Interim Report
on
Evaluation of Asphalt Additives:
Lava Butte Road - Fremont Highway Junction

by

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16. Abstract

This report summarizes the design, construction, and initial performance phases of an asphalt concrete pavement test project concerned with the evaluation of asphalt additives. The project consisted of ten test sections, including rubber modified asphalt concrete, fiber reinforced asphalt concrete, asphalt concrete with a chemical antistripping agent, or combinations thereof. The design report includes a summary of both the structural and mix design results. The construction phase includes descriptions of the construction process, problems encountered, and cost data. The initial performance phase includes the results of laboratory tests on both box samples and cores, and field tests (deflection, ride, and skid resistance) performed shortly after construction. A follow-up report will present detailed results of the performance of the ten test sections.

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4) Mark Hanson - Research Assistant, OSU.

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1.0 INTRODUCTION

1.1 Problem Statement

A considerable number of Oregon highways are in need of a stable and durable overlay to regain an acceptable serviceability rating. Principle reasons for this include surfacing deficiencies such as fatigue cracking, raveling, deformation, and thermal distress. The primary overlay treatments to date have been thick (2 to 6 in.) dense-graded hot mixes on high volume highways plus open-graded cold mixes on lower volume highways. In recent years, thick hot asphalt concrete overlays have been effective in delaying the reflective cracking but have experienced premature longitudinal cracking and stripping. Emulsion cold mixes, surface seals using cationic or high float emulsions, and hot mixes with lime-treated aggregates have not appeared to exhibit these early performance problems.

Today, there are numerous additives being sold which are reported to improve the performance of asphalt concrete overlays by eliminating or reducing deformation, surface raveling (stripping is a major problem), and reflective or thermal cracking. Because these additives usually add significantly to the project costs, it is important to determine their effectiveness under field conditions and to evaluate the cost-effectiveness of their use.

1.2 Objectives

The purpose of this study is twofold, as follows, to:

1) evaluate the effectiveness of ten "hot mix" overlay test sections, incorporating various additives to extend the life of asphalt concrete pavements; and

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2) determine the cost effectiveness of each when compared to a conventional asphalt concrete mix.

The products evaluated include:

1) PlusRide[R] 12 - coarse ground rubber in a mix with modified aggregate gradation and asphalt containing Pave Bond (anti-stripping agent).

2) Arm-R-Shield - asphalt concrete containing fine ground rubber in asphalt in a mix with conventional aggregate gradation.

3) Fiber Pave[R] - polypropylene fiber in a mix with asphalt containing Pave Bond and a conventional aggregate gradation.

4) BoniFibers[R] - polyester fiber in a mix with asphalt containing Pave Bond and a conventional aggregate gradation.

5) Pave Bond[R] - asphalt containing an anti-stripping agent in a mix with a conventional aggregate gradation.

6) Pave Bond[R] and Lime - lime-treated aggregate and asphalt containing an anti-stripping agent in a mix with a conventional aggregate gradation.

7) Class "C" with Lime (control) - lime-treated aggregate in a mix with a conventional aggregate gradation.

8) Class "C" (control, no additive) - a conventional asphalt concrete mix.

9) CA(P)-1 - polymer contained in asphalt in a mix with a conventional aggregate gradation.

10) CA(P)-1 and Lime - polymer contained in asphalt with lime-treated aggregate in a conventional mix.

1.3 Study Approach

The study, as outlined in the work plan, involved six separate tasks. The first was the collection of historical information on the project and the laying out of the test sections. This information is reported in Chapter 2. The second task consisted of the evaluation of overlay thickness and development of project mix designs. This information is covered in Chapter 3. The third task, monitoring the construction processes, is presented together with quality control and cost data in Chapter 4. Preliminary results for the fourth task, evaluation of mix properties, and the fifth task, measurement of performance (after construction) are given in Chapters 5 and 6. Chapter 7 presents the preliminary conclusions and recommendations of the study.

2.0 PROJECT DESCRIPTION

2.1 General

This experimental project is located on US-97 (Oregon Highway No. 4), approximately 20 miles south of Bend (see Figure 2.1). It was a part of an overlay project scheduled for a 20-mile section of roadway which was structurally inadequate and suffering considerable distress. The cross section of the existing pavement is given in Figure 2.2.

An asphalt concrete overlay was selected to correct the present deficiencies. Instead of using conventional asphalt concrete throughout the project, ten sections with experimental features were selected for evaluation. Each test section was a minimum of one-half mile in length and included a 12-ft. wide travel lane. A one-half mile section of dense-graded hot mix with no additive served as the control. A layout of the test sites as they were actually constructed is given in Figure 2.3. The one-half mile sections were selected for the following reasons:

1) the handling and placement characteristics of each material are different and adjustments would be necessary during construction, and
2) it is advantageous to measure performance over long sections to minimize statistical errors.

Other important physical characteristics (traffic and environmental) are given in Table 2.1.

2.2 Pavement Condition

Prior to construction of the overlays, an extensive survey was made to evaluate the type and extent of distress along the existing pavement. Within each designated test section, a 250-ft. site was selected which represented

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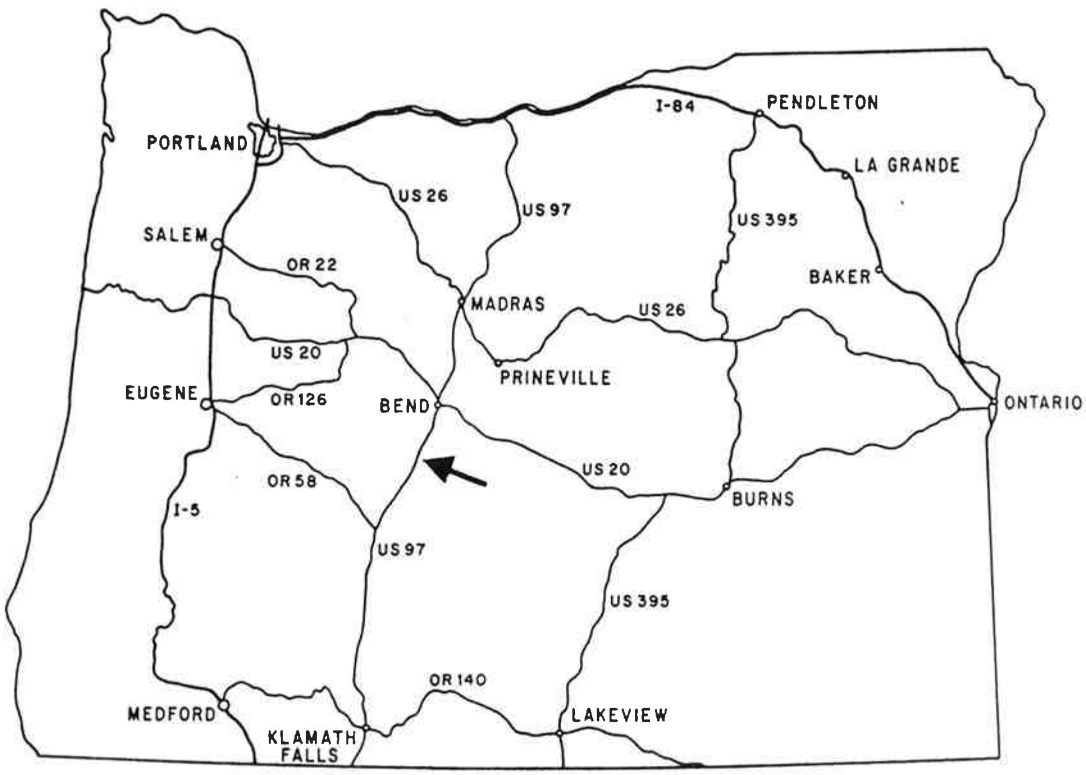
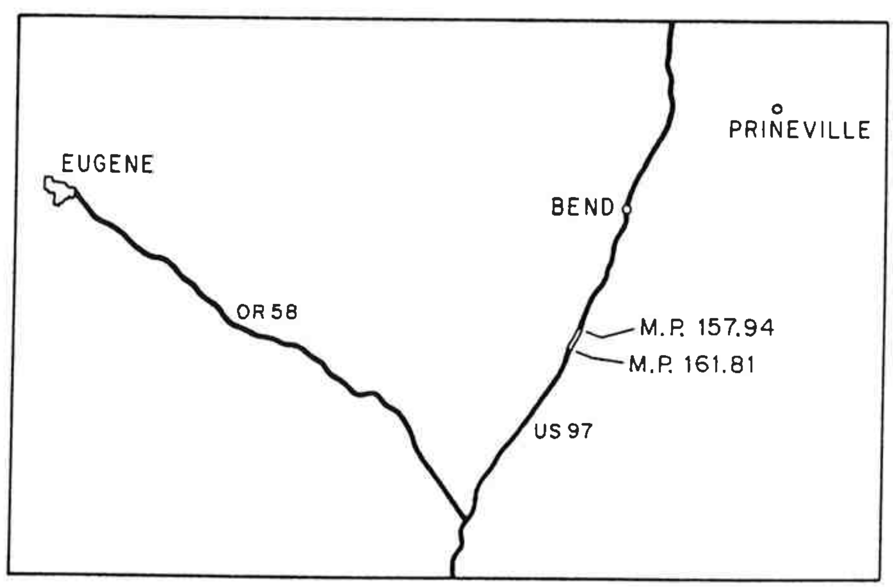


(a) General Location



(b) Close Up of Project Site

Figure 2.1 - Location of Asphalt Additives Test Road

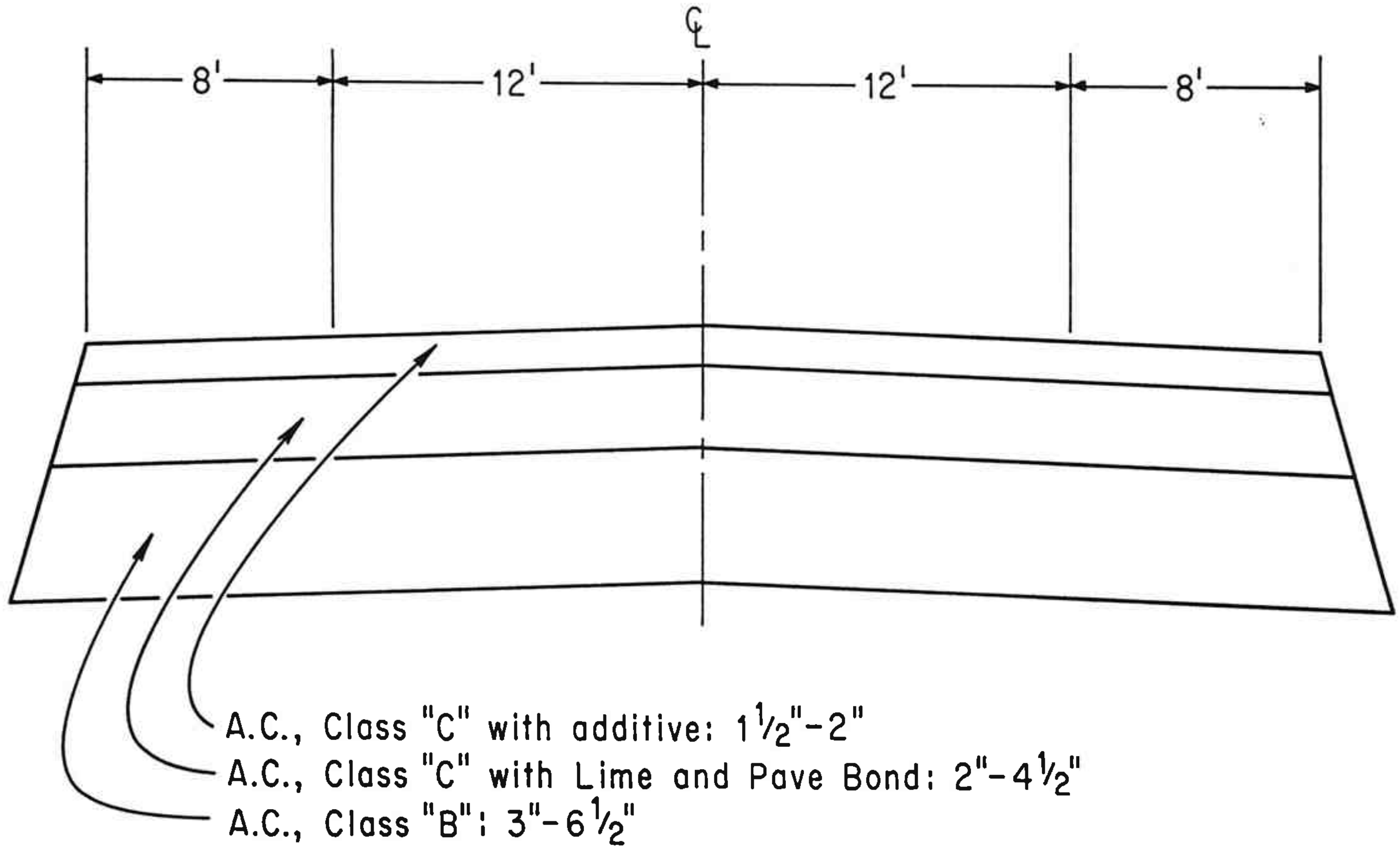


Figure 2.2 - Cross Section of Existing Pavement

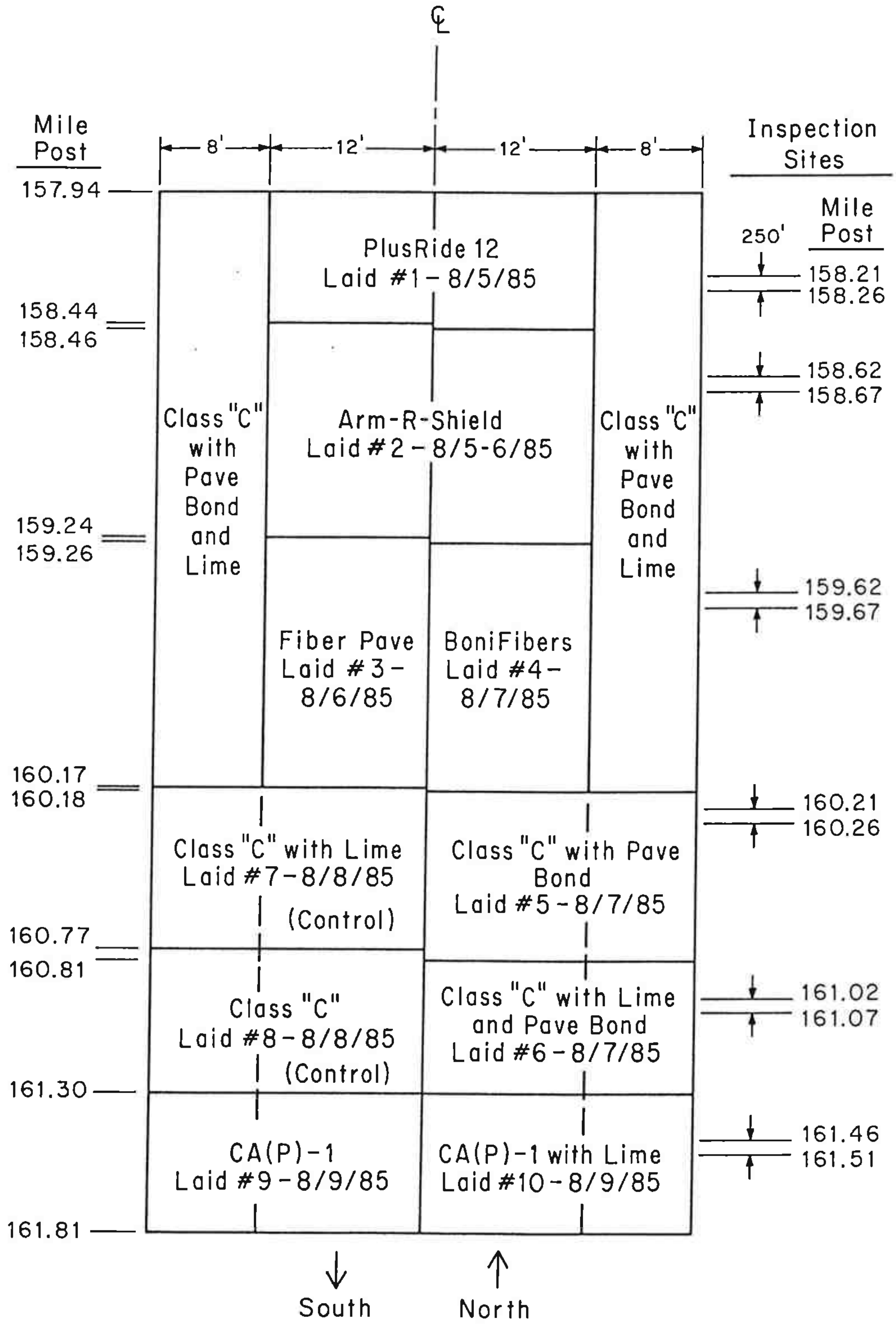


Figure 2.3 - Layout of Test Sections

Table 2.1 - Other Physical Characteristics at Project Site

(a) Traffic and Precipitation

Item	Value
Average daily traffic	4400
% trucks	15
Daily equivalent single axle loads	555
Annual precipitation (in.)	
Rainfall	12
Snow	39

(b) Temperature Data

	Average Daily		
*Average Temperature (°F)	Maximum	Minimum	Average
January	41	21	31
February	46	24	35
March	50	24	37
April	57	28	43
May	65	34	50
June	73	40	57
July	82	44	63
August	80	43	62
September	74	37	56
October	63	31	47
November	49	26	38
December	43	23	33
Year	60	31	46

* Temperatures from 1951-1980 normals

conditions for the entire section. For each 250-ft. inspection site, photos and a record of distress types, including a map of all cracks, were recorded. Figure 2.3 also shows the general location of the inspection sites.

Figure 2.4 through 2.9 are photos of the original pavement before overlay. The photos show there was considerable alligator and thermal cracking as well as patching. The overall condition rating for the project was poor. Table 2.2 summarizes, by distress type, the extent of distress for each inspection site during the May 31, 1985, survey.

2.3 Pavement Deflections

Pavement surface deflections were measured on May 29, 1985, to evaluate the structural adequacy of the existing roadway. The Oregon DOT Dynaflect was used to measure surface deflections.

Deflection measurements were taken every 50-ft. within each test section for a distance of about 500-ft. This 500-ft. section was selected to overlap the 250-ft. inspection site for evaluating pavement condition. Deflections were recorded for each of the five sensors. Table 2.3 summarizes the deflection for sensor No. 1 for each section. Deflection values were corrected for temperature using the factors shown in Table A.2, Appendix A. These values were converted to equivalent Benkelman Beam deflections using the following relation:

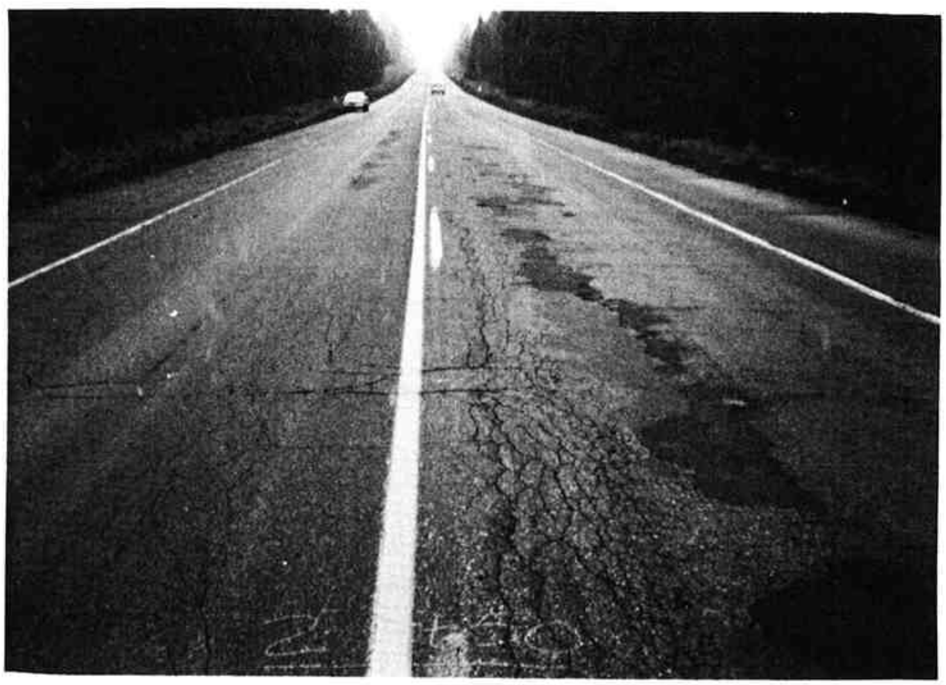
$$BB = 3.83(DF)^2 + 18.78(DF) - 0.87 \qquad (2.1)$$

where BB = Benkleman Beam deflection

DF = Dynaflect Measurement

Table 2.3 summarizes these values. As indicated, there is considerable variation between the sections in terms of structural adequacy. Appendix A contains additional information on Dynaflect equipment, procedure, and data evaluation.

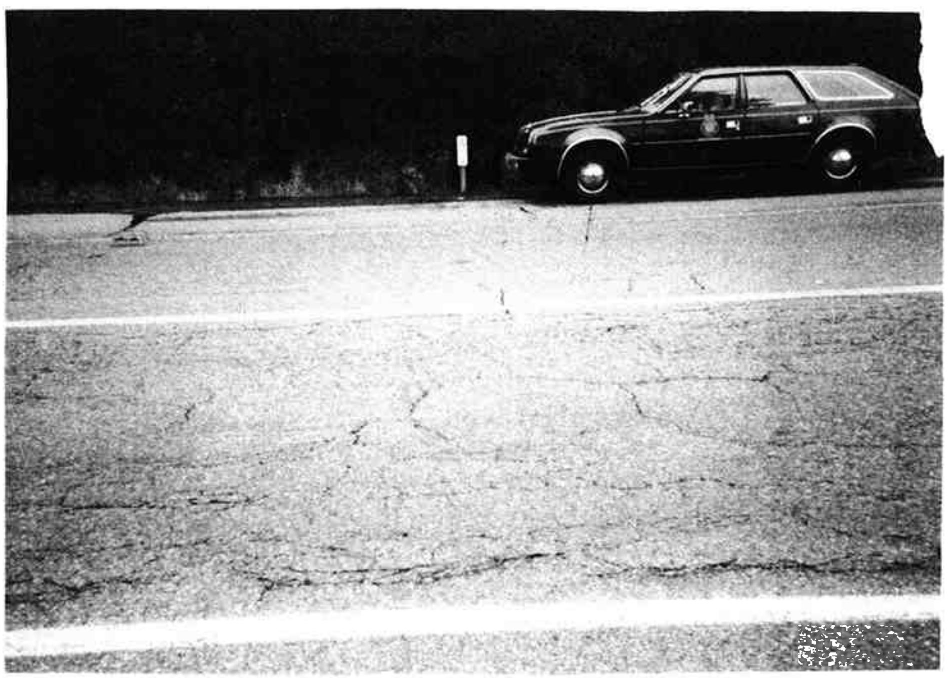
(a) MP 158.21 Looking South



(b) MP 158.26 Looking North

Figure 2.4 - Typical Pavement Condition Before Overlay

(a) MP 158.62 Facing South



(b) MP 158.62 Looking West

Figure 2.5 - Typical Pavement Condition Before Overlay

(a) MP 159.62 Facing South

(b) MP 159.67 Facing North

Figure 2.6 - Typical Pavement Condition Before Overlay

(a) MP 160.21 Facing South

(b) MP 160.26 Facing North

Figure 2.7 - Typical Pavement Condition Before Overlay

(a) MP 161.02 Facing South

(b) MP 161.07 Facing North

Figure 2.8 - Typical Pavement Condition Before Overlay

(a) MP 161.46 Facing South

(b) MP 161.51 Facing North

Figure 2.9 - Typical Pavement Condition Before Overlay, Wet Surface

Table 2.2 - Summary of Pavement Surface Condition at Inspection Site Before Overlay

(Average Cracking, Potholes, and Rut Depths over a 250-ft. Section)

M.P.	Product Area	CRACKING Trans. (#)	Long. (#)	Map (%)	Blk. (%)	Slp. (%)	Pot-holes (%)	Rut Depth (ft.)
158.20	SB PlusRide	33	11	30	0	0	5	.02
	NB PlusRide	60	10	24	9	0	8	.03
158.65	SB Arm-R-Shield	46	10	36	6	0	2	.03
	NB Arm-R-Shield	41	14	27	5	0	2	.03
159.65	SB Fiber Pave	40	10	14	3	0	0	.02
	NB BoniFibers	35	11	20	13	0	1	.03
160.20	SB Control with Lime	26	12	34	8	8	6	.03
	NB Class "C" with Pave Bond	34	17	29	5	0	1	.03
161.00	SB Control	21	9	4	0	1	4	.02
	NB Class "C" with Lime and Pave Bond	21	8	0	0	0	8	.02
161.45	SB CA(P)-1	25	13	10	0	0	7	.02
	NB CA(P)-1 with Lime	30	11	0	0	0	11	.01

Notes: 1) Trans. - Transverse
Long. - Longitudinal
Blk. - Block
Slp. - Slippage

2) Each 250-ft. inspection site was divided into five equal sections, one lane in width. The values presented are the average of the five sections.

Table 2.3 - Summary of Preconstruction Deflection Measurements, May 1985
(Corrected to 70°F)

Milepost	Lane	Product Area	Dynaflect Deflection, mils		Equivalent Benkleman Beam, mils	
			Average*	S	Average**	S
158.20	SB	PlusRide	1.51	0.31	36.6	9.9
	NB	PlusRide	2.00	0.31	52.4	10.4
158.65	SB	Arm-R-Shield	2.18	0.54	59.3	20.5
	NB	Arm-R-Shield	2.03	0.55	53.9	20.7
159.65	SB	Fiber Pave	1.59	0.34	39.2	10.6
	NB	BoniFibers	2.07	0.34	56.1	25.9
160.20	SB	Control with Lime	2.63	0.40	75.8	15.5
	NB	Class "C" with Pave Bond	2.51	0.54	71.2	20.6
161.00	SB	Control	1.87	0.29	48.0	9.5
	NB	Class "C" with Lime and Pave Bond	1.89	0.28	48.9	9.7
161.45	SB	CA(P)-1	1.92	0.37	49.8	12.9
	NB	CA(P)-1 with Lime	1.38	0.43	32.3	5.7

* Average of 11 readings from sensor No. 1

** Dynaflect data converted to equivalent Benkleman Beam using equation 2-1.

Finally, the location of each inspection site is identified with delineator posts. These will be used to assure follow-up condition and deflection surveys are conducted at the same locations.

3.0 DESIGN PHASE

This section of the report describes the procedures used and results of the overlay design and bituminous mix design processes. The structural overlay design was performed by the Surfacing Design Unit of Oregon DOT. The mix design for the control mix was performed by the Materials Section (Bituminous Mix Design Group) of Oregon DOT. Mix designs used for the experimental sections were performed by the suppliers of the additives or by the Materials Section of Oregon DOT. After the project was completed, the Bituminous Mix Design Group (ODOT) performed a mix design on each of the experimental sections to evaluate their current mix design procedures for the various additives.

3.1 Structural Design

The condition of the existing pavement was discussed previously in Section 2.0 of this report. As stated, the asphalt surface was badly deteriorated. Rehabilitation alternates were limited to a thick overlay or recycling plus an overlay. The conventional overlay was selected as the design alternate.

The data used in the structural design are given in Table 3.1. A modification of the California Overlay Design procedure was used to determine the overlay thickness (OSHD, 1985). This resulted in a minimum overlay thickness of 2½ in. of hot mix needed for structural purposes. The final recommendation was:

AC Class "E" (Open-graded)	0.75 in.
AC Class "C" (Dense-graded)	2.50 in.
	3.25 in. TOTAL

In addition, 1 in. was allowed for leveling the existing pavement. For the test sections, it was decided to split the overlay needs as follows:

Table 3.1 - Structural Design Data

Parameter	Value
Traffic coefficient	9.8
Daily 18 kip axles	555
Design deflection*, in.	0.038
Average R-value	18
Frost penetration, in.	36

* 80 percentile equivalent Benkelman Beam

Table 3.2 - Design Recommendations for New (or Widened) Areas

Layer	Thickness, in.
Asphalt concrete - Class "C" mix	3.25
Asphalt concrete base - Class "C" mix	4.00
Cement treated base	9.00

1) Top lift (1-3/4 in.) - experimental feature

2) Bottom lift (1-1/2 in.) - Class "C" mix

3) Leveling course (nominal 1-in.) - Class "C" mix

For new work (widening), the Oregon R-value method was used to determine the structural requirements (OSHD, 1985). For a design R-value of 18 and a traffic coefficient of 9.8, the resultant crushed base equivalent (CBE) was determined to be 28.5 inches. The thickness recommendation for new areas is given in Table 3.2.

3.2 Job Mix Designs

For each of the experimental sections, the additive supplier or ODOT Materials Section recommended the job mix asphalt content and gradation. All mixes, except PlusRide, were designed using the C-mix aggregate gradation given in Table 3.3. In some cases, both coarse and fine aggregate was treated by pug mill mixing dry lime and water. The 5-day minimum period for mellowing aggregates in a stockpile was extended 60 to 90 days to fit the contractor's operations.

The asphalt cement used was an AC-20 from Chevron's Willbridge Refinery in Portland, Oregon. Properties of the AC-20 and its specification requirements are given in Table 3.4. This material was used in all experimental features except where the Arm-R-Shield and polymer modified binders were used. Table 3.5 summarizes the properties of Chevron's CA(P)-1.

The list of additive suppliers are given in Table 3.6. Claimed benefits of each additive are given below:

1) PlusRide - Improved fatigue resistance, ability to shed ice, and improved resistance to stripping.

2) Arm-R-Shield - Improved fatigue resistance and improved low and high temperature properties.

Table 3.3 - Gradation of Mix and Properties of Aggregate Used

(a) Gradation of Mix

Gradation	Class "C" Mix	PlusRide
3/4 in.	100	-
5/8 in.	-	100
1/2 in.	99	89
3/8 in.	89	76
1/4 in.	66	38
#10	32	31
#30	-	19
#40	14	17
#200	5.8	8.9

(b) Aggregate Properties and Specifications

	Actual		Specification	
Property	Coarse	Fine	Coarse	Fine
Specific Gravity (AASHTO T-85)				
Bulk	2.57	2.63	-	-
SSD	2.64	2.69	-	-
L.A. Abrasion (AASHTO T-96)	28.4%	-	30% max	-
Sand Equivalent (AASHTO T-176)	-	-	-	-
% Crushed Faces (OSHD T-213)	90	-	60 min	60 min
Sulphate Soundness (OSDH T-206)	0.6%	2.7%	12% max	12% max
Degradation (OSHD T-208)				
P_{20}	21.9%	10.8%	30% max	30% max
Sediment Ht (in.)	0.3	0.3	3.0 max	4.0 max
Friable Particles (AASHTO T-112)	0.2	0.4	1.0 max	1.5 max

Table 3.4 - Properties of Asphalt Cement, AC-20

Property	Actual	Specification
Viscosity @ 140°F, Poises	2040	2,000 ± 400
Viscosity @ 275°F, cst	352	230 min
Penetration @ 77°F, dmm	58	50 min
Flash Point, COC, °F (AASHTO T-73)	600	450 min
Solubility, in trichloroethylene, %	99.87	99 min
Tests on residue		
Viscosity @ 140°F	6122	8,000 max
Ductility @ 77°F	-	75 min

Table 3.5 - Preliminary Product Specification,
Chevron Polymer Asphalt, CA(P)-1

Original Test Properties	ASTM Test Method	CA(P)-1 Specification	CA(P)-1 Properties
Penetration at 77°F, dmm	D 5	85 min	113
Viscosity at 140°F, Poises	D 2171	1600-2400	2,092
Viscosity at 275°F, cst	D 2170	325 min	676
Flash Point, COC, °F	D 92	450 min	500
Ductility at 77°F, cm	D 113	100 min	150+
Ductility at 39.2°F, cm (5 cm/min pull rate)	D 113	25 min	32
Toughness, Inch-Pounds	*	75 min	124
Tenacity, Inch-Pounds	*	50 min	101
Properties After Rolling Thin Film Oven Test	D 2872		
Viscosity at 140°F, Poises	D 2171	10,000 max	4,980
Ductility at 77°F, cm	D 113	100 min	150+
Ductility at 39.2°F, cm (5 cm/min pull rate)	D 113	8 min	13
Toughness, Inch-Pounds	*	100 min	325
Tenacity, Inch-Pounds	*	75 min	346

* Benson Method of Toughness and Tenacity:
20 in/min pull rate, 7/8 in diameter tension head

Table 3.6 - Additives Used and Addresses of Suppliers

1) PlusRide 12

All Seasons Surfacing Corporation
2281 116th Ave., N.E., Suite 2
Bellevue, WA 98004-3015
(206)454-3830

2) Arm-R-Shield

Arizona Refining Company
5319 SW Westgate Dr., Suite 253
Portland, OR 97221
(503) 292-8151

3) Polypropylene Fibers (Fiber Pave - 3010)

Hercules Incorporated
910 Market Street
Wilmington, DE 19899
(302) 575-6315

4) Polyester Fibers (BoniFibers)

Kapejo Incorporated
3 Peirce Road
Wilmington, DE 19803
(302) 453-8955

5) Chevron Polymer-Modified Asphalt CA(P)-1

Chevron USA, Inc.
P.O. Box 4424
Portland, OR 97208
(503) 221-7804

3) Fiber Pave - Increased resistance to rutting and reflective cracking.

4) BoniFibers - Improved resistance to reflection and thermal cracking, rutting, shoving, and pushing.

5) Asphalt Cement Treated with Pave Bond - Improved resistance to stripping.

6) Hydrated Lime Additive - Improved resistance to stripping.

7) Polymer Modified Asphalt (Chevron CA(P)-1) - Improved rutting resistance, increased toughness, and crack resistance.

For each experimental feature, the mix design procedures and criteria are given in Table 3.7. The resulting asphalt contents are given in Table 3.8.

3.3 Oregon DOT Mix Designs

After the project was constructed, ODOT performed detailed mix designs using their current mix design procedures (Sullivan et al., 1986). The reason for this was to verify the potential use of the current ODOT design method for use with modified asphalts. Mix design criteria used to evaluate the various experimental features (except PlusRide) are summarized below:

1) Asphalt film thickness	Sufficient to Thick
2) Air voids, %	3.0 to 5.0
3) Stability, 1st compaction	30 min.
4) Stability, 2nd compaction	30 min.
5) Index of retained strength, IRS %	75 min.
6) Modulus ratio, %	70 min.

The results of these mix designs, with appropriate comments are summarized in Table 3.9. As indicated, there are only slight differences in asphalt contents recommended by the additive supplier (Table 3.8) and ODOT (Table 3.9).

Table 3.7 - Mix Design Procedures and Criteria Used, Additive Suppliers and ODOT

Feature	Method	Compactive Effort	% Additive	Design Criteria	Comments
PlusRide	Marshall	50 blows/side	3% rubber granules by weight of total mix	3% air voids	Mix is rich in asphalt and filler. Mix has high coarse aggregate content and is gap graded.
Arm-R-Shield	Marshall	75 blows/side	20% rubber by weight of asphalt binder	Stability: 1500 min Flow: 8-18 Voids: 3-5%	Asphalt/rubber is reacted at elevated temperature before use. Mix is rich in asphalt.
Fiber Pave (polypropylene)	None Given	-	0.3% fiber by weight of total mix	Asphalt content increased 0.3% over the standard mix	
BoniFibers (polyester)	None Given	-	0.25% fiber by weight of total mix	Asphalt content increased 0.3% over the standard mix	
Chevron CA(P)-1	Hveem	150 blows/ 500 psi	5.0% of asphalt binder	Stability: 30 min Appearance: shiny	Polymer with and without lime-treated aggregate.
All other mixes	Hveem (ODOT)	150 blows/ 500 psi	Either 0.5% Pave Bond by weight of asphalt binder and/or 1.0% lime slurry by weight of aggregate	Stability: 30 min Voids: 4-5% IRS: 75% min Mod. Ratio: 70% min	For details of mix design procedure see report by Sullivan et al., 1986.

Table 3.8 - Mix Design Results (from Additive Suppliers)

Additive Type	Recommended Asphalt Content, %*	
	With Lime	Without Lime
PlusRide	-	8.0
Arm-R-Shield	-	8.0
Fiber Pave	-	6.7
BoniFibers	-	6.7
CA(P)-1	6.5	6.5

* % by weight of total mix

Table 3.9 - Summary of Mix Designs Performed by ODOT Following Construction

			Properties of Mix @ Design Asphalt Content					
Material	% Additive	Basis for A/C Recommendation	Rec. Asphalt Content, % of Total Mix	Hveem Stability	IRS,%	Voids,%	Diametral Modulus, psi	Modulus Ratio (Freeze-thaw)
PlusRide	3.00	3% voids	7.5	4	53	2.9	183,900	0.65
Arm-R-Shield	20.00*	3% voids	8.2	31	47	4.8	86,500	0.53
Fiber Pave**	0.30	Std ODOT criteria	7.0	36	100+	5.9	182,600	0.58
BoniFibers**	0.25	Std ODOT criteria	7.0	38	90	5.7	273,000	0.74
Treated with Pave Bond**	0.50*	Std ODOT criteria	5.9	39	99+	4.9	327,000	0.75
Treated with Pave Bond	0.50*	Std ODOT criteria	6.5	32	100+	4.7	350,000	1.03
Control	-	Std ODOT criteria	6.5	37	79	5.0	280,000	0.44
Control**	-	Std ODOT	6.0	39	93	4.9	337,000	0.92
Chevron CA(P)-1	5.00*	Std ODOT criteria	6.5	39	73	4.9	160,000	0.68
Chevron** CA(P)-1	5.00*	Std ODOT criteria	6.9	39	91	4.9	110,000	0.79

* % of liquid binder
** Aggregate is precoated with 1% lime slurry

4.0 CONSTRUCTION PROCESS

Ten test sections, using various additives, were constructed on US Highway 97, south of Bend, in central Oregon. The test sections were built during the first week of August, 1985, by R.L. Coats Construction Co. The sections included the following materials:

1) PlusRide - PlusRide, Inc.
2) Arm-R-Shield - Arizona Refinery
3) Fiber Pave (polypropylene fiber) - Hercules, Inc.
4) BoniFibers (polyester fiber) - Kapejo, Inc.
5) Pave Bond - Carstab
6) Hydrated lime - Ash Grove Cement, Portland, OR
7) CA(P)-1 (polymer modified asphalt) - Chevron, USA

The first three sections were set up under the original contract which was awarded to R.L. Coats Construction Co. during the summer of 1984. After the contract was awarded, a change order was negotiated to add a test section incorporating BoniFibers. This brought the number of products scheduled for evaluation to four. Test sections with additional polymer and emulsified asphalt products were also considered for inclusion in the project. These additional products would have increased the project scope to 13 sections. Since the contract was already awarded, the added sections required a negotiated change order with the contractor. Unfortunately, the contractor's price for the additional work was approximately $300,000 above the state's estimated cost. Despite extensive negotiations, an agreement could not be reached. Construction began with only four products scheduled for evaluation (PlusRide, Arm-R-Shield, Fiber Pave and BoniFibers).

Subsequently, Chevron USA offered to furnish CA(P)-1, polymer modified asphalt, at the same price as the AC-20 asphalt cement furnished for the rest of the project. This offer was accepted and two additional test sections were added to the study. One section utilized the CA(P)-1 with lime-treated aggregate and the other without lime-treated aggregate. This expanded the project to six experimental sections.

Dale Allen, Highway Division Region 4 Engineer, decided to expand the scope of the project by using some of the prepared test sites to evaluate the effectiveness of anti-stripping agents and lime-treated aggregates. The contract documents included provisions to add anti-stripping agents and lime treat the aggregate, so no change orders were required. Pave Bond anti-stripping agent was selected for evaluation since it was being used in the conventional mix. With the various combinations of Pave Bond, lime-treated aggregate, and a control section, a total of ten test sections was constructed. This chapter summarizes the construction procedures, quality control data, and cost data for each test section.

4.1 Construction Procedures

This section describes the equipment used and procedures followed during construction of the test sections. For all features, the equipment listed in Table 4.1 was used. For the PlusRide and fiber sections, the additive was added as a dry mix cycle prior to the mixing operation. For the Arm-R-Shield, Pave Bond and Chevron polymer modified mixes, the additive was added to the asphalt prior to mixing. The standard tack coat was 0.03% gal/yd^2 of Chevron CSS-1. For all sections, the target percent compaction was 92% of maximum gravity (AASHTO T-209).

Table 4.1 - Equipment Used for Construction

Operation	Equipment Used
Mixing & Storage	Cedar Rapids Batch Plant Model 6000 rated @ 200-300 ton/hr
Placement	Bottom dump trucks with pickup machine and Cedar Rapids Paver Model 520
Compaction	9.6 ton vibratory roller 5 ton pneumatic roller 10 ton steel roller (3 wheel)

PlusRide

Granulated rubber produced from shredded tires replaced a portion of the aggregate from the 1/4" to No. 10 size. The PlusRide material was added to the batch plant via the top hopper (Figure 4.1). One hundred and eighty pounds of rubber were added to every 3-ton batch of mix produced (3.0%). Asphalt content was set at 8% of the total weight of mix. Mix temperature was 340-355°F, and laydown temperature was approximately 320°F in the windrow ahead of the paver. Compaction temperature was about 270-280°F.

The construction proceeded rapidly without any major problems. The supplier recommended that rubber tire rollers not be used and that a soap solution be used with the other rollers to prevent "pick-up." Three roller passes, one static (breakdown) followed by a vibration pass and a static finish pass at 140°F, achieved the desired percent compaction. Pneumatic rolling was not allowed due to "pick-up." Two additional passes increased the density, but the next pass resulted in cracking and lowering the density. Traffic traveled over the mat after it had been finish-rolled and the temperature had dropped to approximately 140°F. Initially, the mixture appeared to flush under traffic, but by the next day evidence of flushing could not be found. The mixture was also quite sticky and tacky on the surface.

Arm-R-Shield

The second section constructed incorporated a rubber-modified asphalt from Arizona Refining Company. Recycled rubber was melted with the AC-20 asphalt at 400°F in a mobile mixing truck supplied by Arizona Refining. Once the rubber and asphalt were blended, the asphalt-rubber mixture was transferred to a distributor truck for storage. Introduction of this additive into the mix presented some unique problems. Since the plant storage tanks already contained ummodified liquid asphalt, the asphalt modified with

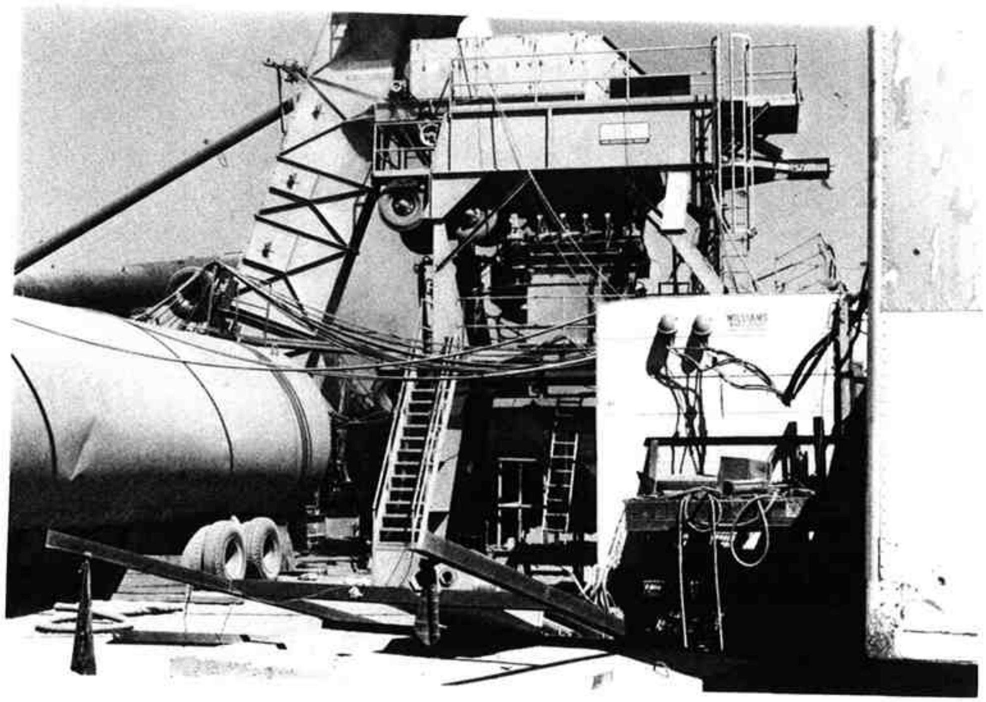


Figure 4.1 - Cedar Rapids Batch Plant

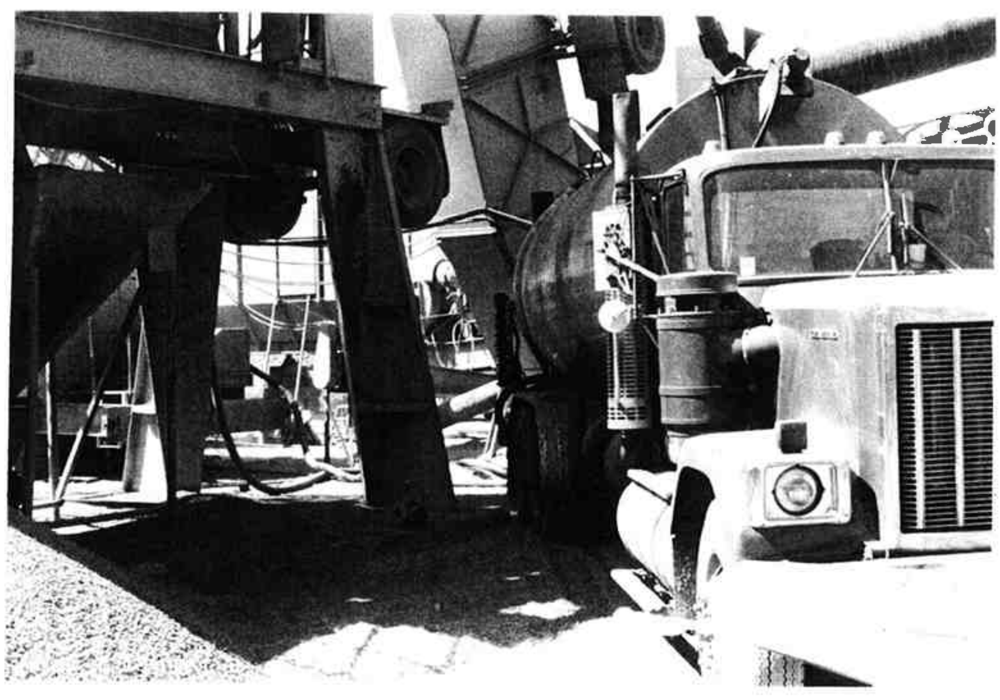


Figure 4.2 - Distributor Truck - Arizona Refinery

Arm-R-Shield had to be pumped from the distributor truck into the pug mill. Figure 4.2 shows the distributor truck at the batch plant. The asphalt content for mix containing modified asphalt was set at 8% by weight of total mix. Since the binder contains 20% rubber, the actual components were 6.4% liquid asphalt and 1.6% rubber additive. Each 3-ton batch was mixed for 3 to 15 seconds before adding the modified asphalt and for 35 additional seconds after it was added. The production of the mix was extremely slow: 3-ton batches took from 2 to 7 minutes to mix. The plant operator felt that the slow production resulted from the material being very viscous and extremely hard to pump. Under normal production, this problem probably would not have occurred since the larger plant storage tanks and hoses would have been used. Approximately 506 tons of this material were placed August 5. An additional 489 tons were placed August 6.

Mix temperatures of 340-350°F at the plant discharge, laydown temperatures of 315-350°F in the windrow ahead of the paver, mat temperatures after laydown of 285-295°F and surface temperatures of 110°F were recorded August 5. Mix temperatures of 340°F at the plant discharge, laydown temperatures of 315-325°F in the windrow ahead of the paver, mat temperatures of 284-288°F and surface temperatures of 60-77°F were recorded August 6. Blue smoke and steam appeared during the laydown operation. No cause for this behavior was identified.

The roller operator attempted to compact directly behind the paver; however, the mix lacked stability and started to shove and "pick-up" on the roller wheels. Due to these problems and the hot laydown temperature, the breakdown compaction equipment started rolling 600-800 ft. behind the paver. The normal rolling pattern both days was two vibratory and one static pass with another vibratory roller for finish. On August 5, the mix moved under the rollers and wrinkled badly even though it was laid down without excessive cracking under the finish roller. Mix placed August 6 did not exhibit the tendency to "crawl." Neither the factory representative nor others at the jobsite could determine a reason for the difference in mix behavior from the 5th to the 6th. The only significant change in conditions recorded was the 40-50°F reduction in surface temperature. It was difficult to achieve the desired 92% compaction as measured by the nuclear gauge. Even after eleven passes with both static and vibratory rollers, the mixture never achieved the specified compaction of 92%. However, compaction of 93.1% was obtained for a core taken August 8. Readings with the nuclear density gauge taken August 8 at the same location indicated compaction of 91.9%.

The pavement material was much "stickier" than the PlusRide and remained in this condition until traffic had been on it for some time. This presented no problem. However, extraction of asphalt from the mix (using a vacuum extractor) was very difficult, taking approximately two hours to wash.

Polypropylene Fiber - Fiber Pave[R]

The next test section constructed used the Hercules polypropylene fiber. The manufacturer for the Fiber Pave 3010 is Hercules, Incorporated. The fiber material was added to the pug mill in a similar fashion as the PlusRide material. Figure 4.3 shows the fiber material on the jobsite. Figures 4.4 through 4.7 depict the plant and field operations for the fiber products. A crane hoisted the crates of material to the top of the batch plant and two workers fed one 18-lb. bag of material for each 3-ton batch (0.3%). Each batch took approximately 30 seconds; the workers were signaled from the control shack when to add the fibers. The operation had some initial clogging problems, but this was resolved by dumping the material down another hopper chute.

(a) Being Transported

(b) Conveyed to the Plant

Figure 4.3 - Fiber Materials at the Job Site

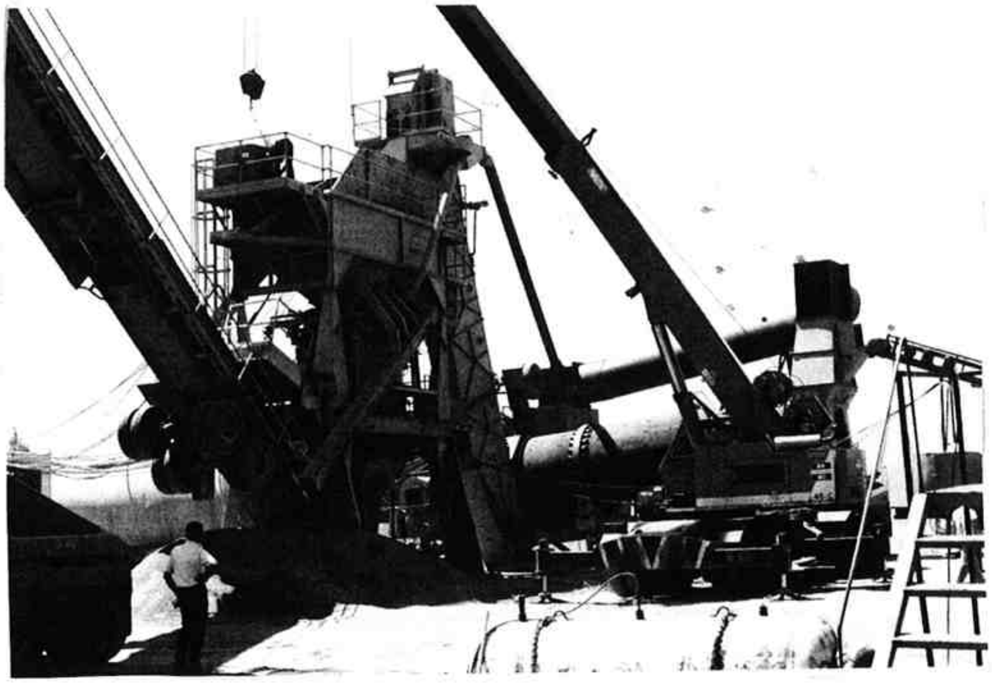


Figure 4.4 - Materials Added to Batch Plant

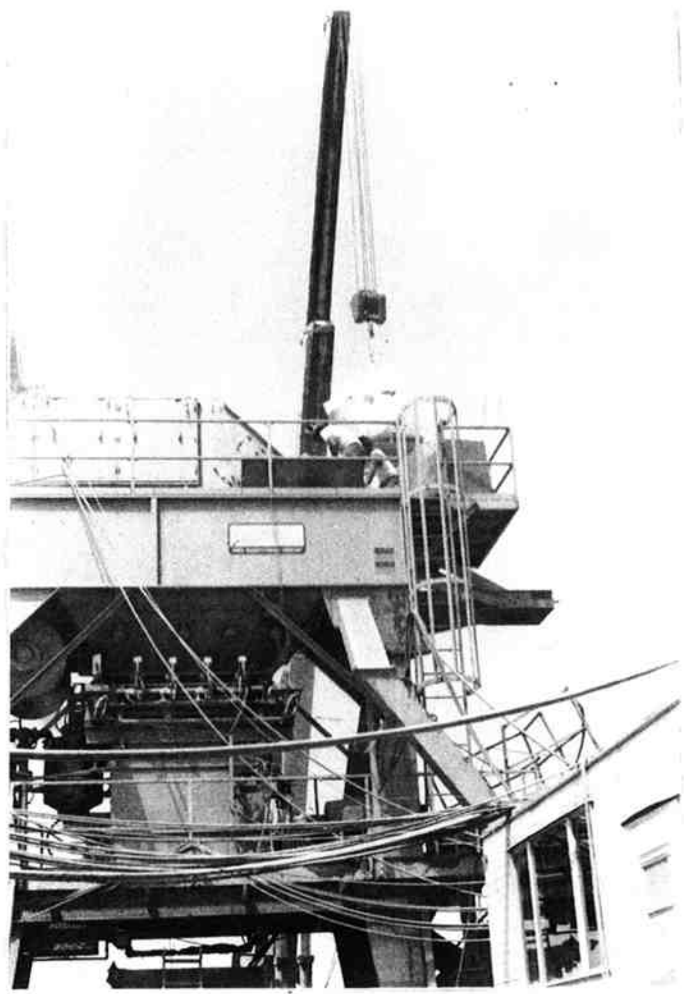


Figure 4.5 - Loading Additive to Hopper

Figure 4.6 - Depositing Mix into Truck

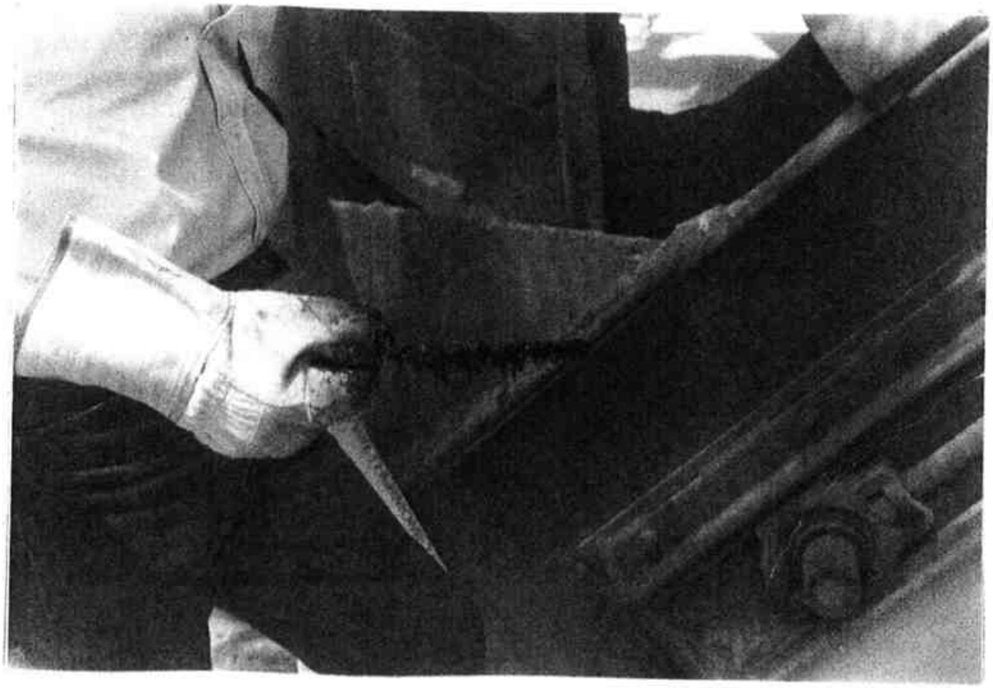
Figure 4.7 - Pick Up Machine

The specification for use of this material stated that the mix temperature could not be above 290°F. The addition of fiber and a 0.3% increase in the liquid asphalt content were the only deviations from normal Class "C" mix components. The technical representative from Hercules was on-site to oversee production. He used a thermometer to test the mixture at the pug mill exit. The mixture should have a stringy texture as shown in Figure 4.8(a). If the mix temperature is too hot, the fibers will melt and not produce the desired consistency, Figure 4.8(b). The stringy texture made the mix difficult to rake.

Mix temperatures recorded were 285°F at the plant discharge, 265-280°F in the windrow ahead of the paver, 239-248°F behind the paver, and the existing surface temperatures ahead of the paver were 120-125°F. The original rolling pattern consisted of two vibratory rollers, but was later modified to include a pneumatic roller for breakdown (Figure 4.9). The pneumatic rollers were added because the two vibrators just barely met compaction criteria and the laydown production was too far ahead of rolling. The representative from Hercules indicated a pneumatic roller could be used on the mix. Photos of typical compaction problems are shown in Figure 4.10. The desired 92% compaction was also difficult to achieve on this section.

Polyester Fiber - BoniFibers[R]

BoniFibers is the trade name of the polyester fiber used on this section. The method used to add Fiber Pave to the mix was also used for BoniFibers, with two workers feeding 15-lbs. of material into each 3-ton batch (0.25%). Asphalt content was increased 0.3% from the standard mix to 6.7% in the mix. The rest of the material and plant settings were not changed from the standard Class "C" requirements. Mix temperatures of 305-310°F at the plant discharge, laydown temperatures of 275-305°F in the windrow ahead of the paver, mat



(a) Stringy Nature of Fiber

(b) Mix Too Hot - Fibers Melting

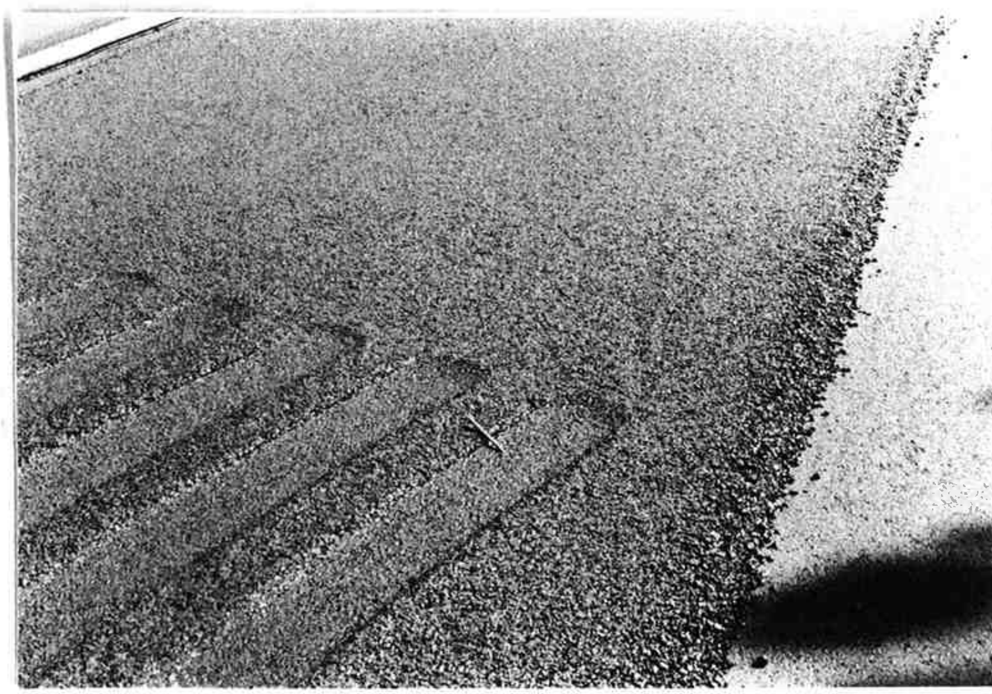
Figure 4.8 - Unique Features of Polypropylene Fiber Mix

(a) Vibratory Roller

(b) Rubber Tire Roller

Figure 4.9 - Compaction of Polypropylene Fiber Mix

(a) With Vibratory Roller



(b) With Rubber Tired Roller

Figure 4.10 - Compaction Problems

temperatures directly behind the paver of 256-285°F, and surface temperatures ahead of the paver of 60-70°F were recorded. After the first pass with the breakdown roller, this material appeared very brown, similar to a conventional mix with insufficient binder content. After two days of traffic, it turned black. It should be noted the fibers were not dry mixed prior to the addition of the asphalt. This resulted in poor fiber dispersion in the mix and formation of fiber balls throughout the section. It is uncertain what effect this will have on the performance of this section.

The desired 92% compaction was difficult to attain which could have resulted from one roller having mechanical difficulty thus delaying the paving operation. To provide adequate equipment, one static steel roller and two pneumatic rollers were added. The use of additional rollers resulted in over-compaction and a subsequent reduction in the density values.

Class "C" with Pave Bond (with and without lime)

Two sections were specifically constructed to evaluate asphalt treated with 0.5% Pave Bond: one with lime, and one without. Mix temperature at the plant was recorded at 300°F±10°. Laydown temperatures of 295-305°F in the windrow ahead of the paver, mat temperatures of 280-290°F and a surface temperature of 80°F were recorded. Four rollers were used to obtain compaction: two passes of a 3-wheeled roller for breakdown; three passes with a vibratory roller (one static and two vibratory), 2-4 passes with a rubber tire roller for intermediate rolling; and 1 to 2 static passes with the vibratory roller for finish rolling. Densities were reasonably close to the desired 92% compaction. No problems were encountered during construction with either of the two mix sections. Both mixes layed the same as a standard Class "C" asphalt concrete mix.

Control (with and without lime)

Control sections consisted of a standard Class "C" asphalt concrete mix. Mixing and compaction techniques were similar to those used for sections containing Pave Bond. Two control sections were constructed: one with lime treatment and one without. No special problems were encountered during construction of either section.

Chevron Modified Asphalt (CA(P)-1)

Two sections were constructed using Chevron polymer modified asphalt: one section with lime-treated aggregate, and one without. The material with lime was placed from 8:00 am to 11:00 am. The material without lime was placed from 12:00 pm to 3:00 pm. Mix temperatures at the plant discharge were originally set at 340°F. At approximately 10:00 am, the target was reduced to 325°F at the plant discharge for four truckloads. Laydown temperatures were 315-320°F in the windrow ahead of the paver, while a mat temperature behind the paver of 285°F and an air temperature of 66°F were recorded for the mixture without lime-treated aggregate. A mix temperature of 340°F at the plant discharge, laydown temperatures of 315-335°F in the windrow ahead of the paver, mat temperatures behind the paver of 290-305°F, and surface temperatures ahead of the paver of 110°F were recorded for the mixture with lime-treated aggregates. The Chevron representative considered the elevated temperature essential to obtain good bond of binder to stone, so all trucks were covered with tarps. The increased temperature was the only deviation from normal Class "C" mix settings and components.

Breakdown rolling was accomplished with two passes of a 3-wheel steel roller, intermediate rolling with 2-3 passes with the pneumatic roller and three passes with the vibratory roller (one static and two vibratory), and finish rolling with one static pass of the vibratory roller. The mix without lime was deformed under the rollers while the mix with lime was very stable. This may have been caused by the CSS-1 tack coat. The section without lime-treated aggregate received 0.05 gal/yd^2 while the section with lime-treated aggregate and all other test sections received 0.03 gal/yd^2. When construction was complete, both sections looked satisfactory and compaction exceeded the desired 92%.

4.2 Quality Control Data

This section summarizes results of the construction daily plant reports and nuclear density work sheets. Table 4.2 summarizes the daily plant reports and Table 4.3 summarizes the results of compaction tests. The results of the tests generally indicate:

1) The asphalt content and mix gradation generally fell within the mix design tolerances for all mixes. The exception was the asphalt content for PlusRide. All tests for the PlusRide mix showed an asphalt content 0.1 to 0.6% higher than the design tolerance.
2) The mix and laydown temperatures generally conformed to specifications.
3) Many of the nuclear density tests failed to meet the specified 92% minimum value based on AASHTO T-209.

In general, the quality control tests indicated no major problems in the mix with the exception of low densities (high voids).

4.3 Unit Cost Evaluation

Unit costs shown in Table 4.4 are predominantly contractor bid prices with a few negotiated costs included. Even though small quantities are involved and the contractor had no experience with most of the materials,

Table 4.2 - Summary of Daily Plant Reports

	PLUS RIDE		ARM-R-SHIELD		FIBER PAVE	
Gradation	Mix Test Value	Mix Design Tolerances	Mix Test Value	Mix Design Tolerance	Mix Test Value	Mix Design Tolerance
3/4	-	-	100	100	100	100
5/8	100	94-100	-	-	-	-
1/2	-	-	98	95-100	97	95-100
3/8	78-79	70-82	-	-	-	-
1/4	47-48	32-44	60	60-72	63	60-72
10	36-37	27-35	31	28-36	31	28-36
30	21	15-23	-	-	-	-
40	-	-	12	8-26	14	8-26
200	7.4-7.9	6.9-10.9	5.0	3.8-7.8	5.5	3.8-7.8
Asphalt Content, %						
	8.5-9.0	7.6-8.4	7.6*	7.5-8.5*	6.7	6.3-7.3
Additives,%						
	3.0 rubber in mix 0.5 Pave Bond 0.0 lime	2.85-3.15	20 rubber in asphalt 0.0 Pave Bond 0.0 lime		0.3 fiber 0.5 Pave Bond 0.0 lime	
Mix Temperature,°F						
	325-355	325-360	340-350	340 min	285	290 max
Laydown Temperature,°F						
	317-321	300 min	315-350	285-325	265-280	245-290

* Includes asphalt additive

Table 4.2 - Summary of Daily Plant Reports (cont.)

Gradation	BONIFIBERS Mix Test Value	BONIFIBERS Mix Design Tolerances	CLASS "C" WITH PAVE BOND Mix Test Value	CLASS "C" WITH PAVE BOND Mix Design Tolerance	CLASS "C" WITH LIME AND PAVE BOND Mix Test Value	CLASS "C" WITH LIME AND PAVE BOND Mix Design Tolerance
3/4	100	100	100	100	100	100
5/8	-	-	-	-	-	-
1/2	97	95-100	97	95-100	98	95-100
3/8	-	-	-	-	-	-
1/4	66	60-72	66	60-72	64	60-72
10	32	28-36	33	28-36	31	28-36
30	-	-	-	-	-	-
40	14	8-26	14	8-26	14	8-26
200	5.5	3.8-7.8	5.9	3.8-7.8	5.4	3.8-7.8
Asphalt Content, %						
	6.5	6.2-7.2	6.2*	5.9-6.9*	6.2*	5.9-6.9*
Additives, %						
	0.25 fiber 0.50 Pave Bond 0.00 lime		0.5 Pave Bond 0.0 lime		0.5 Pave Bond 1.0 lime	
Mix Temperature, °F						
	305	325 max	305	325 max	305	325 max
Laydown Temperature, °F						
	275-305	280±	285	280±	285	280±

* Includes asphalt additive

Table 4.2 - Summary of Daily Plant Reports (cont.)

	CONTROL WITH LIME		CONTROL	
Gradation	Mix Test Value	Mix Design Tolerances	Mix Test Value	Mix Design Tolerances
3/4	100	100	100	100
5/8	-	-	-	-
1/2	98	95-100	98	95-100
3/8	-	-	-	-
1/4	69	60-72	64	60-72
10	32	28-36	32	28-36
30	-	-	-	-
40	14	8-26	13	8-26
200	5.8	3.8-7.8	5.5	3.8-7.8
Asphalt Content, %	6.4	5.9-6.9	6.3	5.9-6.9
Additives, %	0.0 Pave Bond 1.0 lime based on aggregate weight		0.0 Pave Bond 0.0 lime	
Mix Temperature, °F	305	325 max	305	325 max
Laydown Temperature, °F	290	280±	290	280±

* Includes asphalt additive

Table 4.2 - Summary of Daily Plant Reports (cont.)

	CA(P)-1		CA(P)-1 WITH LIME	
Gradation	Mix Test Value	Mix Design Tolerances	Mix Test Value	Mix Design Tolerance
3/4	100	100	100	100
5/8	-	-	-	-
1/2	97	95-100	97	95-100
3/8	-	-	-	-
1/4	65	60-72	65	60-72
10	30	28-36	32	28-36
30	-	-	-	-
40	14	8-26	14	8-26
200	6.5	3.8-7.8	6.2	3.8-7.8
Asphalt Content, %				
	6.4*	5.9-6.9*	6.6*	5.9-6.9*
Additives, %				
	5.0 Polymer based on asphalt weight 0.0 Pave Bond 0.0 lime		5.0 Polymer based on asphalt weight 0.0 Pave Bond 1.0 lime	
Mix Temperature, °F				
	325-340	340	340	340
Laydown Temperature, °F				
	315-320	-	315-335	-

* Includes asphalt additive

Table 4.3 - Summary of Nuclear Density Tests

Material	Date	Unit wt. (pcf)	Density (%)
PlusRide 12	8/5/85	131.5-137.5	92.5-96.7
PlusRide 12	8/7/85	132.0-133.5	92.8-93.9
Arm-R-Shield	8/5/85	129.0-139.5	85.9-92.9
Arm-R-Shield	8/6/85	134.0-139.0	88.6-91.9
Arm-R-Shield	8/8/85	138.0-139.0	91.9
Fiber Pave	8/6/85	132.0-141.0	86.0-91.9
Fiber Pave	8/8/85	139.5	90.9
BoniFibers	8/7/85	132.0-142.0	86.2-92.7
Class "C" with Pave Bond	8/7/85	137.0-141.0	89.1-91.7
Class "C" with Lime and Pave Bond	8/7/85	140.0-141.5	91.4-92.4
Control with Lime	8/8/85	142.5-145.0	93.1-94.7
Control	8/8/85	136.5-143.5	89.4-94.0
CA(P)-1	8/9/85	142.0-145.5	93.1-95.4
CA(P)-1 with Lime	8/9/85	141.0-143.5	92.8-94.5

Table 4.4 - Unit Prices

Material	Asphalt Concrete Mixture* $/ton	Liquid Asphalt** % Binder/ton $/ton Mix	Lime Credit $/ton Mix	Total Cost $/ton
PlusRide	$30.00	8.0% $15.72		$45.72
Arm-R-Shield	$20.00	8.0% $60.00		$80.00
Fiber Pave	$30.00	6.8% $13.36	- $1.45	$41.91
BoniFibers	$30.00	6.7% $13.17	- $1.45	$41.72
Class "C" with Pave Bond	$11.00	6.4% $12.58	- $1.45	$22.13
Class "C" with Lime and Pave Bond	$11.00	6.4% $12.58		$23.58
Control with Lime	$11.00	6.4% $12.10		$23.10
Control	$11.00	6.4% $12.10	- $1.45	$21.65
CA(P)-1	$11.00	6.4% $17.86	- $1.45	$27.41
CA(P)-1 with Lime	$11.00	6.4% $17.86		$28.86

* Excludes liquid asphalt and additives in liquid asphalt.
** AC-20 = $189.00/ton; AC-20 with 0.5% Pave Bond = $196.50/ton
AC-20 with CA(P)-1 = $279.00/ton; Arm-R-Shield = $750.00/ton

these bid prices are considered a reasonable approximation of the actual installation costs.

A separate bid item was included for each class of asphaltic concrete mix to cover the contractor's cost of aggregate, mixing, handling, and placing. The cost of fibers and crumb rubber added directly into the mixture was also included in the mixture bid item. Liquid asphalt, including additives added to the liquid asphalt before mixing, were bid separately. Total cost of the mix in place was also dependent on the quantity of liquid asphalt incorporated in the mix. The designed percent asphalt for each type of mix is also included in Table 4.4 and used to calculate the cost/ton of mix.

Lime treatment of aggregate was specified for all mixtures except PlusRide and Arm-R-Shield. Therefore, when lime treatment was not used in a mixture, a $1.45/ton credit is subtracted from the mix unit price.

CA(P)-1 polymer modified asphalt was furnished by Chevron USA at the price of AC-20 liquid asphalt. Chevron reported that the polymer modified asphalt is being sold at $80-$100/ton premium. For the sake of a fair evaluation, the average of $90.00 was assumed.

5.0 MIX PROPERTIES

5.1 ODOT Tests - 1985

This section summarizes the results of tests on cores taken shortly after construction. For each experimental feature, two 4-in. and three 6-in. cores were taken in September, 1985. The 4-in. cores were tested for density, voids, modulus, and stability. The 6-in. cores were tested for gradation, asphalt content, and asphalt properties. In addition, mix samples during construction (box samples) taken in August, 1985, were compacted and tested for Hveem Stability, modulus, fatigue, and index of retained strength.

The results of the tests on the 4-in. cores are given in Table 5.1. The following significant items are noted:

1) the modulus values (@ 77°F) range from 93,000 psi for Arm-R-Shield to 590,000 psi for the C-Mix with Pave Bond and lime-treated aggregate (Fig. 5.1);

2) the in-place voids range from 3.7% for the PlusRide section to 8.1% for the BoniFibers section (Fig. 5.2). This indicates compaction is at a satisfactory level.

3) the Hveem stability values (in-place density) are within the expected range except for PlusRide (Fig. 5.3). They range from 2 for PlusRide to 29 for the Pave Bond section.

Table 5.2 summarizes the results of the gradation and asphalt property test results from box samples of mix (obtained during construction) and from 6-in. cores obtained shortly after construction. The results presented in this table indicate:

1) the gradation and asphalt content to be more-or-less in compliance with the job mix formula,

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Table 5.1 - Summary of Test Results, 4-in. Cores (September, 1985)

Property	PlusRide	Arm-R-Shield	Fiber Pave	BoniFibers	Class "C" with Pave Bond	Class "C" with Lime and Pave Bond	Control with Lime	Control	CA(P)-1	CA(P)-1 with Lime
Unconditioned Modulus (1000 psi) @ 77°F	264	93	111	137	275	590	209	256	352	366
Gravity:										
In place (voids)	2.21 (3.7)	2.27 (6.9)	2.28 (6.5)	2.26 (8.1)	2.34 (5.3)	2.31 (6.6)	2.31 (6.9)	2.30 (7.1)	2.36 (4.9)	2.31 (6.9)
Recompacted (voids)	2.23 (2.8)	2.38 (2.4)	2.42 (0.8)	2.41 (2.0)	2.44 (1.2)	2.45 (0.9)	2.43 (2.1)	2.41 (2.6)	2.46 (0.9)	2.45 (1.2)
% Relative Compaction	96.3	93.1	93.5	91.9	94.7	93.4	93.1	92.9	95.1	93.2
Max Theoretical Gravity	2.295	2.438	2.439	2.458	2.470	2.473	2.481	2.475	2.481	2.480
Hveem Stability @ 140°F:										
In place	2	29	12	14	29	16	24	18	25	22
Recompacted	1	18	21	29	19	32	3	34	22	24

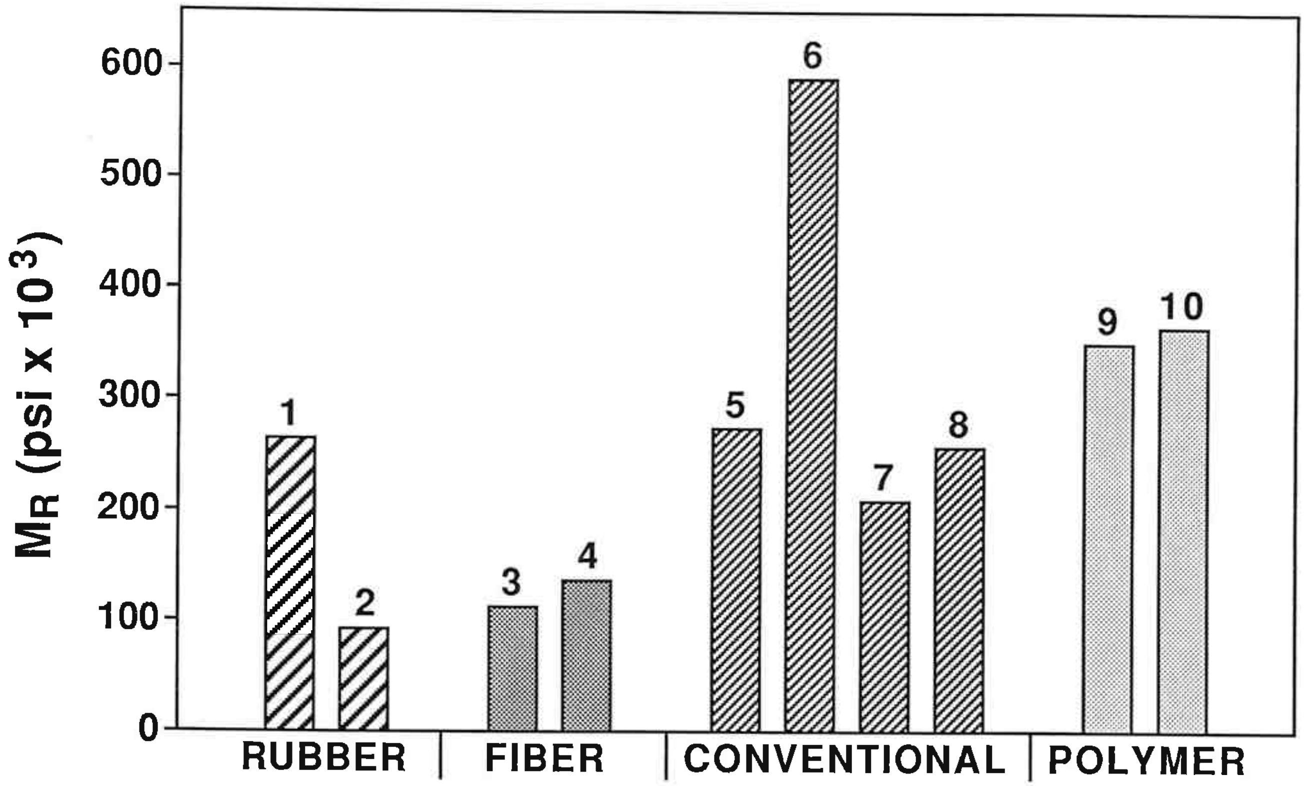


Figure 5.1 - Pavement Modulus at Construction @77°F, September 1985 Cores

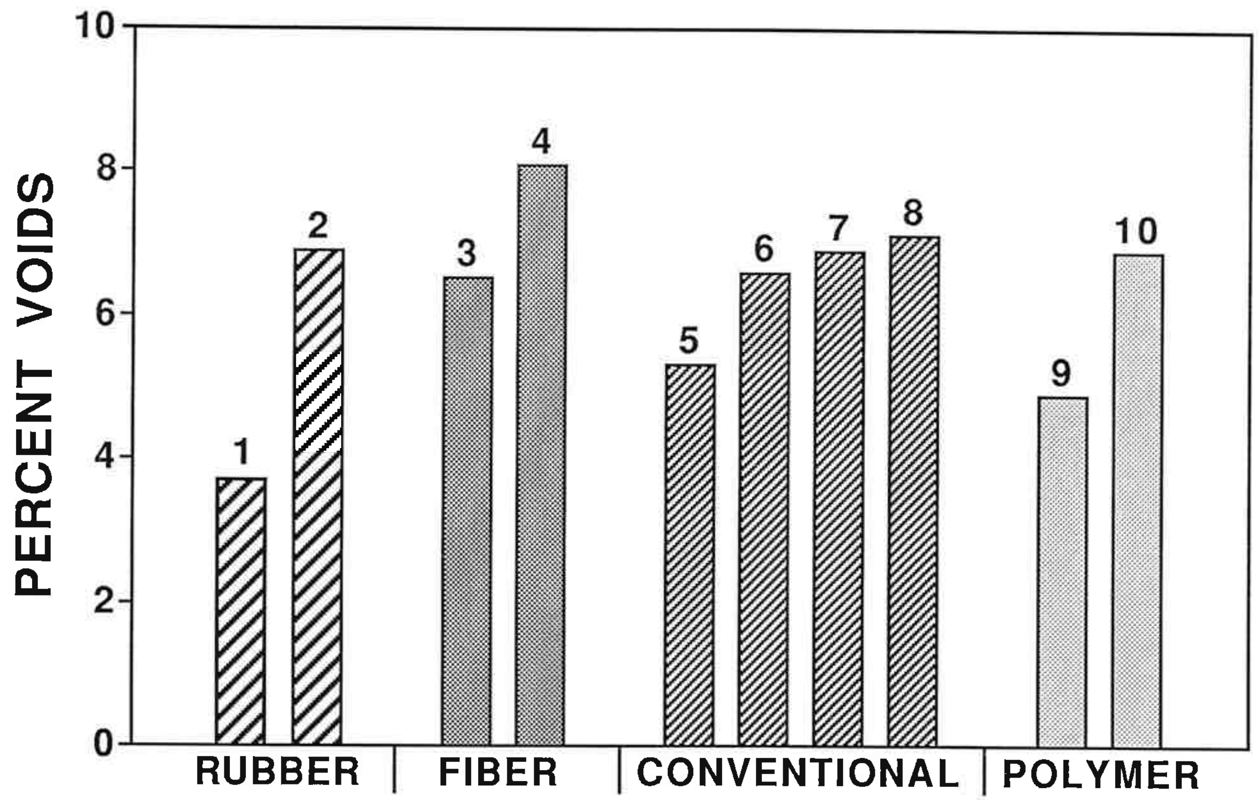


Figure 5.2 - Pavement Voids at Construction, September 1985 Cores

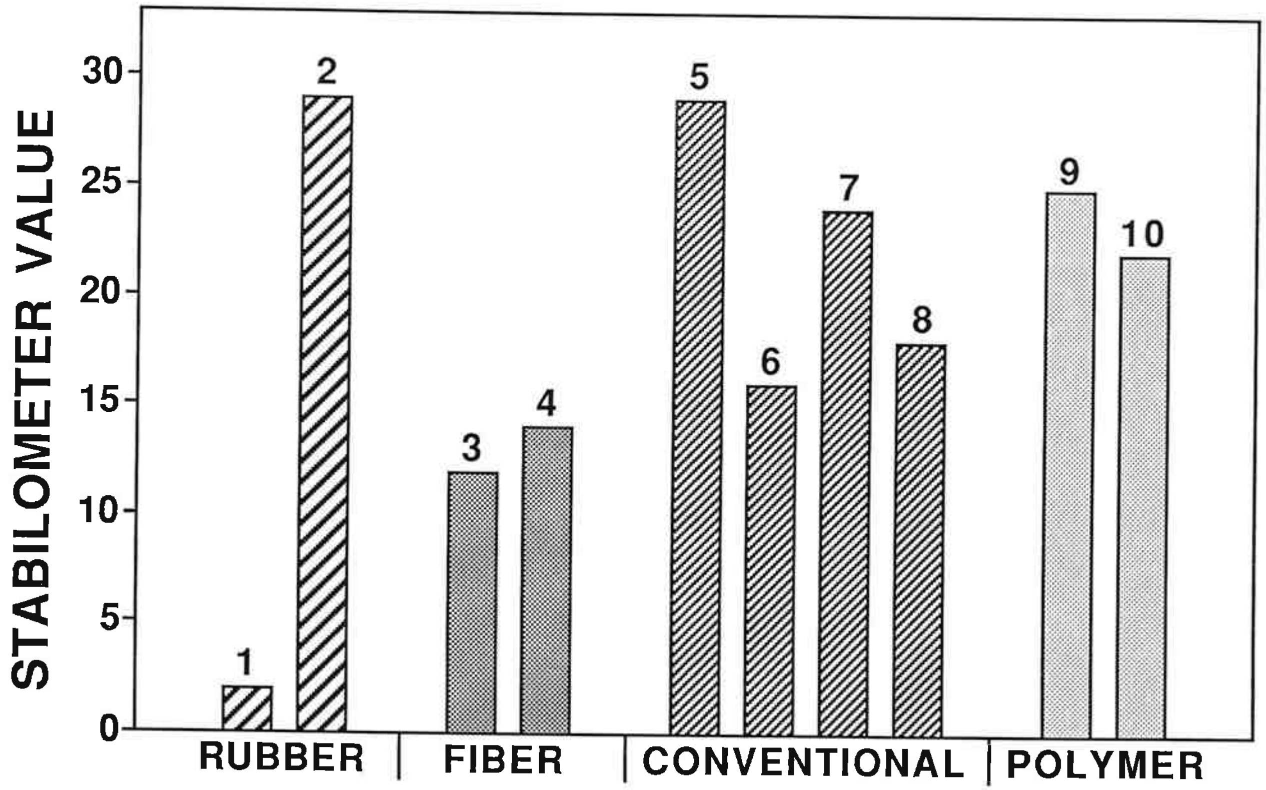


Figure 5.3 - Hveem Stability in Place @ 140°F, September 1985 Cores

Table 5.2 - Summary of Mix and Asphalt Property Test Results, 6-in Cores and Box Samples

	PlusRide #1	PlusRide #2	Arm-R-Shield	Fiber Pave	BoniFibers	Class "C" with Pave Bond	Class "C" with Lime and Pave Bond	Control with Lime	Control	CA(P)-1	CA(P)-1 with Lime
Gradation*											
3/4 in.	100	100	100	100	100	100	100	100	100	100	100
1/2 in.	97	95	98	97	98	97	99	98	98	100	99
3/8 in.	77	72	86	84	85	88	88	83	84	88	85
1/4 in.	47	43	62	64	66	68	67	66	66	66	63
4	42	38	51	54	54	56	56	55	54	54	52
10	35	33	30	32	31	32	32	32	32	32	32
40	18	16	13	14	14	14	14	14	13	14	14
200	7.0	6.2	5.8	6.1	5.8	6.2	6.4	6.7	6.0	5.9	5.5
Asphalt Content, %	8.5	7.8	6.8	7.0	6.9	6.2	6.3	6.3	6.3	7.2	6.4
Asphalt Properties*											
Viscosity @ 140°F, Poises	3319	4479	3302	8064	9130	8120	7637	5650	6560	8010	10,100
K Viscosity @ 275°F, cst.	445	514	849	597	591	624	572	534	568	1040	1137
Penetration, dmm	40	42	75	27	22	23	22	25	21	40	36
Asphalt Properties**											
Viscosity @ 140°F, Poises	2070	-	2733	5739	7231	7669	2574	6542	8435	9962	12,478
K Viscosity @ 275°F, cst.	374	-	929	539	599	599	635	560	609	1093	1369
Penetration, dmm	55	-	78	32	29	28	25	26	28	37	34

* Box samples taken in August 1985
** 6-in. cores taken in September 1985

2) the viscosities of the recovered asphalt for the box samples generally were higher than those measured on the core samples. This is due to the fact that these loose materials were tested up to 1-2 months after sampling. The highest viscosity at 140°F in both cases was measured on the polymer-modified asphalt (Fig. 5.4),

3) the viscosities at 140°F of the rubber-modified asphalts were lower than those of the other mixes (Fig. 5.4), and

4) the penetration values at 77°F for the rubber- and polymer-modified asphalts were higher than the other materials (Fig. 5.5).

Table 5.3 summarizes the mix property test results for box samples. All material was compacted using the standard compactive effort. Properties measured include (1) stability, (2) voids, (3) modulus and modulus ratios, and (4) index of retained strength. The results generally indicate:

1) The stability values at 140°F are all above 30 (except for PlusRide with values of 8 and 5).

2) Void contents are all less than 6% (Fig. 5.6).

3) Resilient modulus values at 77°F (unconditioned) range from about 250,000 to 575,000 psi. Modulus ratios (b/a and c/a) are all above 0.70 (except for PlusRide with a value of 0.63).

4) The index of retained strength values are above 75% (except for PlusRide with a value of 64).

The results of these tests would tend to be higher than normal because of the time lag between sampling and compaction.

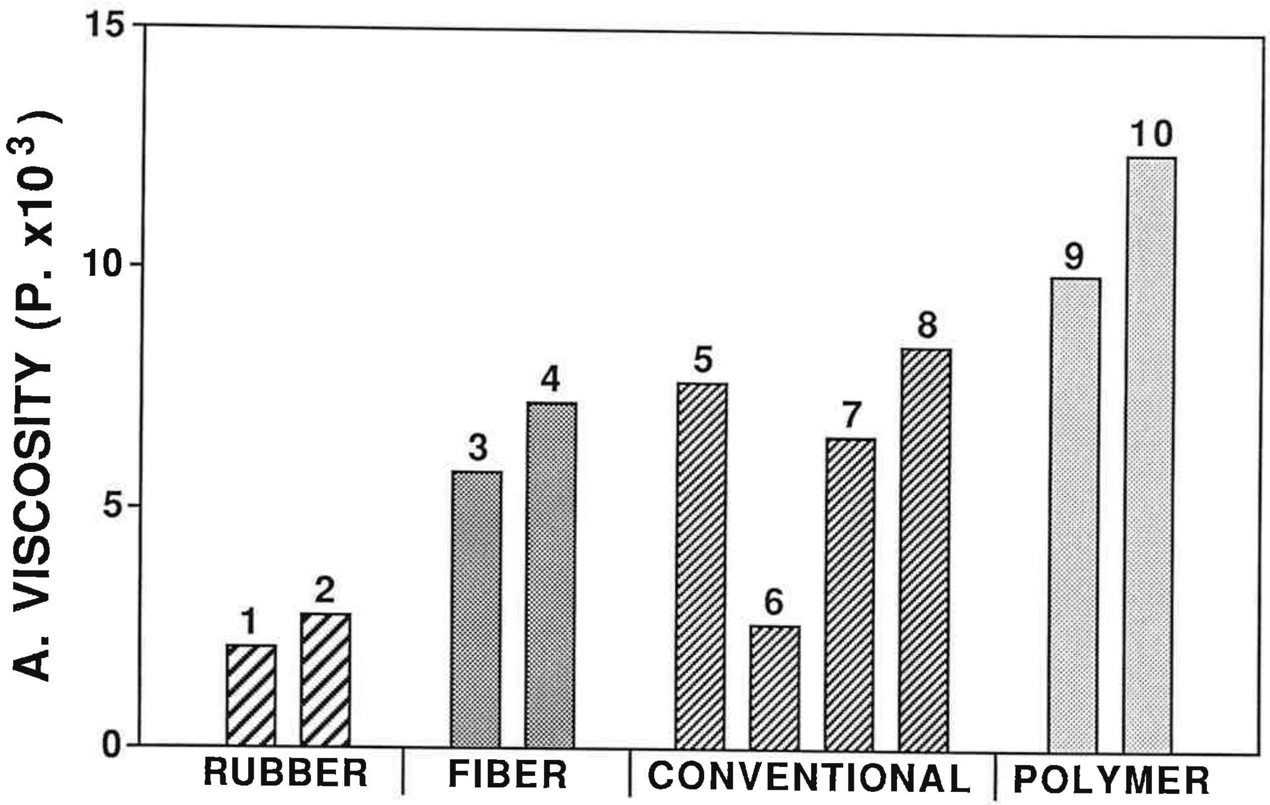


Figure 5.4 - Recovered Asphalt Viscosity @ 140°F, September 1985 Cores

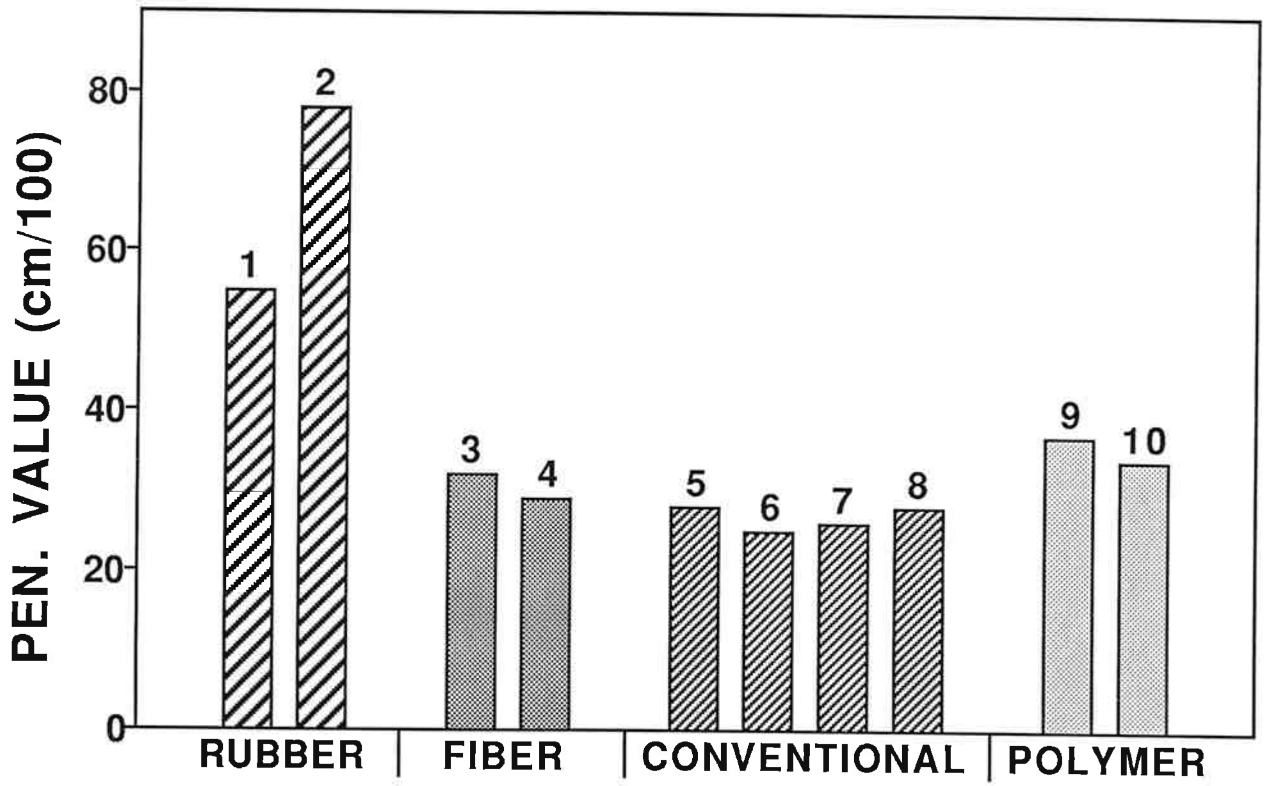


Figure 5.5 - Recovered Asphalt Penetration @ 77°F, September 1985 Cores

Table 5.3 - Summary of Laboratory-Compacted Mix Property Test Results for Box Samples, August 1985

	PlusRide #1	PlusRide #2	Arm-R-Shield	Fiber Pave	BoniFibers	Class "C" with Pave Bond	Class "C" with Lime and Pave Bond	Control with Lime	Control	CA(P)-1	CA(P)-1 with Lime
Mix Properties											
Rice Gravity	2.338	2.337	2.447	2.466	2.481	2.497	2.490	2.486	2.488	2.477	2.491
Bulk Sp Gr	2.28	2.24	2.36	2.38	2.34	2.38	2.37	2.39	2.34	2.40	2.39
Stability	8	5	37	44	39	44	40	39	41	41	37
Voids, %	2.5	4.2	3.6	3.5	5.7	4.7	4.8	3.9	6.0	3.1	4.1
Resilient Modulus											
Unconditioned (a)x10^3	340	258	263	574	421	483	473	397	446	364	245
Vac. Saturated (b)x10^3	312	232	219	525	410	456	421	396	414	281	216
Freeze Thaw (c)x10^3	249	162	185	437	352	444	399	358	348	265	246
b/a	0.92	0.90	0.83	0.91	0.97	0.94	0.89	1.00	0.93	0.77	0.88
c/a	0.73	0.63	0.70	0.76	0.84	0.92	0.85	0.90	0.78	0.73	1.00
Index of Retained Strength											
UC Dry Strength, psi	325	341	489	740	907	716	783	683	740	697	947
UC Wet Stength, psi	208	279	454	692	836	678	837	645	719	583	859
Ratio, %	64	82	93	94	92	95	100+	94	97	84	91

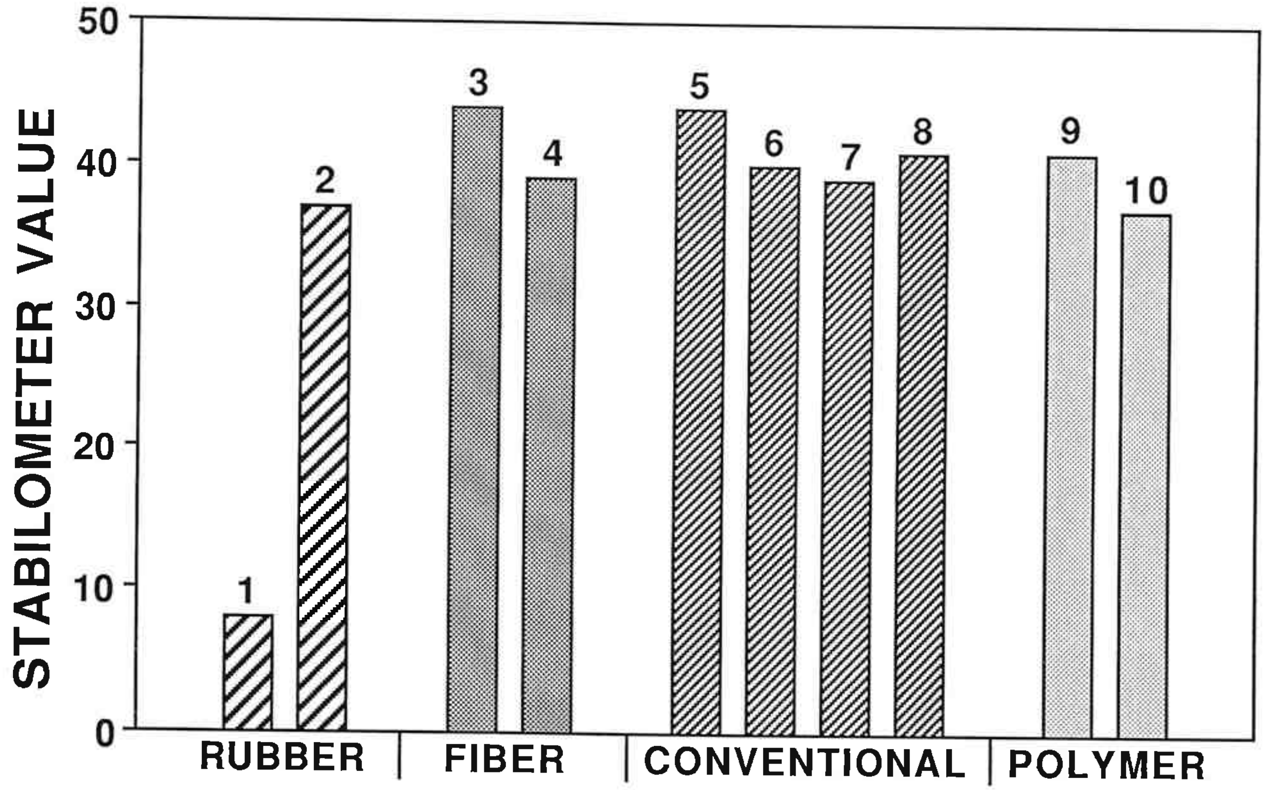


Figure 5.6 - Lab Compacted Hveem Stability @ 140°F, August 1985 Mix Sample

5.2 Modulus and Fatigue Data - OSU

Diametral modulus and fatigue tests were performed at Oregon State University. Two sets of data were tested:

1) box samples compacted at Oregon DOT materials laboratory, and

2) core samples taken in the winter of 1986 by Region 4.

All tests were run in accordance with ASTM D-4123. The modulus and fatigue tests were run at 100 microstrain and 200 microstrain and tested at 73°F.

Table 5.4 summarizes the results of the tests on the laboratory compacted samples and Table 5.5 summarizes the results of tests on field cores taken in March, 1986.

5.3 Discussion of Results

The results of the testing indicate the following:

1) Hveem Stability. All materials except PlusRide have "in-place" stability values within the expected range for cores. PlusRide has a stability value of 2. Despite this low value, there is no evidence of rutting. This would indicate that the use of stability criteria may be inappropriate for evaluating the PlusRide mixes.

2) Modulus Values. At present, modulus values are not considered directly in the mix design or selection of additives. The tests on cores taken in 1985 and 1986 would indicate that most materials are increasing in stiffness (Fig. 5.7). The exceptions are the polymer-modified asphalt mixes.

3) Modulus Ratio. A minimum modulus ratio of 0.7 is required in mix designs to provide adequate resistance to pavement damage from freeze-thaw effects. The mix design modulus ratios (Table 3.9)

Table 5.4 - Modulus and Fatigue Data* (Lab Compacted Samples)

Mix Type	Unit Weight (pcf)	Modulus, psi (10^3)	Load Applications To Failure**
PlusRide	139.8	364	-
Arm-R-Shield	131.0	351	66,235
Fiber Pave	132.2	1061	20,768
BoniFibers	131.7	819	17,104
CA(P)-1	150.4	562	36,554
CA(P)-1 with Lime	149.8	436	8,943

* Samples compacted in September 1985 and tested in December 1985

** All tests run @ 73°F and 100 microstrain

Table 5.5 - Modulus and Fatigue Data (Field Cores, March 1986)

Summary of Test Data

Mix Type	Unit Weight (pcf)	Avg. Modulus* (1000 psi)	Load Applications to Failure*
PlusRide	137.4 137.8	272	15,942
Arm-R-Shield	141.4 141.9	194	4,171
Fiber Pave	144.3 144.0	400	6,708
BoniFibers	141.6 142.8	387	4,487
Class "C" with Pave Bond	144.0 143.9	475	5,347
Class "C" with Lime and Pave Bond	145.3 144.6	506	6,052
Control with Lime	147.3 147.5	511	4,986
Control	144.5 145.3	457	7,094
CA(P)-1	148.2 148.5	284	21,187
CA(P)-1 with Lime	144.4 144.4	298	37,375

* @ 73°F and 200 microstrain

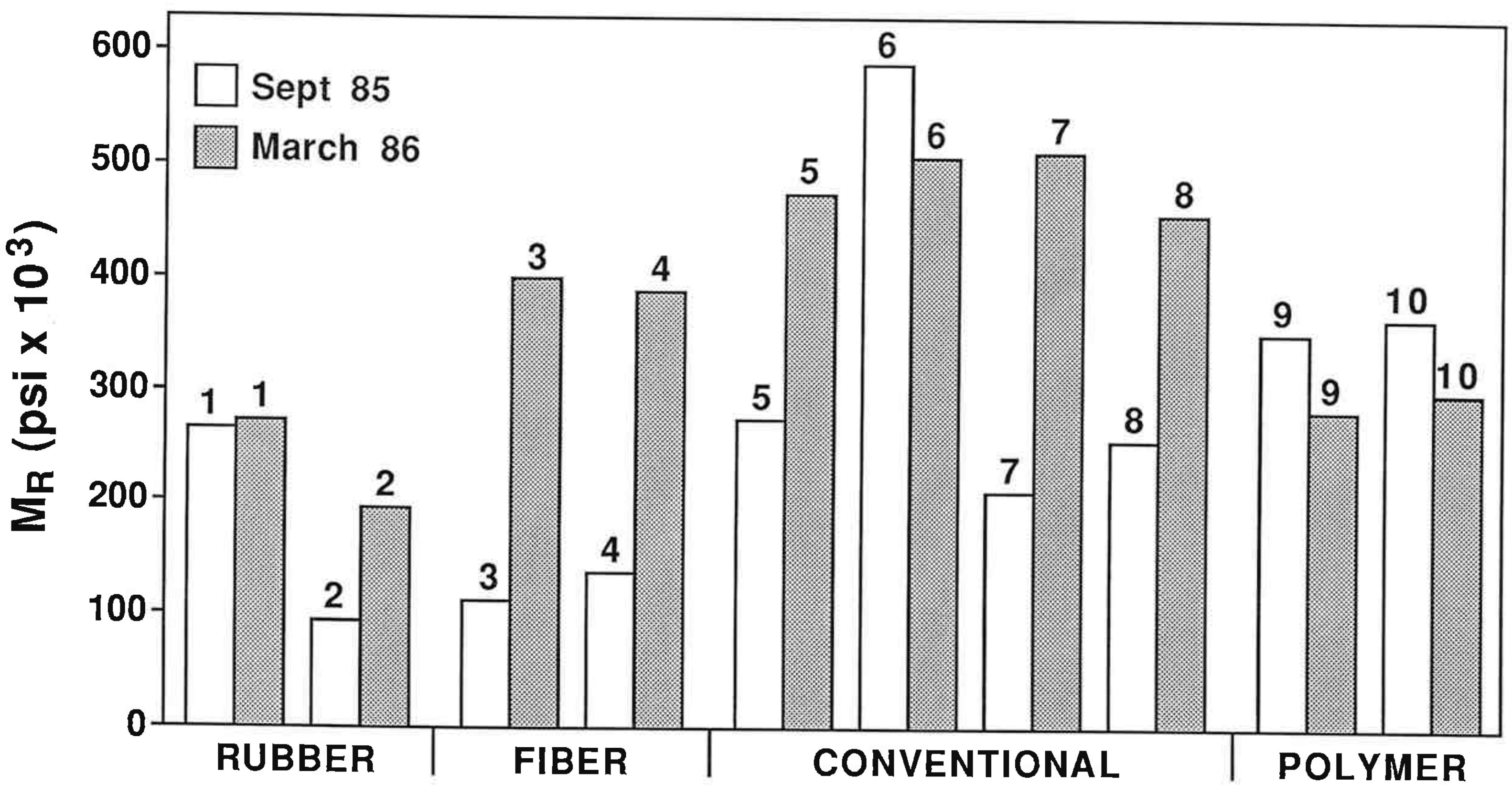


Figure 5.7 - Variation in Asphalt Concrete Stiffness with Time

indicate satisfactory freeze-thaw resistance for all mixes with lime-treated aggregate, Pave Bond, and BoniFibers.

4) Fatigue Results. The fatigue results on the cores clearly indicate the polymer-modified mixes and the PlusRide mix to be more resistant to cracking (Fig. 5.8). The significance of the testing is that all of the other mixes have fatigue properties comparable to those on conventional mixes. The design of a durable flexible pavement requires high level fatigue properties along with adequate resistance to freeze-thaw effects.

5) The Hveem stability of laboratory compacted box samples were all greater than 30 except for the PlusRide mix with values of 8 and 5.

6) The index of retained strength (IRS) of all mixes were greater than the 75% minimum, except for PlusRide with values of 64 and 82.

7) The modulus ratios (after freeze-thaw conditioning) were all greater than the 0.70 min except for PlusRide with values of 0.67 and 0.73.

5.4 Future Test Schedule

Additional cores are scheduled to be taken during September of 1986, 1987, and 1988. These results are expected to provide an indication of the change in mix properties/features over time.

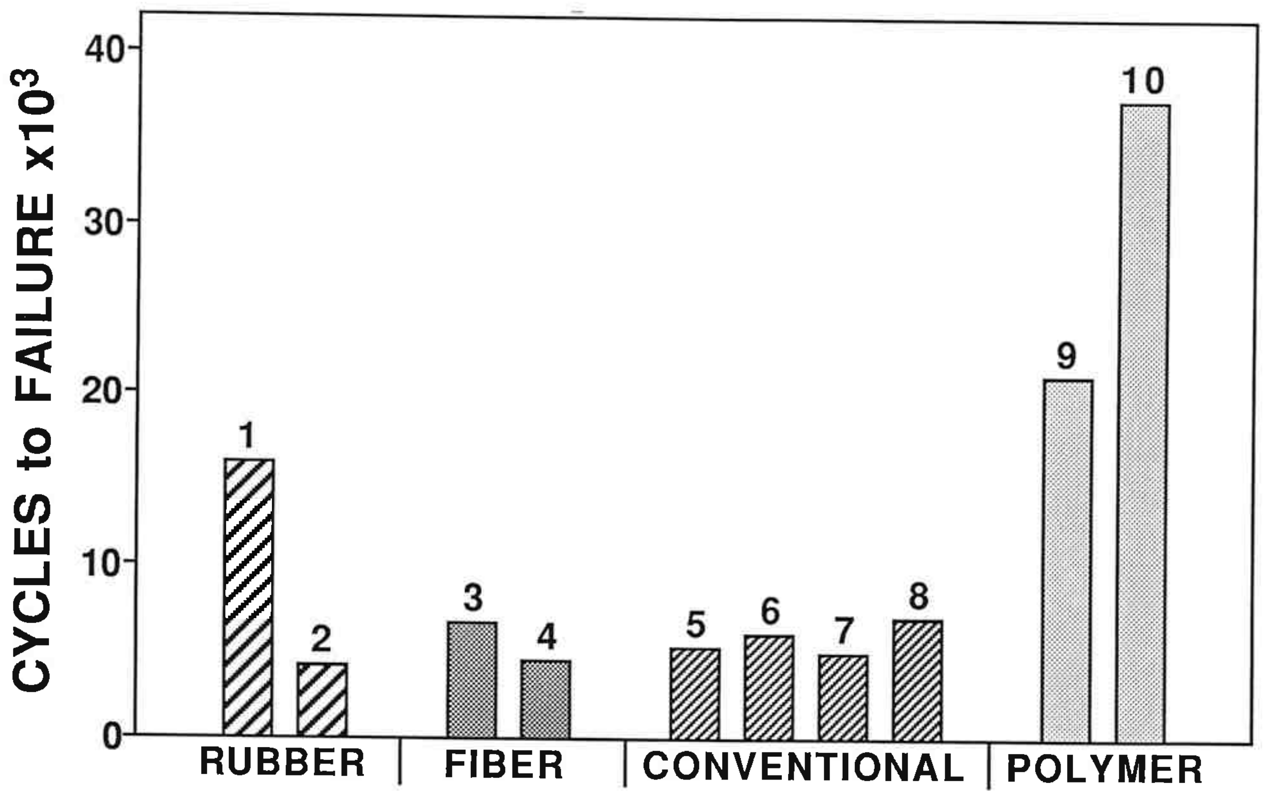


Figure 5.8 - Fatigue Test @ 73°F and 200 microstrain, March 1986 Cores

6.0 INITIAL PERFORMANCE EVALUATION

This chapter summarizes the results of a performance evaluation conducted shortly after construction and describes future plans for evaluation.

6.1 1985 Survey

During September and October 1985, the test road was evaluated for:

1) pavement condition,
2) surface deflection,
3) skid resistance, and
4) ride.

The pavement surface within the limits of the project and within the limits of the test site is in very good condition. Within the limits of the test sites, only one very small crack and no significant rutting were observed. Figures 6.1 through 6.12 are photos of the condition of the pavement in October, 1985.

Table 6.1 summarizes the results of cores taken after construction, while Tables 6.2 and 6.3 summarize the results of deflection measurements, skid, and ride tests.

6.2 Discussion of Results

The results generally indicate the following:

1) The average deflection of the before condition (May, 1985) varied considerably between sections (Fig. 6.13).
2) The average deflections of the after condition (September, 1985) are fairly uniform with most values ranging between .015 to .021 in.
3) The reduction in deflection generally ranged between 50 and 70%.

4) The skid numbers for all sections are considered to be good and were about the same, the exception being the PlusRide section which exhibited the lowest value.

5) The ride numbers for all sections were about the same and generally on the same order as those for conventional state projects.

In general, the results would indicate little variation in structural adequacy, skid, or ride between the various sections.

6.3 Future Schedule

Additional surveys for condition, deflection, skid, and ride will be conducted annually (each September).

Figure 6.1 - Typical Pavement Condition of PlusRide after Overlay, MP 158.21, Looking South

Figure 6.2 - Typical Pavement Condition of Arm-R-Shield after Overlay, MP 158.62, Looking South

Figure 6.3 - Close-up of PlusRide, MP 158.21, SB

Figure 6.4 - Close-up of Arm-R-Shield, MP 158.62, SB

Figure 6.5 - Typical Pavement Condition of Fiber Pave (right) and BoniFibers (left), MP 159.62, Looking South

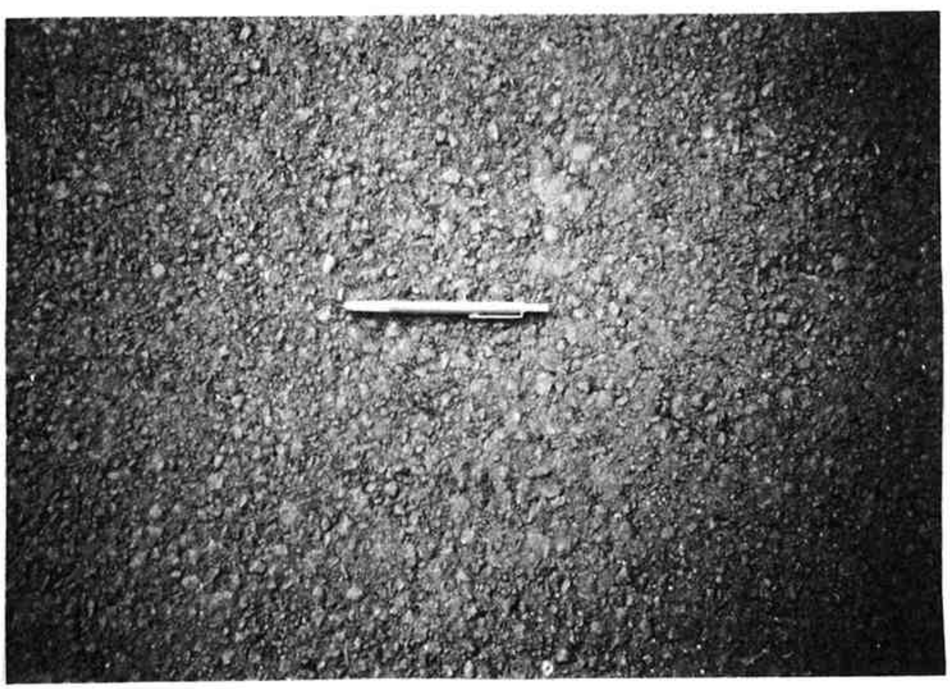


Figure 6.6 - Close-up of Fiber Pave, MP 150.62

Figure 6.7 - Typical Pavement Condition of Control with Lime (right) and Class "C" with Pave Bond (left), MP 160.21

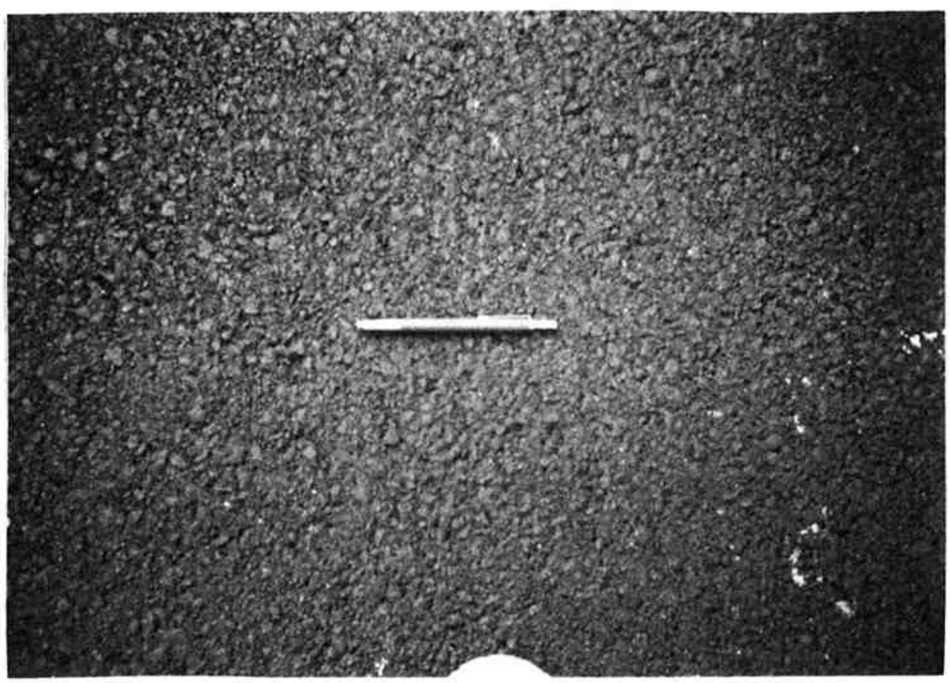


Figure 6.8 - Close-up of Class "C" with Pave Bond, MP 160.21, NB

Figure 6.9 - Typical Pavement Condition of Control (right) and Class "C" with Lime and Pave Bond (left), MP 161.02

Figure 6.10 - Close-up of Control, MP 161.02

Figure 6.11 - Typical Pavement Condition of CA(P)-1,
MP 161.46, Looking South

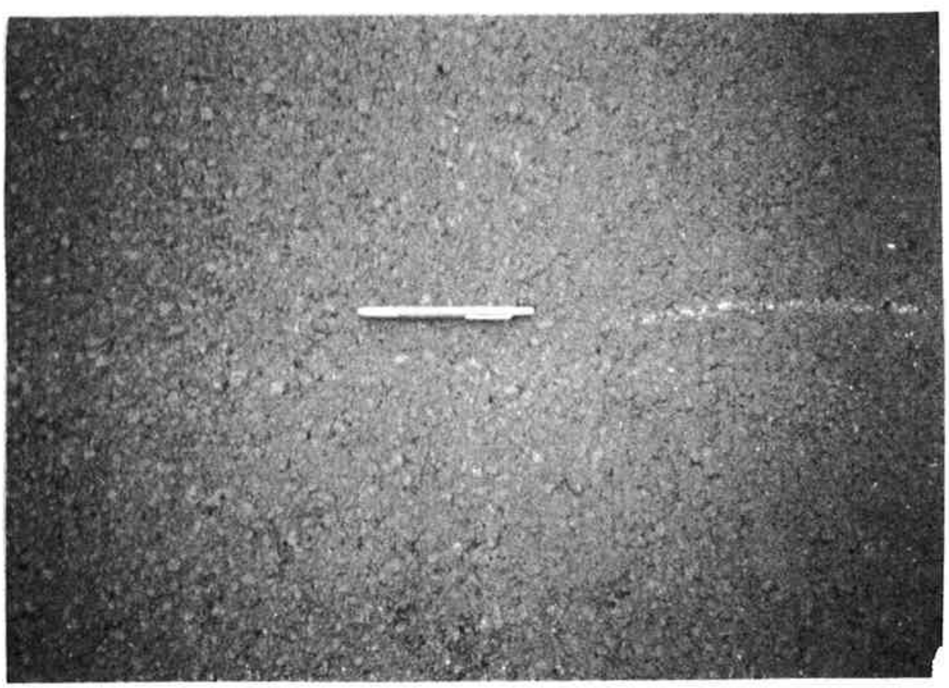


Figure 6.12 - Close-up of CA(P)-1 with Lime, MP 161.46

Table 6.1 - Results of Cores Taken after Construction

	Thickness, inches				
Additive in Wearing Course	Experimental Feature	ACP (base)	ACP (original)	Oil Mat (original)	Total
PlusRide	1-3/4	2-1/2	4-1/2	2	10.75
Arm-R-Shield	1-1/2	2-1/2	4-1/2	2-1/2	11.00
Fiber Pave	1-1/2	2-3/4	5-1/2	-	8.00
BoniFibers	1-1/2	2-3/4	5-1/2	-	9.75
Class "C" with Pave Bond	1-1/2	3-1/2	5-1/2	-	10.50
Control with Lime	1-1/2	2-1/2	6	-	10.00
Control	2	4-1/2	4-1/2	1	11.00
CA(P)-1	1-3/4	2	6-3/4	-	10.50
CA(P)-1 with Lime	1-1/2	3-1/2	6	-	11.00

Table 6.2 - Summary of Post-Construction Dynaflect Measurements, September 1985 (corrected to 70°F)

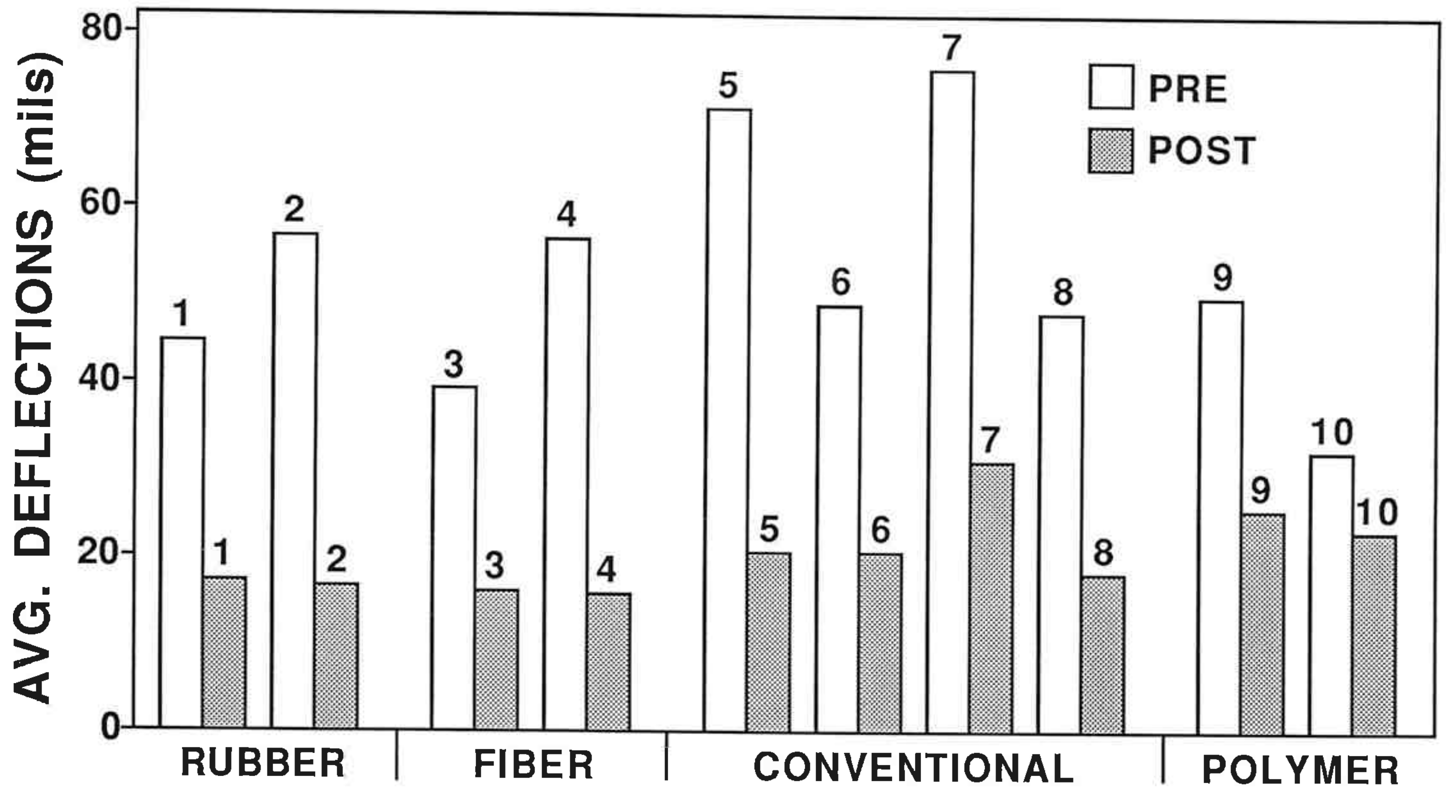
Direction	Product Area	Dynaflect Data (in mils) Average*	Dynaflect Data (in mils) S.D.	Equivalent Benkleman Beam (in mils) Average**	Equivalent Benkleman Beam (in mils) S.D.
SB	PlusRide	0.78	0.16	16.2	3.9
NB	PlusRide	0.86	0.90	18.2	2.3
SB	Arm-R-Shield	0.82	0.11	17.2	2.8
NB	Arm-R-Shield	0.67	0.10	15.7	3.3
SB	Fiber Pave	0.77	0.09	15.9	2.3
NB	BoniFibers	0.76	0.13	15.7	3.3
SB	Control with Lime	1.33	0.14	31.1	4.0
NB	Class "C" with Pave Bond	0.95	0.11	20.6	2.9
SB	Control	0.86	0.10	18.1	2.4
NB	Class "C" with Lime and Pave Bond	0.95	0.11	20.6	2.9
SB	CA(P)-1	1.13	0.14	25.4	3.9
NB	CA(P)-1 with Lime	1.04	0.27	23.1	7.2

* Average of 11 readings by sensor No. 1

** Dynaflect data converted to Benkleman Beam equivalents using equation 2.1

Table 6.3 - Summary of Skid Tests and Ride Tests, October 1985

Direction	Product Area	Skid Tests SN 40 Average	Mays Meter Ride Tests in/.1 mi/mi Average
SB	PlusRide	44.3	34.3
NB	PlusRide	46.9	34.8
SB	Arm-R-Shield	48.4	33.7
NB	Arm-R-Shield	51.1	39.1
SB	Fiber Pave	52.1	34.9
NB	BoniFibers	52.9	26.4
SB	Control with Lime	53.3	32.4
NB	Class "C" with Pave Bond	55.6	35.0
SB	Control	56.7	30.0
NB	Class "C" with Lime and Pave Bond	57.3	23.6
SB	CA(P)-1	52.9	28.4
NB	CA(P)-1 with Lime	56.9	35.5



*Dynaflect Converted to Benkleman Beam at 70° F

Figure 6.13 - Pre- and Post-construction Deflections*

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Based on the results of this design and construction report, the following conclusions appear warranted:

1) the test site appears to be an excellent choice to evaluate the effects of asphalt additives to resist cracking and stripping because of prior performance problems in the vicinity,
2) mix design techniques used by some additive suppliers are not well defined or documented,
3) mix design results generated by Oregon DOT agree reasonably well with those recommended by the additive suppliers,
4) there were no major problems with the construction of the different mixes,
5) there are significant differences in the mix properties for the different materials, and
6) the performance of all the test sections as of March, 1986 is good. There is no cracking, rutting or extensive raveling of the pavement sections. However, pavement failures have been experienced in this general area within two to four years after construction.

7.2 Recommendations

The following recommendations are warranted as a result of the findings:

1) continue to monitor each of the sections for changes in performance. This should be done twice a year (spring, fall),
2) continue to core the project to detect changes in mix properties. This should be done at least one a year, beginning fall 1986.

3) use standard DOT mix design procedures when using the additives evaluated in this project.

8.0 REFERENCES

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3. George, Tony, "Development of Temperature Correction Factors for Dynaflect," Oregon Department of Transportation, 1985.

4. Majidzadeh, K., and Kumar, V., "Manual of Operation and Use of Dynaflect for Pavement Evaluation," FHWA/OH-83-004, Federal Highway Administration, October 1983.

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6. Oregon State Highway Division, "Flexible Pavement Design Procedures," 1985.

7. Smith, Roger and Darter Michael, "Highway Pavement Distress Identification Manual for Highway Condition and Quality of Highway Construction Survey," DOT-FH-11-9175, March 1979, USDOT/FHWA.

8. Sullivan, Jack, et al., "Mix Design Procedures and Guidelines for Asphalt Concrete, Cement Treated Base and Portland Cement Concrete," Oregon Department of Transportation, February 1986.

9. USDA Forest Service, Willamette National Forest, Region 6, "Test Procedures for Repeated Load Diametral and Triaxial Equipment," July 1984.

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APPENDIX A

Deflection Measurements and Their Evaluation

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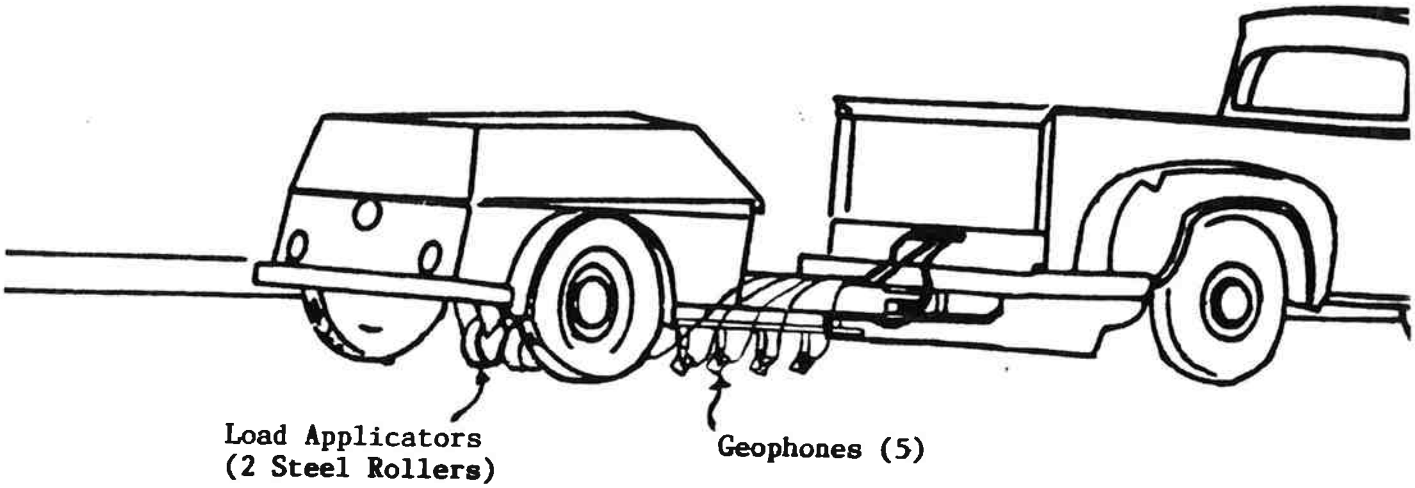
Deflection Measurements and Their Evaluation

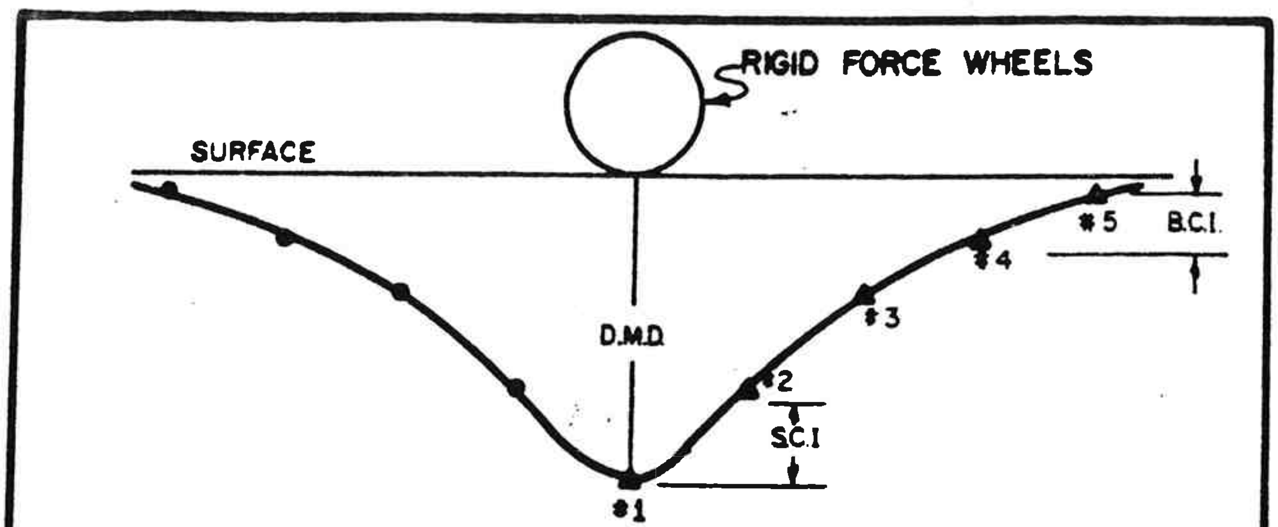
A schematic of the Dynaflect system is shown in Figure A.1(a). The main component of the system is the trailer unit. The two steel wheels are lowered onto the pavement, lifting the trailer off the ground. Unbalanced flywheels within the trailer unit create a dynamic peak-to-peak load of 1,000 pounds which is applied to the pavement through the wheels. Five geophones (G1-G5), spaced 1-ft. apart, measure the shape of the of the deflected pavement surface. A typical deflection basin is shown in Figure A.1(b). The actual shape of each basin is dependent upon the pavement and subgrade conditions.

Table A.1 summarizes the Dynaflect data collected at the test sites, and the corresponding pavement subgrade evaluations. The criteria used for the condition evaluations are described below. First, however, a brief description of the test procedure is presented:

1) Eleven tests were taken within a 500-ft. distance. The average of these readings is given in Table A.1. Because the pavement deflection is also temperature-dependent, it was necessary to correct all geophone readings to a standard temperature using the factors given in Table A.2. Therefore, the columns titled, "Avg CG1" is the average of the 11 temperature-corrected geophone-1 readings, for a 500-ft. test section.
2) Testing began at Mile Post (MP) 158.200, in the northbound lane. Eleven readings were taken at 50-ft. intervals. At the end of the first 500-ft. section, MP 158.295, the truck turned and repeated this procedure in the northbound lane, ending at MP 158.200. This was done for all 10 product zones, first in May 1985, before the overlay application, and again in September 1985, after the application.



(a) Dynamic Deflection Determination System (Dynaflect)



D.M.D. = DYNAFLECT MAXIMUM DEFLECTION (Numerical value of sensor No. 1).

S.C.I. = SURFACE CURVATURE INDEX (Numerical difference of sensor No. 1 and No. 2).

B.C.I. = BASE CURVATURE INDEX (Numerical difference of sensor No. 4 and No. 5).

SPR. = SPREADABILITY = $\Sigma Gn/5 \times G1$ (n=5)

(b) Deflection Basin Parameters

Figure A.1 - Dyanflect System and Basin Parameters

Table A.1 - Summary of Deflection Data Collected at Each Site
(May and November, 1985)

RESEARCH SECTION PAVEMENT DEFLECTION REPORT
SUMMARY OF DYNAFLECT DATA COLLECTED ON HIGHWAY 4
FROM MILE POINT 158.2 TO MILE POINT 161.545
INCLUDING SUMMARY OF PAVEMENT AND SUBGRADE CONDITION 03/06/86

CG1 = GEOPHONE 1, ETC. ALL READINGS ARE IN MILS (THOUSANDTHS INCH)
CSCI = SURFACE CURVATURE INDEX (CG1-CG2)
CBCI = BASE CURAVATURE INDEX (CG4-CG5)
CSPR = SPREADABILITY (CG1+CG2+CG3+CG4+CG5)/(5*CG1)

BEG MILE PT	YR	MO	DOT	PAV TEMP	AVG CG1	AVG CG2	AVG CG3	AVG CG4	AVG CG5	AVG CSCI	AVG CBCI	AVG CSPR	GT 6 PVMT COND	GT 6 SBGR COND	LE 6 SURF COND	LE 6 SBGR COND
158.200	85	5	SB	48	1.51	1.00	.55	.38	.28	.50	.09	.50	WEAK	GOOD		
		9	SB	70	.78	.64	.47	.35	.26	.13	.08	.64	OK	GOOD		
158.295	85	5	NB	48	2.00	1.24	.61	.42	.31	.75	.11	.46	WEAK	POOR		
		9	NB	70	.86	.73	.51	.37	.28	.13	.09	.64	OK	GOOD		
158.650	85	5	SB	46	2.18	1.32	.62	.39	.26	.86	.13	.43	WEAK	GOOD		
		9	SB	75	.82	.69	.47	.33	.23	.13	.10	.62	OK	GOOD		
158.745	85	5	NB	46	2.02	1.29	.66	.41	.27	.73	.13	.46	WEAK	GOOD		
		9	NB	75	.67	.58	.42	.32	.23	.08	.08	.67	OK	GOOD		
159.650	85	5	SB	45	1.59	1.12	.67	.43	.26	.46	.16	.51			WEAK	GOOD
		9	SB	86	.77	.68	.52	.36	.24	.08	.12	.67	OK	GOOD		
159.745	85	5	NB	45	2.06	1.41	.71	.41	.23	.65	.17	.47			WEAK	GOOD
		9	NB	86	.76	.68	.53	.37	.24	.07	.12	.68	OK	GOOD		
160.200	85	5	SB	45	2.63	1.83	1.03	.62	.37	.80	.25	.49			WEAK	POOR
		9	SB	75	1.33	1.11	.80	.53	.34	.22	.19	.62	OK	POOR		
160.295	85	5	NB	45	2.50	1.83	1.01	.61	.36	.67	.25	.51			WEAK	POOR
		9	NB	75	.95	.85	.68	.49	.34	.09	.15	.69	OK	POOR		
161.000	85	5	SB	45	1.87	1.24	.70	.42	.24	.62	.17	.48			WEAK	GOOD
		9	SB	83	.85	.73	.56	.37	.23	.12	.13	.64	OK	GOOD		
161.095	85	5	NB	46	1.89	1.26	.70	.42	.25	.63	.17	.48			WEAK	GOOD
		9	NB	83	.79	.69	.53	.35	.23	.09	.12	.66	OK	GOOD		
161.450	85	5	SB	56	1.92	1.47	.97	.65	.44	.44	.21	.57			WEAK	POOR
		9	SB	83	1.13	1.02	.83	.60	.42	.10	.18	.71	OK	POOR		
161.545	85	5	NB	56	1.37	1.11	.79	.57	.40	.26	.16	.62			OK	POOR
		9	NB	83	1.04	.97	.79	.58	.40	.07	.18	.74	OK	POOR		

ALL DEFLECTIONS ADJUSTED TO A STANDARD PAVEMENT TEMPERATURE
OF 70 DEGREES FAHRNHEIT

Table A.2 - Summary of Temperature Correction Factors (George, 1985)

	Pavement Thickness, in.			
Temp°F	2	4	6	10
90	0.7526	0.8244	0.8916	0.8980
85	0.8144	0.8683	0.9187	0.9235
80	0.8763	0.9122	0.9458	0.9490
75	0.9382	0.9561	0.9729	0.9745
70	1.0000	1.0000	1.0000	1.0000
65	1.0618	1.0439	1.0271	1.0255
60	1.1237	1.0878	1.0542	1.0510
55	1.1856	1.1317	1.0813	1.0765
50	1.2474	1.1756	1.1084	1.1020

Correction factor = 1 - (*Temp - 70°F)K

K = 0.01237 (T=2)

= 0.00878 (T=4)

= 0.00542 (T=4)

= 0.00510 (T=10)

* Pavement temperature

Another set of data is to be obtained in the summer of 1986, after one year of overlay service.

3) The computer program which generated the summary (Table A.1) uses a computerized flow chart to determine the pavement and subgrade condition, similar to those seen in Figures A.2 and A.3. Figure A.2 is used with pavements 4- to 6-in. thick (t) and Figure A.3 for pavements greater than 6-in. (T). The term "pavement structure" refers to the "bound" upper surface layers. The "unbound" base and subbase then become the "support layers" or "subgrade."

4) Using the geophone designation and definition of SCI, BCI, and SPR shown in Figure A.1, the following generalities can be made. A high G1 reading (greater than 0.7 for T, and greater than 1.5 for t) indicates a weak pavement structure. A high G5 reading (greater than 0.3 for T and t) indicates a poor subgrade. A low spreadability factor, SPR (less than 0.6), can mean a weak pavement layer for thick structures. The SPR has little significance for pavements less than 6 in. For thick pavements, a high G5 (greater than 0.3) <u>and</u> low SPR (less than .06) indicates both the support and the pavement layers are weak. In flexible pavements (generally asphaltic concrete), SCI values of 0.25 to 0.35 indicates the pavement structure is within a transition zone from satisfactory to poor performance. BCI values of greater than 0.15 generally correspond to support conditions of less than 1,000 psi and should be treated with concern.

Cracks in the pavement decrease the effective stiffness. This results in greater deflections and lower spreadability factors. In a practical sense, a G1 reading of greater than 1.0, and low spreadability factors, indicates greater vertical stresses in the unbound base and subgrade layers, and/or the

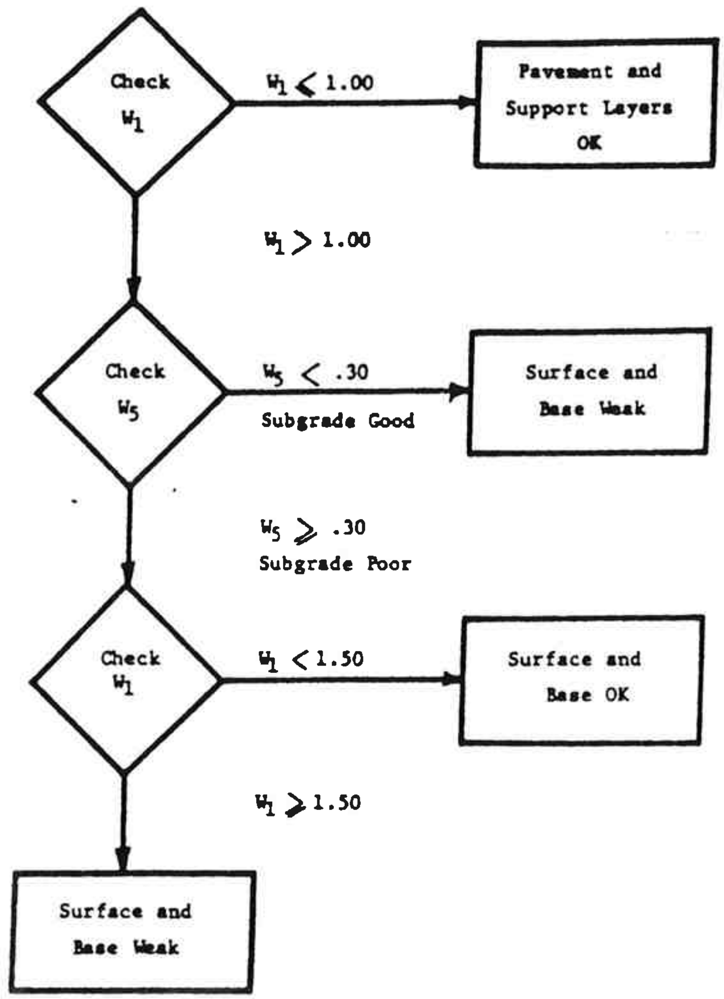


Figure A.2 - Evaluation of Thin Flexible Pavements (t = 4-6-in) from Dyanflect Measurements (Majidzadeh, et al., 1983)

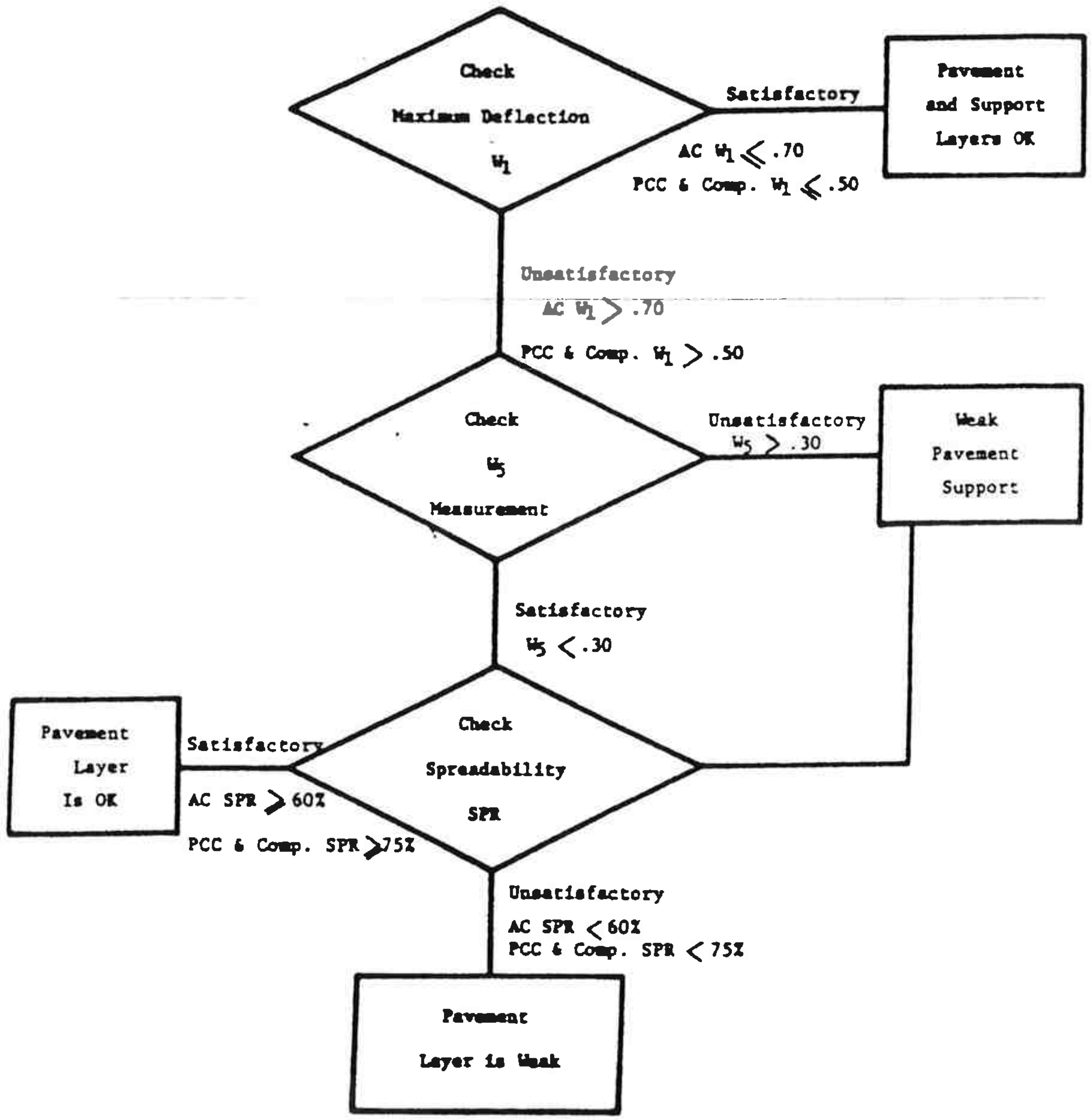


Figure A.3 - Rigid and Flexible (T 6-in) Pavement Evaluation from Dynaflect Measurements, (Majidzadeh, et al., 1983) combined pavement and support conditions are in a state of transition from satisfactory to unsatisfactory conditions. These "generalities" correspond closely to actual data obtained for this project.

Other items worth noting are the column pairs labeled "GT6" and "LE6" shown in Table A.1. Since the evaluation criteria are related to pavement depth, the "bound pavement" depth actually increases with the addition of the overlay. This means a pavement structure less than 6-in. in May could be (and actually was in most cases), greater than 6-in. in September, after the overlay.

The G5 readings obtained for the test comprise a narrow range of values, except for a definite "jump" after MP 161.450. This relates well to the existing subgrade conditions. A large part of the highway lies on a volcanic cinder base, providing "good" subgrade conditions. However, a substantial fill lies below the test section MP 161.450 - MP 161.545. This explains the rise in CG5 readings to values of 0.4 mils and greater. Photographs of the roadway show MP 162.000 lies in a marshy, meadow area. Corresponding G5 readings reach nearly 0.50 mils, and maximum deflections, CG1 readings, are over 3.0 mils. This indicates a very weak subgrade.

These are only a few of the observations which can be made from these data. The Dynaflect system provides an excellent record of comparison for past and present roadway conditions.