoring Asphalt-Rubber Test Pavements

Sponsored by the
Texas Department of Transportation
in cooperation with the
U.S. Department of Transportation
Federal Highway Administration

May 1993
Revised February 1994

TEXAS TRANSPORTATION INSTITUTE
Texas A&M University System
College Station, Texas 77843-3135

IMPLEMENTATION STATEMENT

The findings of this study indicate that asphalt-rubber interlayers are effective at reducing the rate of reflection cracking in an overlay. Variables contributing to the performance of these interlayers are also discussed in the report. The results of this study can best be conveyed to operational personnel by means of this research report and/or a research summary.

Implementation of these research results will aid the Texas Department of Transportation, as well as other state DOTs, in meeting the requirements of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). Beginning in 1994, ISTEA provides for a minimum utilization requirement for asphalt pavement containing crumb rubber modifier as a percentage of the total tons of asphalt laid in such state. Use of crumb rubber modifier as an asphalt-rubber interlayer can be used to meet these requirements. Use of crumb rubber modifier in hot-mixed, asphalt concrete is a relatively new technology, and early pavement failures have been observed due to this lack of experience by the highway community; however, the use of crumb rubber in interlayers or seal coats is backed by many more years of experience and can be built with a greater success rate.

This research indicates that the use of asphalt-rubber as an interlayer reduces the rate of reflection cracking and has the potential for a longer pavement service life thereby saving time and money by possibly reducing maintenance and rehabilitation activities. The crumb rubber used in asphalt-rubber interlayers is a waste material which cannot easily be disposed of. The use of crumb rubber in this application contributes to the solution for the environmental problem of waste tire disposal.

The findings of this research do not warrant the application of new procedures, specifications, standards or designs.

DISCLAIMER

This report is not intended to constitute a standard, specification or regulation and does not necessarily represent the views or policy of the FHWA or the Texas Department of Transportation. Additionally, this report is not intended for construction, bidding, or permit purposes. Supervising Engineer: Cindy Estakhri (Texas Serial Number 77583).

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF TABLES

SUMMARY

This report presents the field performance results of three asphalt-rubber interlayer test roads in terms of the effectiveness of the interlayer at reducing the rate of reflection cracking. Several variables were included in the field experiments: concentration of rubber, binder application rate, type or source of rubber, and digestion (or mixing) time of asphalt and rubber. Control sections were made up of no interlayer and interlayer binders of polymer-modified asphalt and conventional asphalt cement.

Results of the statistical analyses of the data indicated that, in general, asphalt-rubber interlayers are more effective at reducing reflection cracking than no interlayer at all. Asphalt-rubber also performed better than control sections composed of asphalt cement interlayers and polymer-modified interlayers except in one case where the interlayer was composed of a double application of asphalt cement/aggregate.

The data also indicated that higher binder application rates lead to improved cracking resistance; however, on many test sections, excessively high binder application rates caused flushing at the pavement surface.

Rubber type or source did not appear to be a factor in determining reflection cracking, but the lower concentrations of rubber appeared to perform better than high concentrations.

FINDINGS

The objective of this study was to evaluate the field performance of test roads constructed with asphalt-rubber interlayers. Three test roads were constructed throughout the state, and their resulting performance is summarized below.

Summary of El Paso Test Road Performance

Nine test sections of different asphalt-rubber interlayers and one control section (no interlayer) were constructed at the El Paso Test Road. Asphalt-rubber interlayer variables which were evaluated included rubber concentration, rubber type, and application rate. Type of rubber did not seem to be a factor in affecting the degree of transverse cracking.

It appeared that the fairest measure of how well a treatment performed was the length of time required for the pavement to reach its preconstruction distress level. Using this measure, the control section which had no interlayer performed worse than all of the interlayer sections. However, the control section was not a good control for the treated sections because it had very little distress to start with and then changed very little over the entire study period (low cracking rate). The asphalt-rubber interlayer sections were more distressed to begin with, and so even though the cracking rates were higher, they performed better, relative to their preconstruction status.

Rubber concentrations of 22, 24, and 26 percent by total weight of binder were evaluated. Concentrations of 22 percent all had the longest time periods to reach the preconstruction distress level, regardless of the binder application rate. However, researchers can say this with reliability for only one of the test sections. In general, it appears that rubber concentration is a more significant factor in reducing reflection cracking than binder application rate.

Three binder application rates were used to construct the asphalt-rubber interlayers in this study: 0.35, 0.40, and 0.45 gallons per square yard. The average time to preconstruction distress level is greatest for the 0.45 binder application rate, ignoring rubber concentration.

The performance of the El Paso Test Road revealed that asphalt-rubber interlayers are better than no interlayer at all. Among the variables within the test sections of asphalt-rubber interlayers, the general trends in the data showed the following: (1) rubber type does not appear to be a factor in determining the reflection cracking, (2) the lowest concentration of rubber (22%) performed the best, and (3) the highest binder application rate (0.45 gsy) appears to provide for better performance in terms of reflection cracking.

Summary of Buffalo Test Road Performance

The Buffalo Test Road was designed as a full factorial with two fixed factors and two replications. This experiment held rubber type and binder application rate constant, while rubber content and digestion time were varied. A total of four treatments (two rubber contents and two digestion times) were replicated providing eight experimental test sections. Four additional test sections were included as controls. Two sections were constructed using a conventional asphalt cement as the interlayer binder, and the other two sections contained no interlayer.

This test road had just begun to show cracking distress at which time it was recycled. Any conclusions drawn from the performance of this test road are likely to be premature. Most of the test sections exhibited less than 15 percent of the cracking which was present prior to construction.

The treatments are listed below in order of performance, from best to worst. However, it is very important to note that the statistical analysis revealed that only the first treatment (18% rubber, high digestion) is significantly better than the others:

- 18% Rubber, High digestion,
- 22% Rubber, High digestion,
- 18% Rubber, Low digestion,
- 22% Rubber, Low digestion,
- Control, AC interlayer,
- Control, No interlayer.

Summary of Brownsville Test Road Performance

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 were composed of no interlayer and interlayer binders of polymer-modified asphalt and conventional asphalt cement. Interlayers were constructed using various combinations of single and double applications of binder and aggregate. This allowed for different binder application rates. One characteristic of asphalt rubber interlayers or chip seals is that more binder can be applied during construction, and this additional binder may aid in reducing reflection cracking. It was, therefore, of interest to determine how conventional binders (applied in double layers) could compare to asphalt rubber.

Many of the treatments in this test road were eliminated from the analysis due to excessive bleeding at the pavement surface which may have concealed any reflection cracking. In 1991 only four of the test sections had complete data. These are listed in order of performance from best to worst (along with the total interlayer binder application rate):

- Asphalt Cement Double Interlayer (0.60 gallons per square yard),
- Asphalt Rubber Single Interlayer (0.65 gallons per square yard),
- Polymer-Modified Double Interlayer (0.51 gsy),
- No Interlayer.

Prior to 1991 (in 1989) two additional treatments can be included in the analysis: These are listed in order of performance from best to worst (along with the total interlayer binder application rate):

- Asphalt Rubber Double Interlayer (1.62 gsy),
- Asphalt Rubber Single Interlayer (0.78 gsy),
- Asphalt Rubber Single Interlayer (0.65 gsy),
- Asphalt Cement Interlayer (0.60 gsy),
- Polymer-Modified Interlayer (0.51 gsy),
- No Interlayer.

In this listing, the asphalt-rubber interlayers are significantly better than the controls. Of the asphalt-rubber interlayers, only the first (which was applied at 1.62 gsy) was significantly better than the other two.

In summation, this data indicates that an interlayer is effective at reducing the rate of reflection cracking and that asphalt-rubber interlayers are generally better than interlayers constructed of conventional binders. However, the data also indicates that the binder quantity applied to construct the interlayer may have the greatest effect on reducing reflection cracking. In fact, based on the most recent performance measurement (1991), a double application of a conventional asphalt cement interlayer performed better than a single application of an asphalt-rubber interlayer.

INTRODUCTION

The objective of this study was to evaluate the field performance of test roads constructed with asphalt-rubber interlayers. Asphalt rubber is a blend of asphalt cement modified with scrap tire rubber (crumb rubber). An asphalt-rubber interlayer is a membrane beneath an overlay designed to resist the stress/strain of reflective cracks and delay the propagation of the crack through the new overlay. (1) This membrane is a spray application of asphalt-rubber binder and cover aggregate. It is commonly referred to as a stress-absorbing membrane interlayer or SAMI.

Three test roads were built in 1983 and 1984 under research study 347 (2), and their performance has been monitored since that time. (3, 4) This report refers to these test roads as the El Paso Test Road, the Buffalo Test Road and the Brownsville Test Road.

The test sections constructed at the El Paso Test Road contained nine different asphalt-rubber interlayers in which three variables were evaluated: rubber type, rubber content,and asphalt-rubber binder application rate. One test section served as a control containing no interlayer.

The Buffalo Test Road experiment was designed as a full factorial with two fixed factors and two replications. In this experiment, rubber type and binder application rate were held constant, while rubber content and digestion time were varied. A total of four treatments (two rubber contents and two digestion times) were replicated providing eight experimental test sections. Four additional test sections were included as controls. Two sections were constructed using a conventional asphalt cement as the interlayer binder and the other two sections contained no interlayer.

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 were composed of interlayer binders of polymer-modified asphalt and conventional asphalt cement.

The asphalt-rubber binders used at each of these test roads were extensively evaluated by laboratory tests in Study 347. (1) One of these tests used to characterize the asphalt-rubber binder was the force-ductility test. The modulus value obtained from the force ductility test was used to develop a model for establishing a correlation between laboratory properties and reflective transverse cracking. This report presents this model. A computer program was also developed to aid in the analysis of the data using this model.

Using this model and computer program, the El Paso Test Road was analyzed in an attempt to establish correlations between laboratory tests and field performance which would lay the groundwork for a more comprehensive study. No distinct correlations were identified in this analysis; therefore, a more comprehensive study needed to fully develop these correlations was never pursued.

EL PASO TEST ROAD

Test Road Location

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 1. Test sections are each approximately 0.90 miles (1.5 km) in length in the travel lanes as shown in Figure 2.

Pavement Structure

The original pavement structure for the eastbound lanes was U.S. Highway 80 consisting of a 20-foot (6 m) 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 (150 mm) of dense-graded asphalt concrete over 6 inches (150 mm) of cement-treated base and 6 inches (150 mm) of cement-treated subgrade. An overlay of the original portland cement concrete pavement in 1963 consisted of 6 inches (150 mm) of dense-graded asphalt concrete in which 3-inch (75 mm) by 6-inch (150 mm) Number 10 welded wire fabric was embedded in the lower 1½ inches (38 mm).

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.

Traffic

Traffic on the El Paso Test Road consisted of a total traffic volume of 7900 average daily traffic (ADT) at the time of construction. Truck volume was approximately 25 percent of this value with five axle semi-trucks accounting for approximately 60 percent of all trucks.

Pavement Condition Prior to Construction

Pavement distress included slight to severe transverse cracking at random intervals, and combinations of longitudinal and alligator cracking distributed throughout. A summary of the cracking distress prior to construction is presented in Appendix A: Tables A1 and A2.

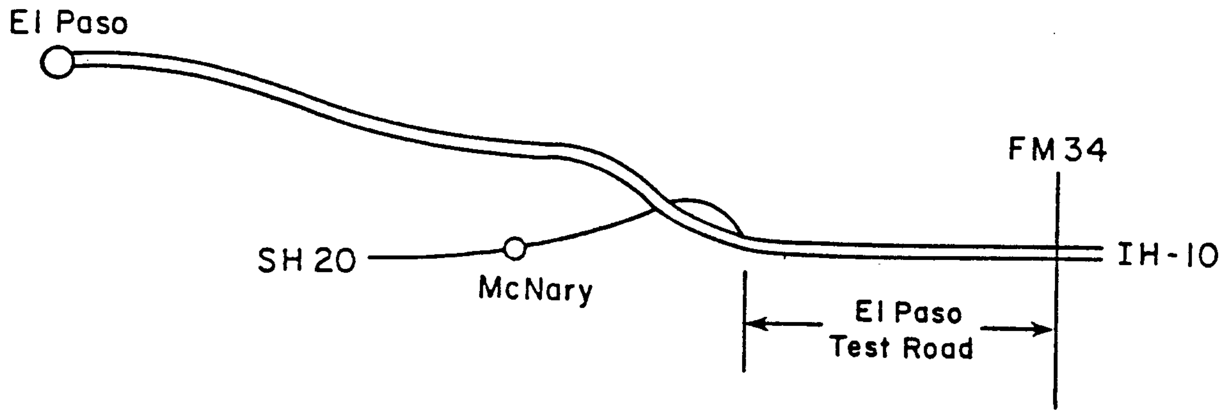

Figure 1. El Paso Test Road Location.

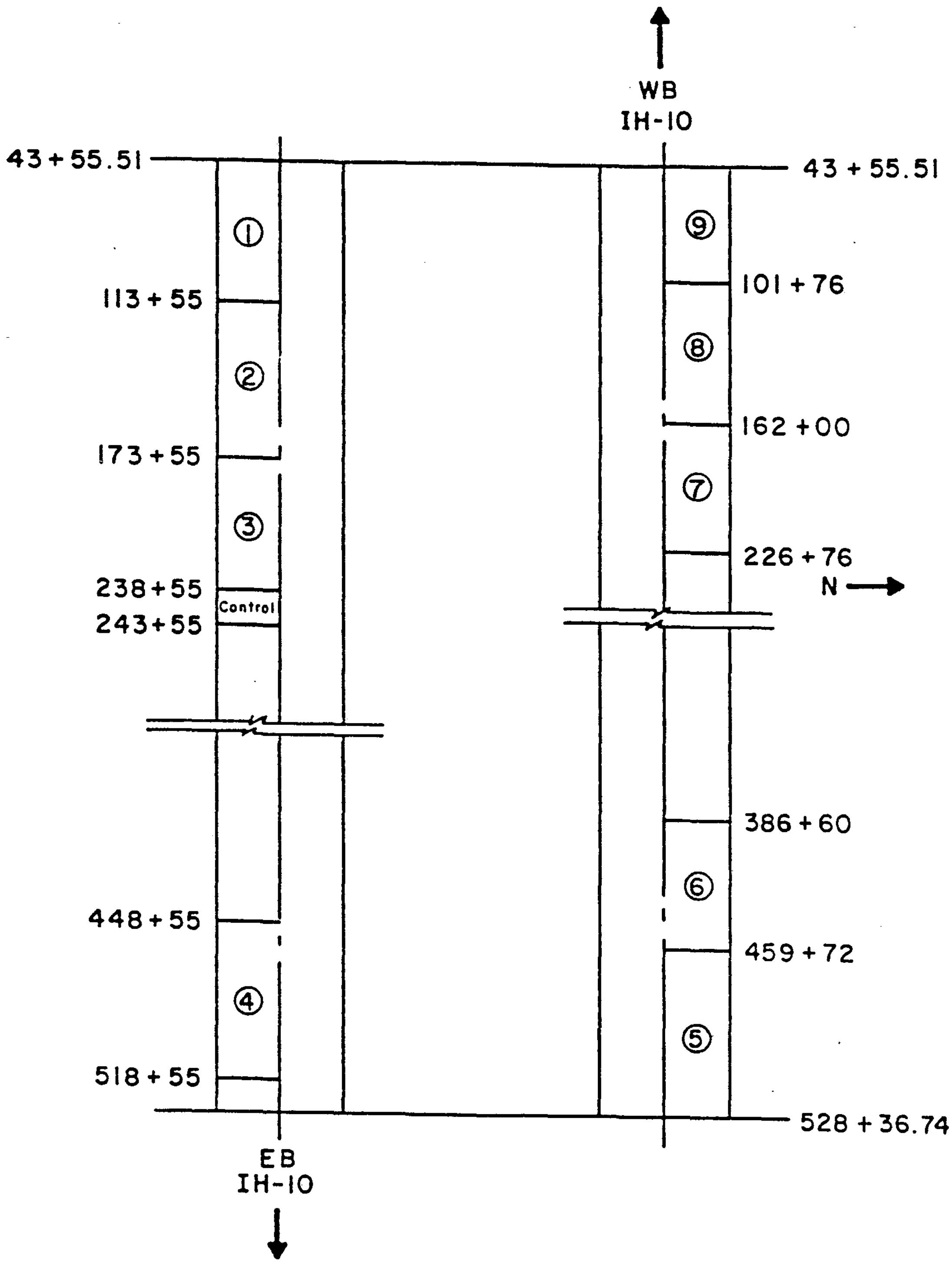

Figure 2. El Paso Test Sections.

Field Experiment Design

The El Paso Test Road was designed as a latin square with three samples per treatment. The latin square was designed without replication; therefore, estimation of interaction effects is not possible. Levels of the independent variables are as follows:

I. Rubber Type,
   A. Type A (Genstar Conservation, Chandler, Arizona)
   B. Type B (Atlos Manufacturing, Los Angeles, California)
   C. Type C (Midwest Elastomers, Wapokonetta, Ohio)

II. Rubber Concentration (Percent by Weight of Total Binder)
   A. 22
   B. 24
   C. 26

III. Binder Application Rate
   A. 0.35 gsy (1.6 l/m^2)
   B. 0.40 gsy (1.8 l/m^2)
   C. 0.45 gsy (2.0 l/m^2)

The matrix arrangement shown in Figure 3 depicts all combinations of variables investigated for field response at the El Paso Test Road.

El Paso Test Road - Preconstruction

Prior to construction, three segments of pavement, each 500 feet (150 m) in length, were located within each test section. These sections were surveyed by photographing the 12-foot (3.6 m) wide and 500-foot (150-m) long pavement section prior to rehabilitation. The locations of these photolog segments within each test section are as shown in Table 1.

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 (2.4 by 3.6 m) with a 6-inch (150 mm) overlap for adjacent segments. Each photograph of the test sections was studied to determine the extent of distress prior to construction.

Application Rate	Rubber Concentration 22	Rubber Concentration 24	Rubber Concentration 26
35	C Section 2	B Section 9	(A) Section 8 ← Rubber Type
40	B Section 4	A Section 1	C Section 6
45	A Section 5	C Section 7	B Section 3

Control (No Interlayer)
Section 10

Figure 3. El Paso Field Response Experiment.

Table 1. El Paso Photolog Locations.

Test Section	Photolog	Station From	Station 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

Distress types and levels of severity were recorded for each test section following the criteria described by Epps, et al. (5) Researchers paid particular attention to recording the total amount of cracking within each photolog since the asphalt-rubber interlayer was intended to reduce the rate at which cracks in the underlying pavement propagate the new asphalt concrete overlay.

El Paso Test Road - Construction

Asphalt-rubber interlayers were placed in June of 1983 and the asphalt concrete overlay was constructed the following month. Details regarding the construction and results of field tests and measurements are contained in Reference 2.

Performance Monitoring

Under this study, systematic condition surveys were conducted semi-annually: once each fall and spring. Distress types and levels of severity were recorded for each test section following the criteria described by Epps, et al. (5) Forms were developed to summarize the distress for each photolog segment as shown in Figure 4. Tables A1 and A2 (Appendix A) summarize the cracking data.

Survey Date Photolog

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

Figure 4. Photolog Distress Summary Form.

Statistical Analysis of El Paso Cracking Data

Linear regression models were fit to the transverse cracking data over the 17 time periods in which the observations were made. The regression models provide estimates of the rate of transverse cracking over time as well as an estimate of the degree of initial cracking. The models can then be compared for the different rubber concentration/binder rate combinations: concentrations of 22,24 and 26 percent rubber and binder application rates of 0.35, 0.40, and 0.45 gallons per square yard (1.6, 1.8, and 2.0 liters per square meter). Concentration and rate factors were crossed, so all nine combinations of these binder rates and concentration levels were observed. The three rubber types were blocked using a latin square design. Type of rubber, however, did not appear to be a factor in determining the degree of transverse cracking.

Photolog Segment Analyses. Three photolog segments of pavement were available for each concentration and binder rate combination and it was of interest to ask if these sections behaved similarly with respect to transverse cracking within each concentration/binder rate group. Four sections were significantly different. These are listed as follows:

- **Binder Rate 0.35 gsy (1.6 l/m^2), Rubber Concentration 22%:**

  Segment 1 had a significantly higher preconstruction distress level than segments 2 and 3.

- **Binder Rate 0.35 gsy (1.6 l/m^2), Rubber Concentration 26%:**

  Segment 1 had a significantly higher transverse cracking rate than segments 2 or 3.

- **Binder Rate 0.35 gsy (1.6 l/m^2), Rubber Concentration 24%:**

  Segment 3 had a significantly higher preconstruction level than segments 1 and 2.

- **Binder Rate 0.40 gsy (1.8 l/m^2), Rubber Concentration 22%:**

  Segment 3 had a significantly lower transverse cracking rate than segments 1 and 2.

- **Binder Rate 0.40 gsy (1.8 l/m²), Rubber Concentration 24%:**

  Segment 1 had significantly lower preconstruction distress levels than segments 2 or 3.

- **Binder Rate 0.45 gsy (2.0 l/m²), Rubber Concentration 22%:**

  Segment 2 had a significantly lower transverse cracking rate than segments 1 and 3.

- **Binder Rate 0.45 gsy (2.0 l/m²), Rubber Concentration 26%:**

  Segment 3 had a significantly lower rate than segments 1 and 2.

Reasons for these differences are not known. However, a possible confounding factor could be the differences in the amount of transverse cracking that existed prior to treatment. Although the differences in preconstruction distress were not statistically significant when tested among rubber concentrations and binder rates, adjustment for preconstruction condition made the replicate sections more comparable.

Analysis. Table 2 lists the regression models adjusted for preconstruction distress. Table 2 lists these models and the statistical measures of R^2 and the upper and lower 95% prediction limits 8.5 years after construction. The dependent variable is the difference between the observed distress and the preconstruction distress. The negative intercept terms reflect the fact that the observed postconstruction distress is initially less than the preconstruction distress.

The data in this table can be interpreted as follows. In the model, the first number, or intercept term, is an estimate of the difference between the initial amount of postconstruction and the preconstruction cracking in linear feet. Thus, for example, for the control, the observed number of postconstruction transverse cracks was 47 feet (14 m) less than the number of preconstruction transverse cracks whereas for the 0.35 (1.6 l/m²) binder rate and 22 concentration treatment, the observed number of transverse cracks was some 420 feet less than the preconstruction number. Thus the control section was not a very good control since it had very few preconstruction transverse cracks as compared to the treatment sections which had significantly greater preconstruction distress. The second number in the model is the rate of cracking per half year. Thus, for concentration 22 and binder rate 0.35 (1.6 l/m^2), one would expect an increase of 19.7 linear feet (6 m) (of cracking in the first half-year or 39.4 feet (12 m) of cracking per year.

Table 2. Regression Model.

Binder Rate, gsy	Rubber Content, percent	Model	R^2	mean	Upper	Lower
Control	Control	y= -47.04 + 8.2(Time)	0.79	26.9	70.2	-16.6
0.35	22	y= -419.5 + 19.7(Time)	0.18	-241.8	169.8	-651.3
0.40	22	y= -474.4 + 21.3(Time)	0.72	-263.2	-119.5	-406.9
0.45	22	y= -369.1 + 11.8(Time)	0.17	-263.1	-5.2	-515.0
0.35	24	y= -280.7 + 17.3(Time)	0.32	-124.6	127.3	-376.5
0.40	24	y= -272.6 + 19.2(Time)	0.36	-99.7	30.8	-354.8
0.45	24	y= -272.3 + 18.5(Time)	0.72	-104.5	9.3	-218.3
0.35	26	y= -261.8 + 24.2(Time)	0.71	-43.8	108.8	-196.4
0.40	26	y= -380.3 + 20.9(Time)	0.73	-192.0	-65.2	-318.8
0.45	26	y= -429.5 +23.8(Time)	0.77	-215.7	-88.1	-343.3

1 gsy = 4.5 l/m^2

The rate of cracking in terms of linear feet per year adjusted for preconstruction distress is listed in Table 3. From this table we see that the control sections had the lowest cracking rate: 16.4 linear feet (5 m) per year. However, the control section, as will be noted later, had very little preconstruction distress and attained that level of distress within 3 years whereas the treated sections had significantly more preconstruction distress and did not return to the preconstruction levels for a much longer period. In other words, the control section was not a good control for the treated sections in that it had very little distress to start with and then changed very little over the entire period of the study (low cracking rate). The treatment sections were more distressed to begin with and so even though the cracking rates were higher, they performed better, relative to their preconstruction status, over the study period.

Table 3. Annual Cracking Rate

Binder Application Rate, gallons/yd^2	Rubber Concentration, percent	Trans. Cracking Rate
Control	Control	16.4
0.35	22	39.4
0.40	22	42.6
0.45	22	23.6
0.35	24	34.6
0.40	24	38.4
0.45	24	37.0
0.35	26	48.4
0.40	26	41.8
0.45	26	47.6

1 gsy = 4.5 l/m^2

The fairest measure of how well a treatment performed is the length of time required for the pavement to reach its preconstruction distress level. This will be examined in the following analysis.

Returning to Table 2, the R^2 value of .18 means that this model accounts for only 18% of the total variation of cracking for this concentration/binder rate category. This is a measure of the reliability of the model and we see that some models are more reliable than others. This was due to the large variability among some of the replicate sections for some treatment combinations. The mean is the average difference in the amount of cracking from the preconstruction cracking level over the entire 17 time periods. Thus, for the control group we see that the average amount of cracking over this time period exceeds the preconstruction level of cracking by 26.9 feet (8.2 m), whereas none of the treated sections had an average cracking exceeding the preconstruction levels during this period.

The upper and lower prediction limits are the ranges of the predicted difference in the amount of cracking after 8.5 years (the mid-point of the study period) and the preconstruction level of cracking. This means, for example, that after 8.5 years, we could predict, with 95% confidence, that the amount of cracking at the control section would be somewhere between 70.2 feet (21 m) greater than the preconstruction level and 16.6 feet (5 m) less than the preconstruction level. Note that these ranges are quite extensive in some cases, the worst being binder rate 0.35 gsy (1.6 l/m^2) and concentration 22 where, after 8.5 years, the predicted amount of cracking can be anywhere from 170 feet (52 m) greater than preconstruction levels to 651 feet (200 m) less! Again, this attests to the tremendous variability in the data.

Table 4. Length of Time to Reach Preconstruction Distress.

Rubber Concentration, percent	Binder Application Rate, gallons/yd^2	Time to Preconstruction Distress, years
Control	Control	2.8
22	0.35	10.6
22	0.40	11.1
22	0.45	15.6
24	0.35	8.1
24	0.40	7.1
24	0.45	7.3
26	0.35	5.4
26	0.40	9.1
26	0.45	9.0

1 gsy = 4.5 l/m^2

Models where the R^2 values are high and the 95% prediction limits stay negative reflect the treatment combinations which yield the least distress and about which we have the most reliability. Examining Table 2 indicates that binder rate 0.40 gsy (1.8 l/m2) and concentration 22 is the best treatment combination with respect to reducing transverse cracking. The next best combination is concentration 26 for binder rates 0.40 (1.8 l/m^2) or 0.45 (2.0 l/m^2). Figure 5 depicts these models. The point at which these lines cross the zero axis is the time at which these sections reached their preconstruction distress levels. Table 4 lists these times in years. Thus we see that the control section is actually the worst in that these sections reach their preconstruction distress levels in 2.8 years. Of course, this is also due to the fact that these sections did not have much preconstruction distress, as noted earlier. Concentrations of 22 took the longest to reach preconstruction distress levels, regardless of the binder rate. However, keep in mind that only for binder rate 0.40 (1.8 l/m^2) can this be stated with any degree of reliability. In general, examining these lines it would appear that concentration is a more significant factor in transverse cracking performance than binder rate, and the middle concentration rate appeared to be the least effective.

Summary of El Paso Test Road Performance

Nine test sections of different asphalt-rubber interlayers and one control section (no interlayer) were constructed at the El Paso Test Road. Evaluated asphalt-rubber interlayer variables included rubber concentration, rubber type, and application rate. Type of rubber did not seem to be a factor in affecting the degree of transverse cracking.

It appeared that the fairest measure of how well a treatment performed was the length of time required for the pavement to reach its preconstruction distress level. Using this measure, the control section which had no interlayer performed worse than all of the interlayer sections. However, the control section was not a good control for the treated sections in that it had very little distress to start with and then changed very little over the entire study period (low cracking rate). The asphalt-rubber interlayer sections were more distressed to begin with, and so even though the cracking rates were higher, they performed better, relative to their preconstruction status.

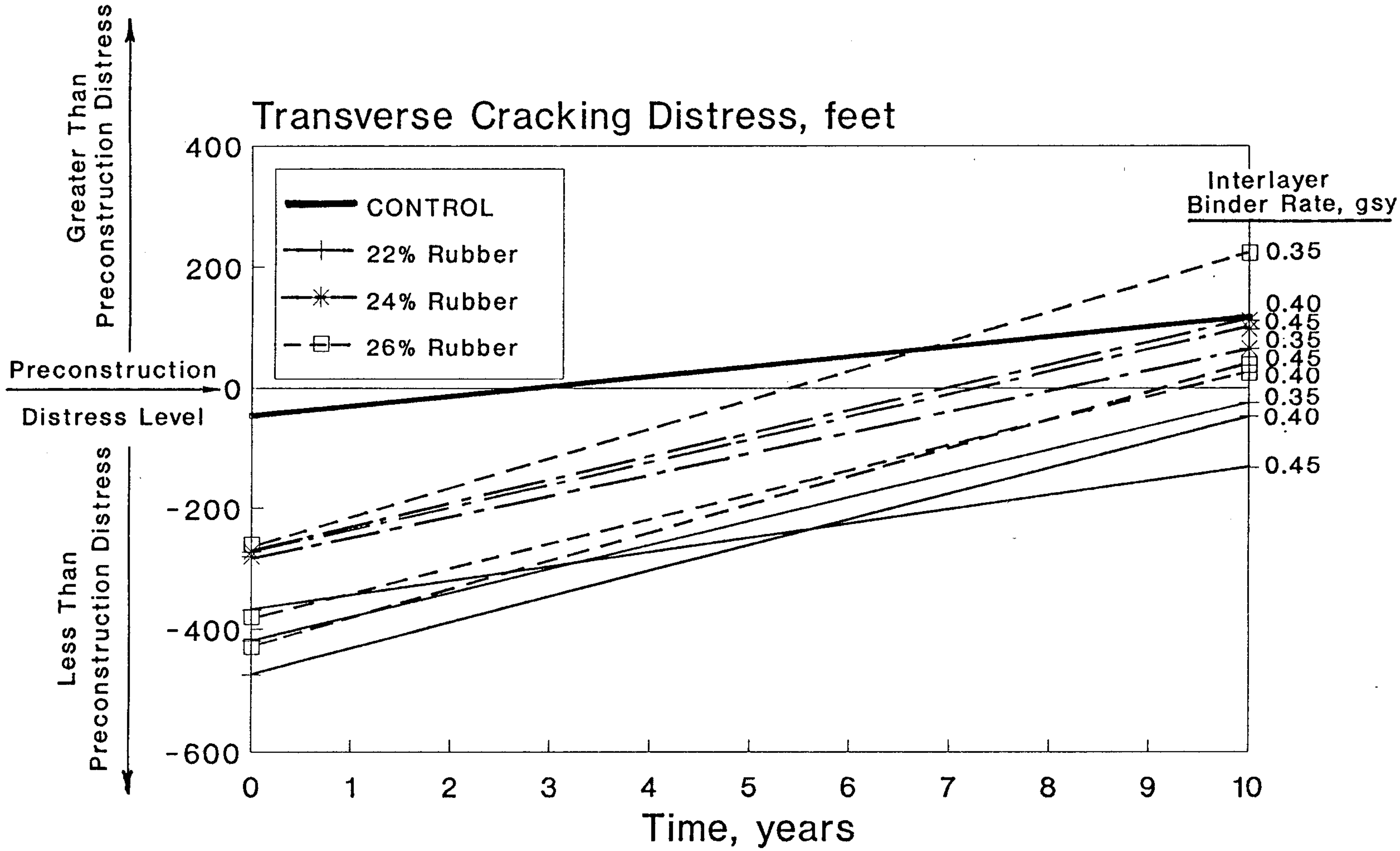

Figure 5. Time to Reach Preconstruction Transverse Cracking Level for El Paso Test Sections.

Rubber concentrations of 22, 24, and 26 percent by total weight of binder were evaluated. Concentrations of 22 percent all had the longest time periods to reach the preconstruction distress level, regardless of the binder application rate. However, only for one of the test sections can this be stated with any degree of reliability. In general, it appears that rubber concentration is a more significant factor than binder application rate in reducing reflection cracking.

Three binder application rates were used to construct the asphalt-rubber interlayers in this study: 0.35, 0.40, and 0.45 gallons per square yard (1.6, 1.8, and 2.0 l/m^2). The average time to preconstruction distress level is greatest for the 0.45 gsy (2.0 l/m^2) binder application rate, ignoring rubber concentration.

The performance of the El Paso Test Road revealed that asphalt-rubber interlayers are better than no interlayer at all. Among the variables within the test sections of asphalt-rubber interlayers, the general trends in the data showed the following: (1) rubber type does not appear to be a factor in determining the reflection cracking, (2) the lowest concentration of rubber (22%) performed the best, and (3) the highest binder application rate (0.45 gsy or 2.0 l/m^2) appears to provide better performance in terms of reflection cracking.

BUFFALO TEST ROAD

Test Road Location

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 6. Test sections are each approximately 0.80 mile (1.3 km) in length in the northbound travel lane as shown in Figure 7.

Pavement Structure

The Buffalo Test Road is constructed on 8 inches (200 mm) of continuously reinforced concrete pavement over 4 inches (100 mm) of asphalt treated basecourse and 6 inches (150 mm) of lime-treated subgrade. The original pavement structure was constructed in 1971.

Subgrade soil types along the Buffalo Test Road alignment were obtained from the Soil Conservation Service logs. (6) 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.

Traffic

Near the time of construction, traffic on the Buffalo Test Road was approximately 15,000 ADT. The total volume of trucks is approximately 20 percent.

Pavement Condition Prior to Construction

Distress consisted of typical hairline random transverse cracks at 3 to 6 foot (0.9 to 1.2 m) intervals and infrequent punchouts.

Field Experiment Design

This experiment was designed as a full factorial with two fixed factors and two replications as shown in Figure 8. Levels of the independent variables are as follows:

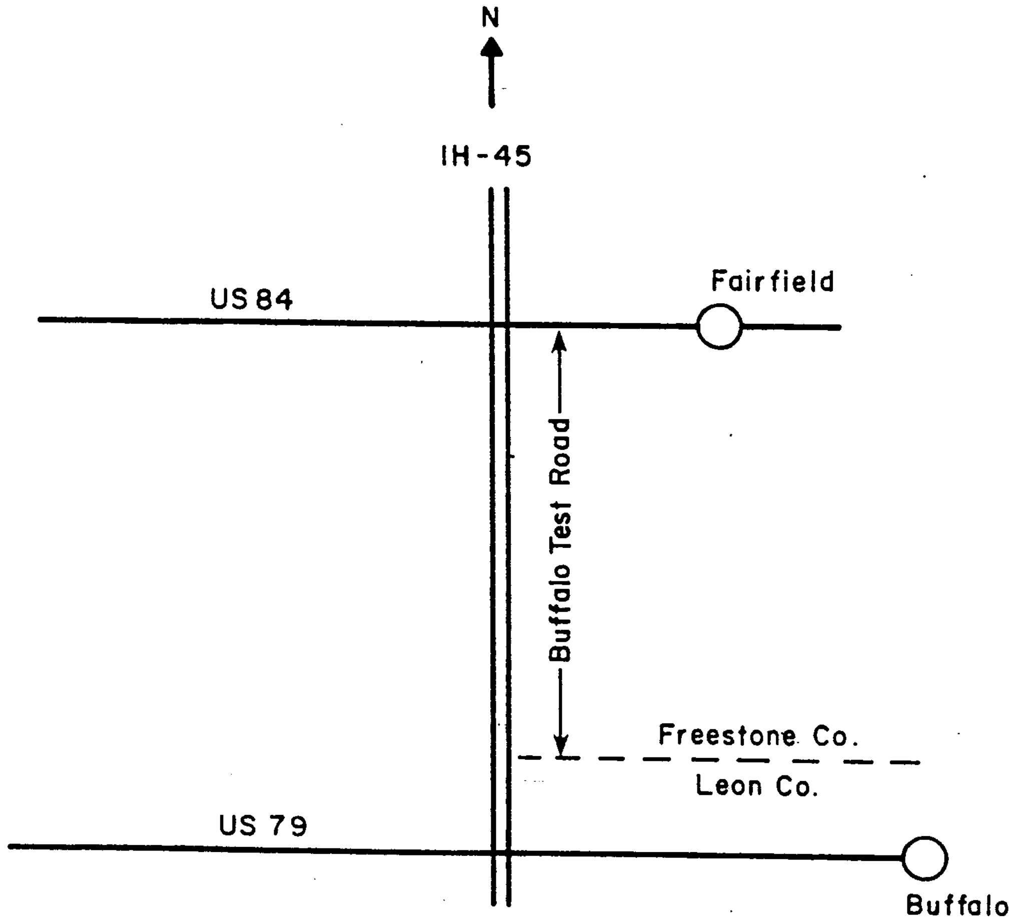

Figure 6. Buffalo Test Road Location.

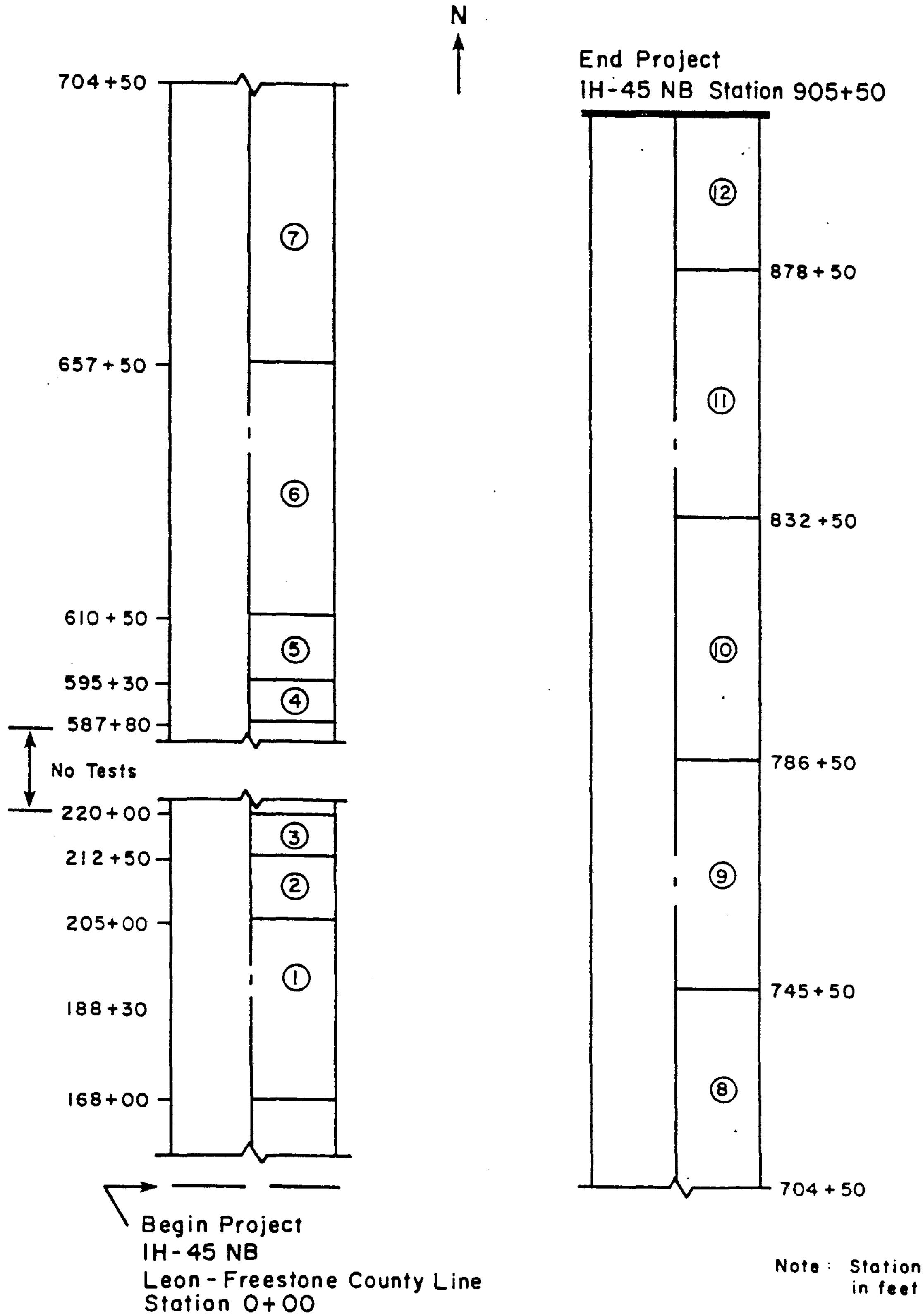

Figure 7. Buffalo Test Sections.

		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 7.

Figure 8. Buffalo Field Response Experiment.

I. Concentration of Rubber, Percent by Total Weight of Binder

    A. 18

    B. 22

II. Digestion Time

    A. Low

    B. High.

In this experiment, rubber type and application rate were held constant. The resulting four treatments were 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 contained no interlayer.

Buffalo Test Road - Preconstruction

Eight sections of pavement each approximately 0.80 lane-mile (1.3 km) in length received the various asphalt-rubber blends shown in Figure 8. Four additional pavement sections, each 750 feet (230 m) in length, were control sections. Three segments of pavement each 500 feet (150 m) in length were selected in each of the eight test sections for photolog surveys as previously described for the El Paso Test Road. The entire length of the control sections were photologged. Locations of photologs are as shown in Table 5. Photolog equipment was as used on the El Paso Test Road.

Buffalo Test Road - Construction

Asphalt rubber was placed over the test sections in August of 1984 and the asphalt concrete overlay was placed between September and November of 1984.

Pre-blending of the asphalt rubber was accomplished 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. Two levels of digestion were achieved. "Low" digestion describes blends of 2 to 2.75 hours. "High" digestion describes blends of 16 to 16.5 hours. Rubber concentrations of 18 and 22 percent by weight of the blend were used.

Table 5. 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

The thickness of the asphalt concrete overlay in the test sections varied from 2.3 to 4.0 inches (58 to 100 mm) as measured from field cores. The statistical analysis of field performance described later in this report accounts for the variable overlay thickness.

Results of observations and tests performed during mixing of the asphalt rubber appear in Reference 2.

Performance Monitoring

Systematic condition surveys were conducted semi-annually as described for the El Paso Test Road. Table A3 (Appendix A) shows a summary of all of the cracking data. The test sections were recycled in 1992 using a hot, in-place recycling process. At the time of recycling, the test sections were exhibiting minor transverse cracking as will be discussed further in the following analysis.

Statistical Analysis of the Buffalo Cracking Data

No sections had any measurable transverse cracking until 4.5 years after construction. At 4.5 years (spring 1990), 7 photolog segments had some transverse cracking. Two of these segments were in the control sections with no interlayers. Of the remaining five segments that first showed transverse cracking, all had low digestion, but both rubber concentration levels were represented.

In spring 1991, five additional sections had measurable transverse cracks. One of these segments was in the control section that had an AC-binder interlayer. The remaining segments again had low digestion with the exception of one segment that had high digestion and rubber concentration of 18 percent. By the spring 1992, all segments within all sections had measurable transverse cracking.

An analysis was performed to determine if there was a significant difference in the amount of cracking as measured in spring 1992. Since sections had different levels of preconstruction transverse cracks, they were adjusted for their preconstruction distress level. An analysis of variance was performed using the difference between the observed amount of cracking in spring 1992 and the preconstruction cracking.

There were no significant differences for any treatment combinations and the controls except for the high digestion/18 percent concentration combination.

When adjusted for the preconstruction distress condition, this combination was significantly better because there were fewer transverse cracks than expected given the preconstruction condition. The sections with rubber concentration of 18 percent and high digestion had significantly higher preconstruction transverse cracking than the other sections. These sections also had significantly more transverse cracking by spring 1992. However, when adjusted for the fact that these sections had more preconstruction cracking to start with, this treatment combination was significantly better than the others (i.e. the amount of cracking was significantly less than would be expected given the amount of preconstruction cracking on these sections).

Overlay thickness was examined in this analysis; however, the variability in thicknesses was not significant, and the analysis conclusions were not changed when thickness adjustments were made.

In summation, it would appear that low digestion will result in transverse cracking sooner than high digestion. High digestion with concentration of 18 percent produces significantly less cracking when adjusted for the fact that this treatment was applied to sections that had significantly more preconstruction distress. Table 6 lists the means and standard deviations for this data.

Table 6. Buffalo Test Road Means and (Standard Deviations).

Interlayer Type	Preconstruction Cracking, ft.	1992 Cracking, ft.	Cracking Difference, ft.	Overlay Thickness, in.
18% Rubber, Low Digest.	1180.2 (72.5)	104.0 (90.3)	-1076.2 (88.1)	3.32 (0.31)
18% Rubber, High Digest.	1718.8 (361.1)	120.0 (76.9)	-1598.8 (428.7)	2.82 (0.47)
22% Rubber, Low Digest.	1134.2 (137.6)	70.0 (17.3)	-1064.2 (131.6)	3.47 (0.18)
22% Rubber, High Digest.	1193.0 (231.5)	54.0 (46.5)	-1139.0 (203.3)	3.73 (0.29)
Control AC Binder	1124.5 (543.0)	75.0 (22.7)	-1049.5 (557.0)	3.18 (0.72)
Control No Interlayer	1120.3 (489.1)	106.0 (28.0	-1014.3 (504.4)	3.30 (0.51)

1 m = 3.28 ft

When comparing all of the asphalt-rubber sections to the control sections, researchers found that the asphalt-rubber sections had less cracking than the control sections; however, statistically, there was no significant difference.

Summary of Buffalo Test Road Performance

The Buffalo Test Road was designed as a full factorial with two fixed factors and two replications. In this experiment, rubber type and binder application rate were held constant, while rubber content and digestion time were varied. A total of four treatments (two rubber contents and two digestion times) were replicated providing eight experimental test sections. Four additional test sections were included as controls. Two sections were constructed using a conventional asphalt cement as the interlayer binder and the other two sections contained no interlayer.

When this test road began to show cracking distress, it was recycled. Any conclusions drawn from the performance of this test road are likely to be premature. Most of the test sections exhibited less than 15 percent of the cracking, which was present prior to construction.

The treatments are listed below in order of performance, from best to worst. However, it is very important to note that the statistical analysis revealed that only the first treatment (18% rubber, high digestion) is significantly better than the others.

- 18% Rubber, High digestion
- 22% Rubber, High digestion
- 18% Rubber, Low digestion
- 22% Rubber, Low digestion
- Control, AC interlayer
- Control, No interlayer

Brownsville Test Road

Test Road Location

Brownsville Test Road State project designation is MW 017(2) located on State Highway 4 (SH4) in Cameron County from the International Bridge north approximately 2 miles (3.2 km). Test sections are located in travel and passing lanes both northbound and southbound as shown in Figure 9.

Pavement Structure

The original pavement structure prior to rehabilitation consisted of approximately 4 inches (100 mm) of asphalt concrete placed over 8 inches (200 mm) of crushed stone base.

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

Traffic

Traffic on the Brownsville Test Road was measured near the time of construction to be approximately 23,000 ADT.

Pavement Condition Prior to Construction

Pavement distress included slight longitudinal and transverse cracking at random intervals. Levels of cracking distress are shown in Appendix A: Table A4.

Field Experiment Design

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.

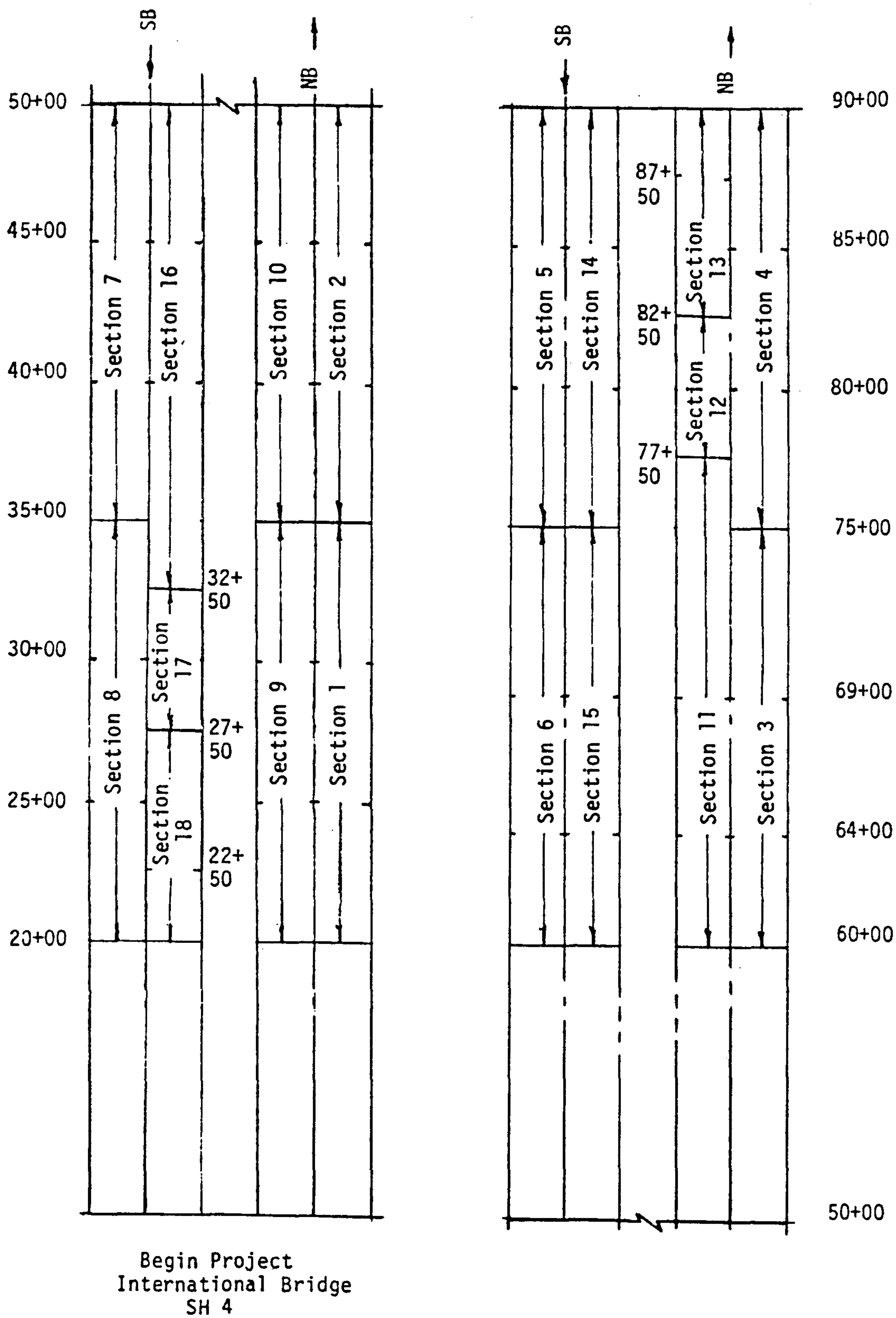

Figure 9. Brownsville Test Road - Test Road Locations.

All combinations of interlayers applied at the Brownsville Test Road are described below in Table 7.

Table 7. Brownsville Test Road Interlayer Combinations.

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

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

Brownsville Test Road - 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. Six additional sections were selected as controls. Control sections consisted of: (1) no treatment, (2) asphalt cement interlayer, and (3) polymer-modified asphalt interlayer. All sections were replicated to provide a statistical basis for analysis of performance between sections. A description of all materials used is shown in Table 8.

A 500-foot (150-m) photolog was recorded in each test section. Locations of photologs are shown in Table 9. Photolog equipment and techniques were as used at Buffalo and El Paso.

Table 8. 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 9. 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.

Brownsville Test Road - Construction

Asphalt rubber binders and control binders were placed on all test sections by the end of October 1984. Observations and tests made during construction were identical to those for the El Paso and Buffalo Test Roads as discussed in Reference 2.

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 asphalt-rubber blend.

Application rates are shown in Table 10 for each test section. Interlayer binder application rates appeared to be excessive as many of the test sections were experiencing flushing distress prior to application of the overlay. This is noted in Table 10 as "Comments". The comments in Table 10 refer to the condition of the interlayer (seal coat) prior to placement of the overlay.

Brownsville overlay asphalt concrete was approximately 1.25-inches thick. Placement of the overlay began after asphalt-rubber and control section interlayers had been in service at least one week.

Performance Monitoring

Systematic condition surveys were conducted semi-annually as described for the El Paso and Buffalo Test Roads. A summary of all of the cracking data is shown in Appendix A: Tables A3 and A4. Due to the excessive interlayer binder rates, many of the test sections displayed flushing distress at the surface of the overlay. It is possible in some of these sections that the flushing binder at the surface visibly obscured reflective cracking.

Statistical Analysis of Brownsville Cracking Data

Many of the test sections began to show cracking in the first few years; however, as flushing became the predominant distress in these sections, the cracking was no longer evident. Therefore the data was incomplete for many treatment combinations over time. The data was divided into subgroups, according to the completeness of the data. For example, only the following four combinations had complete data through 1991:

Table 10. 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

- Control (No interlayer),
- Polymer-Modified Interlayer (Double: Grade 4 over Grade 4),
- Asphalt-Rubber (Single Grade 4),
- Asphalt-Cement (Double: Grade 4 over Grade 3).

The results of the analysis of these data over the entire period showed that the asphalt-rubber interlayer and the asphalt cement interlayer were significantly better than no interlayer or the polymer-modified interlayer when adjusted for preconstruction distress. Table 11 lists the average number of cracks and the average difference from the preconstruction distress. (Note: a negative difference means that the pavements had not reached their preconstruction distress levels over the seven year period, and a positive difference means the pavements exceeded their preconstruction distress levels.) The two control sections (no interlayer and polymer-modified interlayer) reached their preconstruction distress levels by the second 1987 measurement.

Table 11. Average Cracking for Brownsville and Adjustments for Preconstruction Distress for Measurements Taken Through 1991.

Treatment	Average Cracking, linear feet	Adjusted for Preconstruction Distress
No Interlayer	93.33	33.33
Polymer-Mod. Interlayer (Double Grade 4/Grade 4)	82.71	22.71
Asphalt-Rubber Interlayer (Single Grade 4)	61.82	-34.30
Asphalt-Cement Interlayer (Double Grade3/Grade 4)	25.70	-58.18

1 m = 3.28 ft

Two additional treatments had data up to the second 1989 measurement:

- Asphalt-Rubber (Double: Grade 3 over Grade 3) and
- Asphalt-Rubber (Single: Grade 3).

Here, the three control sections (no interlayer, polymer-modified interlayer, and asphalt-cement interlayer) had significantly greater cracking over this period than the asphalt-rubber treatments. The asphalt-rubber interlayer placed as a double application of Grade 3 stone was significantly better than the other asphalt-rubber interlayers followed by the single Grade 3 and the single Grade 4 (which were equal to each other). Table 12 lists these means.

Table 12. Average Cracking for Brownsville and Adjustments for Preconstruction Distress for Measurements Taken Through 1989.

Treatment	Average Cracking, linear feet	Adjusted for Preconstruction Distress
No Interlayer	70.67	10.67
Polymer-Mod. Interlayer (Double Grade 4/Grade 4)	59.80	-0.20
Asphalt-Cement Interlayer (Double Grade 3/Grade 4)	21.29	-38.71
Asphalt-Rubber Interlayer (Single Grade 4)	39.50	-80.50
Asphalt-Rubber Interlayer (Single Grade 3)	36.42	-83.58
Asphalt-Rubber Interlayer (Double Grade 3/Grade 3)	16.33	-203.67

1 m = 3.28 ft

Summary of Brownsville Test Road Performance

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 were composed of no interlayer and interlayer binders of polymer-modified asphalt and conventional asphalt cement. Interlayers were constructed using various combinations of single and double applications of binder and aggregate. This allowed for different binder application rates. One characteristic of asphalt rubber interlayers or chip seals is that more binder can be applied during construction, and this additional binder may aid in reducing reflection cracking. It was, therefore, of interest to determine how conventional binders (applied in double layers) could compare to asphalt rubber.

Many of the treatments in this test road were eliminated from the analysis due to excessive bleeding at the pavement surface which may have concealed any reflection cracking. In 1991 only four of the test sections had complete data. These are listed in order of performance from best to worst (along with the total interlayer binder application rate):

- Asphalt Cement Double Interlayer (0.60 gsy or 2.7 l/m^2),
- Asphalt Rubber Single Interlayer (0.65 gsy or 2.9 l/m^2),
- Polymer-Modified Double Interlayer (0.51 gsy or 2.3 l/m^2),
- No Interlayer.

Prior to 1991 (in 1989) two additional treatments can be included in the analysis: These are listed in order of performance from best to worst (along with the total interlayer binder application rate):

- Asphalt Rubber Double Interlayer (1.62 gsy or 7.3 l/m^2),
- Asphalt Rubber Single Interlayer (0.78 gsy or 3.5 l/m^2),
- Asphalt Rubber Single Interlayer (0.65 gsy or 2.9 l/m^2),
- Asphalt Cement Interlayer (0.60 gsy or 2.7 l/m^2),
- Polymer-Modified Interlayer (0.51 gsy or 2.3 l/m^2),
- No Interlayer.

In this listing, the asphalt-rubber interlayers are significantly better than the controls. Of the asphalt-rubber interlayers, only the first (which was applied at 1.62 gsy (7.3 l/m^2)) was significantly better than the other two.

In summation, this data indicates that an interlayer is effective at reducing the rate of reflection cracking and that asphalt-rubber interlayers are generally better than interlayers constructed of conventional binders. However, the data also indicates that the binder quantity applied to construct the interlayer may have the greatest effect on reducing reflection cracking. In fact, based on the most recent performance measurement (1991), a double application of a conventional asphalt cement interlayer performed better than a single application of an asphalt-rubber interlayer.

RELATIONSHIP BETWEEN LAB PROPERTIES AND FIELD PERFORMANCE

The asphalt-rubber binders used at each of these test roads were extensively evaluated by laboratory tests in Study 347. (2) One of these tests used to characterize the asphalt-rubber binder was the force-ductility test. The modulus value obtained from the force ductility test was used to develop a model for establishing a correlation between laboratory properties and reflective transverse cracking. This model is presented herein. A computer program was also developed to aid in the analysis of the data using this model. The program listing is contained in Appendix B.

The number of temperature cycles (N_f) below 70°F that will cause a transverse crack to propagate to the surface of the pavement is characterized by the following relationship:

$$N_f = \frac{d_o^{(1+n/2+2qn)}}{A\ P^n\ f^n\ (1 + qn)} [1 - (c_o/d_o)^{1+qn}] + 1$$

where

$$P = E_o\ \alpha_o\ d_o\ (\Delta T_o) + \frac{E_u\ d_u\ t}{[1 + (d_u\ n_u + n_s\ t/2)/(d_o - c)]} [A\ (e^L - 1) - B\ (e^{-L} - 1)]$$

and

$$A = (s/2)[\alpha_u(\Delta T)_u]/t \frac{[e^{-L} - (L + 1)]}{[2(e^{s/2} - e^{-s/2})(L + 1) + 2(e^L - e^{-L})(s^2/8 + s/2)]}$$

$$B = -(s/2)[\alpha_u(\Delta T)_u]/t \frac{[e^L - (L + 1)]}{[2(e^{s/2} - e^{-s/2})(L + 1) + 2(e^L - e^{-L})(s^2/8 + s/2)]}$$

where

E_o = elastic modulus of the overlay at low temperature,
E_u = modulus of the underlay at low temperature,
$n_u = E_u / E_o$,
d_u = depth of underlay,
d_o = depth of overlay,
c_o = radius of largest aggregate; initial crack length,
t = thickness of strain relieving interlayer,
α_o = thermal coefficient of overlay,
α_u = thermal coefficient of underlay,
$n_s = E_{sr} / E_o$,
E_{sr} = modulus of strain relieving interlayer at low temperature,
s = crack spacing, and
L = slippage length.

Using this model and the computer program in Appendix B, the El Paso Test Road was analyzed in an attempt to establish correlations between laboratory tests and field performance, which would lay the groundwork for a more comprehensive study. No distinct correlations were identified in this analysis; therefore, a more comprehensive study needed to fully develop these correlations was never pursued.

REFERENCES

1. "Crumb Rubber Modifier Workshop," Workshop Notes presented in Arlington, Texas, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., March 30-31, 1993.

2. Shuler, S., Adams-Estakhri, C., and Lamborn. M., "Asphalt-Rubber Binder Laboratory Performance," Research Report 347-1F, Texas Transportation Institute, Texas A&M University, College Station, Texas, August, 1985.

3. Adams-Estakhri, C. and Gonzales, J., "Asphalt-Rubber Interlayer Field Performance," Research Report 449-1F, Texas Transportation Institute, Texas A&M University, College Station, Texas, June, 1987.

4. Estakhri, C., "Asphalt-Rubber Interlayer Field Performance," Unpublished Research Report 187(4)-1, Texas Transportation Institute, Texas A&M University, College Station, Texas, November, 1987.

5. Epps, J. A., Meyer, A. H., Larrimore, I. E., Jr., and Jones, H. L. "Roadway Maintenance Evaluation User's Manual", Research Report 151-2, Texas Transportation Institute, Texas A&M University, College Station, Texas, September, 1974.

6. Soil Interpretation Records of Edward I. Janak, Jr., Soil Scientist, Soil Conservation Service, from personal correspondence, Corsicana, Texas, December, 1983.

APPENDIX A

SUMMARY OF TEST ROAD CRACKING DATA

BEFORE AND AFTER CONSTRUCTION

Table A1. El Paso Test Road - Transverse Cracking.

Transverse Cracking, Linear Feet.

Test Section	Photolog	Preconstruction 1983	Winter 1984	Spring 1984	Spring 1985	Fall 1985	Spring 1986	Fall 1986	Spring 1987	Fall 1987	Spring 1988	Fall 1988	Spring 1989	Fall 1989	Spring 1990	Fall 1990	Spring 1991	Fall 1991	Spring 1992
1	1	234	87	96	139	134	247	278	311	310	336	305	303	315	324	384	456	444	472
	2	517	160	125	293	177	226	275	341	354	350	371	338	360	420	402	420	441	465
	3	578	178	217	484	298	357	403	525	342	423	459	382	450	512	415	384	510	708
2	4	767	61	66	101	131	168	171	366	220	250	269	296	225	340	340	384	424	420
	5	336	26	22	116	142	192	255	317	330	290	341	364	300	372	370	240	395	468
	6	350	93	56	112	144	168	198	253	187	180	190	230	264	284	300	228	338	372
3	7	390	8	8	4	52	66	90	178	212	280	352	240	245	300	360	408	340	384
	8	498	15	15	12	108	152	210	301	283	360	337	340	288	340	380	408	460	576
	9	436	60	72	66	147	132	189	228	198	242	168	260	300	310	280	180	300	264
4	10	559	0	2	0	32	74	147	289	192	300	294	310	200	335	390	444	424	444
	11	451	6	0	30	46	106	110	246	156	240	250	240	224	300	300	384	400	372
	12	325	12	0	0	28	22	66	134	128	140	160	160	105	180	180	195	200	216
5	13	277	48	50	44	90	120	146	194	264	240	228	215	195	240	200	240	250	263
	14	448	36	0	0	36	36	8	44	68	85	96	110	60	75	92	96	115	120
	15	485	151	0	34	70	118	137	206	169	225	244	210	168	200	236	264	290	324
6	16	321	18	43	34	26	78	110	242	250	240	190	160	135	200	260	324	340	350
	17	383	12	0	54	8	38	60	186	200	185	160	120	80	180	240	324	330	348
	18	383	12	0	83	50	74	115	223	216	200	190	180	170	220	270	324	380	456
7	19	265	24	9	7	52	60	34	138	110	140	100	80	80	120	200	252	252	252
	20	251	92	69	65	94	93	90	185	172	200	185	200	200	240	260	288	380	468
	21	359	103	88	98	168	203	155	244	292	320	275	260	245	300	340	396	420	444
8	22	359	96	24	18	59	130	153	309	222	260	300	300	295	360	400	456	480	516
	23	260	47	6	12	88	122	162	238	200	210	230	220	195	240	280	324	340	372
	24	151	73	10	22	24	101	149	246	192	180	200	180	173	200	270	372	390	408
9	25	278	158	85	114	108	146	173	256	186	200	200	210	224	260	300	348	360	372
	26	245	194	83	62	138	192	185	316	146	180	160	132	132	200	300	372	400	432
	27	499	97	65	7	114	163	185	288	144	180	200	240	250	300	340	372	400	348
Control	28	120	36	55	108	120	128	149	158	162	162	146	160	180	180	170	168	200	216

Table A2. El Paso Test Road - Longitudinal Cracking.

Longitudinal Cracking, Linear Feet.

Test Section	Photolog	Preconstruction 1983	Winter 1984	Spring 1984	Spring 1985	Fall 1985	Spring 1986	Fall 1986	Spring 1987	Fall 1987	Spring 1988	Fall 1988	Spring 1989	Fall 1989	Spring 1990	Fall 1990	Spring 1991	Fall 1991	Spring 1992
1	1	122	30	44	8	0	0	129	44	60	162	162	150	155	175	200	200	130	110
	2	161	0	0	0	0	153	188	320	112	179	200	200	250	262	265	265	290	335
	3	107	0	8	8	0	18	134	105	36	131	120	100	125	125	100	60	85	85
2	4	178	0	0	22	22	52	24	0	46	81	81	120	130	130	120	120	120	90
	5	67	0	0	0	20	36	18	30	10	56	42	45	45	36	0	0	20	35
	6	110	0	0	0	0	0	10	10	6	13	12	12	25	12	0	0	12	10
3	7	94	0	0	0	0	16	48	68	62	62	60	60	60	30	60	10	60	50
	8	83	0	0	0	10	32	68	140	106	106	90	90	75	75	90	90	85	85
	9	84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	10	301	18	18	15	14	103	168	81	99	99	100	100	100	120	120	130	120	110
	11	37	6	0	0	0	38	122	134	97	97	160	200	260	260	260	250	200	190
	12	119	0	0	0	0	38	75	87	115	115	115	115	110	220	200	200	200	200
5	13	130	98	4	22	130	165	344	187	305	305	300	350	400	400	400	551	250	250
	14	156	0	0	0	0	0	118	134	76	76	76	125	125	125	100	100	160	230
	15	353	0	0	0	22	26	166	124	140	140	140	195	195	200	115	115	220	240
6	16	119	0	0	0	14	28	134	157	167	167	160	145	145	140	140	140	140	140
	17	151	12	0	20	20	32	141	208	188	188	220	180	180	160	160	120	220	220
	18	198	0	12	32	8	10	79	76	75	75	75	75	105	105	120	55	120	120
7	19	374	26	0	0	6	14	24	62	28	28	28	40	40	40	40	70	70	50
	20	302	24	30	30	0	0	12	28	18	18	36	36	60	60	60	85	80	80
	21	121	108	125	16	136	147	36	176	118	118	118	130	130	120	120	150	190	230
8	22	85	0	0	0	0	0	4	18	12	12	12	0	20	0	12	20	10	30
	23	33	0	0	0	0	4	6	10	0	0	0	0	20	20	20	0	0	20
	24	43	0	0	0	0	0	10	10	10	10	0	20	20	0	0	0	20	20
9	25	78	0	0	0	6	6	50	24	30	30	30	30	65	35	35	35	35	30
	26	497	58	35	0	36	80	41	58	48	48	48	48	55	60	60	60	90	140
	27	337	58	0	0	18	44	52	78	32	32	32	32	65	65	120	115	115	180
Control	28	432	0	0	0	0	0	10	9	8	8	8	10	20	10	0	0	10	20

Table A3. Buffalo Test Road - Transverse Cracking.

Transverse Cracking, Linear Feet.

Test Section	Photolog	Preconstruction 1984	Fall 1985	Spring 1986	Fall 1986	Spring 1987	Fall 1987	Spring 1988	Fall 1988	Spring 1989	Fall 1989	Spring 1990	Fall 1990	Spring 1991	Fall 1991	Spring 1992
1	1	2104	0	0	0	0	0	0	0	0	0	0	0	0	0	72
	2	2017	0	0	0	0	0	0	0	0	0	0	0	0	0	36
	3	1976	0	0	0	0	0	0	0	0	0	0	0	0	0	48
2	4	1860	0	0	0	0	0	0	0	0	0	0	0	0	0	60
	5	798	0	0	0	0	0	0	0	0	0	0	0	0	0	60
3	6	792	0	0	0	0	0	0	0	0	0	0	0	0	0	96
	7	1567	0	0	0	0	0	0	0	0	0	0	0	0	0	72
4	8	1510	0	0	0	0	0	0	0	0	0	12	12	60	60	120
	9	612	0	0	0	0	0	0	0	0	0	24	24	76	76	136
5	10	643	0	0	0	0	0	0	0	0	0	0	0	36	36	108
	11	1197	0	0	0	0	0	0	0	0	0	0	0	0	0	72
	12	954	0	0	0	0	0	0	0	0	0	36	36	60	60	60
6	13	1092	0	0	0	0	0	0	0	0	0	36	36	50	50	48
	14	1291	0	0	0	0	0	0	0	0	0	24	24	70	70	60
	15	1272	0	0	0	0	0	0	0	0	0	0	0	0	0	60
7	16	1376	0	0	0	0	0	0	0	0	0	0	0	0	0	92
	17	1394	0	0	0	0	0	0	0	0	0	0	0	0	24	124
	18	1290	0	0	0	0	0	0	0	0	0	0	0	0	0	164
8	19	1333	0	0	0	0	0	0	0	0	0	0	0	0	0	188
	20	1593	0	0	0	0	0	0	0	0	0	0	0	12	12	212

Table A3. Continued.

9	21	1228	0	0	0	0	0	0	0	0	0	0	0	36	48	184
	22	1180	0	0	0	0	0	0	0	0	0	12	12	52	52	216
	23	1218	0	0	0	0	0	0	0	0	0	12	12	56	56	152
10	24	1005	0	0	0	0	0	0	0	0	0	0	0	3	0	72
	25	1242	0	0	0	0	0	0	0	0	0	0	0	0	0	90
	26	1221	0	0	0	0	0	0	0	0	0	0	0	3	0	90
11	27	1263	0	0	0	0	0	0	0	0	0	0	0	0	0	36
	28	1068	0	0	0	0	0	0	0	0	0	0	0	0	0	24
	29	1124	0	0	0	0	0	0	0	0	0	0	0	0	0	12
12	30	1066	0	0	0	0	0	0	0	0	0	0	0	0	0	12
	31	1265	0	0	0	0	0	0	0	0	0	0	0	0	0	12
	32	785	0	0	0	0	0	0	0	0	0	0	0	0	0	24

Table A4. Brownsville Test Road - Transverse Cracking.

Transverse Cracking, Linear Feet.

Test Section	Preconstruction 1984	Fall 1985	Spring 1986	Fall 1986	Spring 1987	Fall 1987	Fall 1988	Spring 1989	Fall 1989	Spring 1990	Fall 1990	Spring 1991
1	180	2	2	0	0	8	30	45	45	0	0	0
2	120	0	39	60	72	20	30	45	45	0	0	0
3	120	0	12	0	24	25	0	0	0	0	0	0
4	120	0	16	0	0	76	76	76	72	120	120	124
5	300	0	0	28	36	0	0	0	0	0	0	0
6	120	12	12	42	60	0	0	0	0	0	0	6
7	120	0	12	68	113	0	0	0	0	0	0	0
8	240	0	0	0	0	0	0	0	0	0	0	0
9	180	0	0	24	24	0	0	0	0	0	0	0
10	120	0	0	12	12	0	0	0	0	0	0	0
11	60	0	8	24	36	0	36	36	25	36	36	36
12	60	0	0	12	12	108	108	113	113	180	180	180
13	60	0	0	6	12	115	48	48	48	60	60	60
14	60	0	0	12	24	0	0	0	0	0	0	0
15	0	0	12	12	24	36	0	0	0	0	0	6
16	60	0	12	0	24	25	24	24	24	36	36	36
17	60	0	35	48	54	97	120	120	120	120	120	120
18	60	0	52	60	72	80	80	140	136	220	220	220

APPENDIX B

COMPUTER PROGRAM LISTING USED FOR DETERMINING RELATIONSHIP OF INTERLAYER LABORATORY PROPERTIES TO FIELD PERFORMANCE

```
program cindy;
TYPE
  id = STRING[6];
VAR
  ch                                                               : char;
  d0,du,f,n,A,E0,Eu,a0,au,deltaT0,deltaTu,c0,q,t,Esr,L,s,nu,ns : real;
  de,K1,K2,K3,K4,deltax,par,nf                                     : real;
  m,i                                                              : integer;
  name                                                             : id;
  out,data                                                         : text;
PROCEDURE read_data;
BEGIN
  clrscr;
  REPEAT
    BEGIN
      GOTOXY(1,1);
      WRITE('Want to use default values (section 1) (Y/N)?');
      READ(kbd,ch); DELLINE; WRITELN;
      ch:=upcase(ch);
    END
  UNTIL (ch='Y') or (ch='N');
  IF ch='Y' THEN assign(data,'file1.dat')
  ELSE assign(data,'con:');
  reset(data);
  IF ch='N' THEN
    BEGIN
      WRITELN('Enter the following parameter values:');
      WRITE('Section identification (up to 6 characters):');
    END;
  READLN(data,name);
  IF ch='N' THEN WRITE('d0=');
  READLN(data,d0);
  IF ch='N' THEN WRITE('du=');
  READLN(data,du);
  IF ch='N' THEN WRITE('f=');
  READLN(data,f);
  IF ch='N' THEN WRITE('n=');
  READLN(data,n);
  IF ch='N' THEN WRITE('A=');
  READLN(data,A);
  IF ch='N' THEN WRITE('E0=');
  READLN(data,E0);
  IF ch='N' THEN WRITE('Eu=');
  READLN(data,Eu);
  IF ch='N' THEN WRITE('a0=');
  READLN(data,a0);
  IF ch='N' THEN WRITE('au=');
  READLN(data,au);
  IF ch='N' THEN WRITE('deltaT0=');
  READLN(data,deltaT0);
  IF ch='N' THEN WRITE('deltaTu=');
  READLN(data,deltaTu);
  IF ch='N' THEN WRITE('c0=');
  READLN(data,c0);
```

```
  IF ch='N' THEN WRITE('q=');
  READLN(data,q);
  IF ch='N' THEN WRITE('t=');
  READLN(data,t);
  IF ch='N' THEN WRITE('Esr=');
  READLN(data,Esr);
  IF ch='N' THEN WRITE('L=');
  READLN(data,L);
  IF ch='N' THEN WRITE('S=');
  READLN(data,S);
  close(data);
  nu:=Eu/E0; ns:=Esr/E0;
  de:= d0 + (du * nu) + (ns*(t/2));
  K1:=exp(n*ln(exp((q-1/2)*ln(d0))/(f*E0*a0*deltaT0)))/A;
  K2:=(Eu*au*du*deltaTu)/(2*E0*a0*d0*deltaT0);
  K2:=K2*(1+((L+1)*(1-exp(L)-exp(-L))));
  K2:=K2/(((exp(s/2)-exp(-s/2))*(L+1))+((exp(L)-exp(-L))*((s*s/8)+(s/2))));
END;
{
}
FUNCTION func(c:real):real;
BEGIN
  K3:=exp(q*ln(c))*(1-(c/de));
  K4:=1-(c/de)+(K2*((d0/de)-(c/de)));
  K3:=exp(n*ln(K3/K4));
  K4:=K1*K3;
  func:=K4;
END;
{
}
PROCEDURE integrate;
VAR
  nf_new,nf_old,error : real;
  open                : boolean;
BEGIN
  deltax:=0.01;
  error:=1.0; open:=false;
  REPEAT
    BEGIN
      m:=trunc((d0-c0)/deltax);
      par:=c0;
      nf:=func(par)+func(d0);
      FOR i:=1 TO m-1 DO
        BEGIN
          par:=par+deltax;
          IF (i MOD 2) = 0 THEN nf:=nf+(2*func(par))
          ELSE nf:=nf+(4*func(par));
        END;
      nf:=nf*deltax/3;
      IF not open THEN
        BEGIN
          open:=true;
          nf_old:=nf;
          deltax:=deltax/2;
```

```
        END
      ELSE
        BEGIN
          nf_new:=nf;
          error:=(nf_new - nf_old)/15;
          nf_old:=nf_new;
          deltax:=deltax/2;
        END;
      WRITELN('Nf-1=',nf);
    END
  UNTIL error<=0.01;
  Nf:=Nf+1;
  deltax:=2*deltax;
  REPEAT
    BEGIN
      GOTOXY(1,wherey);
      WRITE('Want a hard copy (Y/N)?'); READ(kbd,ch);
      ch:=upcase(ch);
    END
  UNTIL (ch='Y') or (ch='N');
  WRITELN;
  IF ch='Y' THEN assign(out,'lst:')
  ELSE assign(out,'con:');
  REWRITE(out);
  WRITE(out,' Section     Nu        du        d0        c0        E0       ');
  WRITELN(out,' Eu        t');
  WRITE(out,name:6,'    ',Nu:8,'  ',du:8,'  ',d0:8,'  ',c0:8,'  ');
  WRITELN(out,E0:8,'   ',Eu:8,'   ',t:8);
  WRITELN(out);
  WRITE(out,'    a0       au      deltaT0   deltaTu     Ns       Esr');
  WRITELN(out,'        S');
  WRITE(out,a0:8,'  ',au:8,'  ',deltaT0:8,'  ',deltaTu:8,'  ',Ns:8,'  ');
  WRITELN(out,Esr:8,'  ',s:8);
  WRITELN(out);
  WRITELN(out,'    L        q         f        Nf        Error    mesh');
  WRITELN(out,l:8,'  ',q:8,'  ',f:8,'  ',Nf:8,'  ',error:8,'  ',deltax:8);
END;
BEGIN
  read_data;
  integrate;
END.
```

```
{$U+}
PROGRAM root;
TYPE
  pointer = ^list;
  list    = record
    zero : real;
    next : pointer;
    END;
  name = STRING[20];
VAR
  line,count : integer;
  delta,Eu,alphau,du,deltaTu,s,l,xl,x2,x,yl,y2,y,xmax,xmin : real;
  trace : boolean;
  ch : char;
  point : pointer;
  id : name;
  out : text;
{
}
Function f(l : real):real;
VAR temp : real;
BEGIN
  temp:=Eu*alphau*du*deltaTu*(1+((l+1)*(1-exp(l)-exp(-l))));
  temp:=-temp+(2*s*(exp(l)-exp(-l))*((s*s)/8 + s/2));
  temp:=temp+(2*s*(l+1)*(exp(s/2)-exp(-s/2)));
  f:=temp;
END;
{
}
PROCEDURE insert(v:real);
VAR
  temp : pointer;
BEGIN
  new(temp); temp^.zero:=v;
  temp^.next:=point^.next;
  point^.next:=temp;
END;
{
}
BEGIN    { MAIN }
  clrscr;
  new(point); point^.next:=NIL;
  WRITE('Enter section identification (up to 20 characters):'); READLN(id);
  WRITELN('Input the following parameter values:'); WRITELN;
  WRITE('Eu='); READLN(Eu);
  WRITE('alphau='); READLN(alphau);
  WRITE('du='); READLN(du);
  WRITE('deltaTu='); READLN(deltaTu);
  WRITE('s='); READLN(s);
  WRITELN;
  WRITE('Enter lower limit:'); READLN(xl);
  xmin:=xl;
  WRITE('Enter upper limit:'); READLN(xmax);
  WRITE('Enter mesh size:'); READLN(delta);
```

```
WRITE('Want to trace results (Y/N)?'); READLN(ch);
IF upcase(ch)='Y' THEN trace:=true
ELSE trace:=false;
WRITE('Want to print the result (Y/N)?'); READ(ch);
IF upcase(ch)='Y' THEN assign(out,'lst:')
ELSE assign(out,'con:');
rewrite(out);
GOTOXY(40,25); WRITE('Press any key to continue'); READ(kbd,ch);
clrscr;
count:=0; line:=0;
REPEAT
  BEGIN
    y1:=f(x1);
    IF abs(y1)<0.0001 THEN
      BEGIN
        IF trace THEN WRITELN('********** Root=',x1,'   f=',y1,' **********');
        insert(x1);
        x1:=x1+delta;
        count:=count+1;
        GOTOXY(40,25);
      END;
  END
UNTIL y1<>0;
REPEAT
  BEGIN
    REPEAT
      BEGIN
        x2:=x1+delta;
        y2:=f(x2);
        IF trace THEN
          BEGIN
            WRITE('x1=',x1:6:3,'  f=',y1:10:5,'  x2=',x2:6:3,'  f=');
            WRITELN(y2:10:5); line:=line+1;
            IF line mod 24 = 0 THEN
              BEGIN
                GOTOXY(40,25); WRITE('Press any key to continue');
                READ(kbd,ch); clrscr;
              END;
          END;
        IF abs(y2)<0.0001 THEN
          BEGIN
            IF trace THEN
            WRITELN('********** Root=',x1,'   f=',y2,' **********');
            insert(x2);
            x1:=x2+delta;
            count:=count+1;
          END
        ELSE
          BEGIN
            IF y1*y2>0 THEN
              BEGIN
                IF x2<xmax THEN
                  BEGIN
                    x1:=x2;
```

```
                    y1:=y2;
                  END
                ELSE
                BEGIN
                  IF count=0 THEN
                    BEGIN
                      WRITE('No change in sign was detected between ');
                      WRITE('l=',xmin:4:2,' and l=',xmax:4:2);
                      WRITELN(' by evaluating the ');
                      WRITELN('function at intervals of size ',delta:4:2);
                    END
                  ELSE
                    BEGIN
                      WRITELN(out,id);
                      WRITE(out,'Interval investigated: [',xmin:4:2);
                      WRITELN(out,',',xmax:4:2,']');
                      WHILE point^.next<>NIL DO
                        BEGIN
                          WRITELN(out,'Root=',point^.next^.zero);
                          point:=point^.next;
                        END;
                    END;
                  HALT;
                END;
              END;
          END;
      END
    UNTIL y1*y2<0;
    IF trace THEN
      BEGIN
        WRITELN('***** A change in sign has occurred *****');
        GOTOXY(40,25);
        WRITE('Press any key to continue'); READ(kbd,ch);
        clrscr;
      END;
    REPEAT
      BEGIN
        x:=0.5*(x1+x2);
        y:=f(x);
        IF trace THEN WRITELN('x=',x:6:3,'  f=',y);
        IF abs(y)<0.0001 THEN
          BEGIN
            IF TRACE THEN
            WRITELN('********** Root=',x,'   f=',y,' **********');
            insert(x);
            x1:=x2;
            y1:=y2;
            count:=count+1;
          END
        ELSE
          BEGIN
            IF y1*y>0 THEN
              BEGIN
                x1:=x;
```

```
                y1:=y;
              END
            ELSE
              BEGIN
                x2:=x;
                y2:=y;
              END;
          END;
      END
    UNTIL abs(y)<0.0001;
  END
UNTIL x2>=xmax;
END.
```