MONITORING THE USE OF IMPERVIOUS FABRICS, GEOMEMBRANES, IN THE CONTROL OF EXPANSIVE SOILS

By: Malcolm L. Steinberg

Test Results Through August 31, 1985

Report 187-12

District 15

Texas State Department of Highways
and Public Transportation

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16. Abstract

Swelling soils cause $10 billion in damages in the United States. An estimated 50% of these damages occur to highways. The use of a relatively impervious fabric, geomembranes, was viewed as a possible way of reducing these damages. Geomembranes would hopefully reduce moisture variation in the subgrade underneath the pavement. This would lead to a reduction in the swell of the subgrade and reduce pavement distortion.

These fabrics have been used on five projects in the San Antonio area of District 15, with work on two more projects scheduled to start shortly. Monitoring that began on the first project tests in 1979 is continuing and reported.

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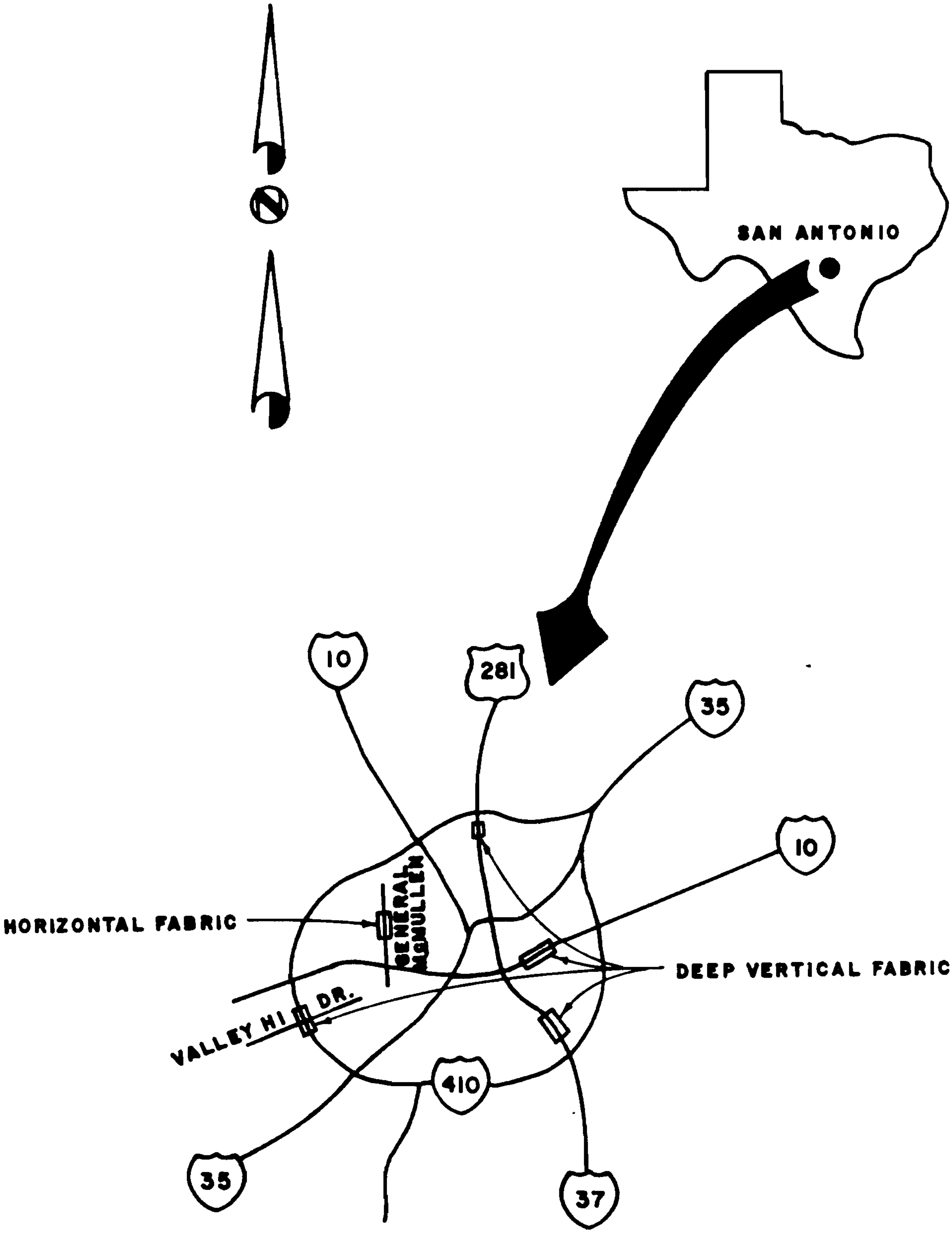
EXECUTIVE SUMMARY

Expansive soils cause in excess of $10 billion damages annually in the United States. Half these damages occur to our nation's highways and streets. These soils, in Texas, extend from the Red River to the Rio Grande and from El Paso to East Texas. Five projects in District 15's San Antonio area, using geomembranes, impervious fabrics, to control these expansive soils are studied. To date, these geomembranes are generally providing a smoother riding roadway than the ones without the fabrics over these destructive subgrades.


SAN ANTONIO
10
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HORIZONTAL FABRIC
GENERAL McMULLEN
DEEP VERTICAL FABRIC
VALLEY HI DR.
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PURPOSE

Swelling soils cause $10 billion in damages in the United States. An estimated 50% of these damages occur to highways. The use of a relatively impervious fabric, geomembranes, was viewed as a possible way of reducing these damages. Geomembranes would hopefully reduce moisture variation in the subgrade underneath the pavement. This would lead to a reduction in the swell of the subgrade and reduce pavement distortion.

These fabrics have been used on five projects in the San Antonio area of District 15, with work on two more projects scheduled to start shortly. Monitoring that began on the first project tests in 1979 is continuing and reported.

PROCEDURES

General McMullen Drive, an Urban Systems Project which began in 1976, represented the first use of a relatively impervious fabric, a geomembrane, in the San Antonio area to control the destructive movements of expansive clays. The fabric was used horizontally and unrolled on the subgrade (Figure 1).

The fabric was a Typar 3353 with some 3153 used along an edge and provided free of charge by the manufacturer, the DuPONT Company. Enough of the geomembrane was provided to cover the subgrade from crown to crown for a length of 600 feet. Adjacent 600 feet unprotected sections were used to provide control. A variety of tests were used to measure the effectiveness of the fabric. Dynaflect testing had taken place prior to construction as did determination of Atterburg Limits, as well as potential vertical rise. The fabric was placed over the subgrade in the area of the greatest potential rise (Figure 2). The contractor built this work half section at a time. The existing pavement was removed for the half section, and the subgrade was prepared. The fabric was unrolled by hand by maintenance personnnel since it was not part of the contract. Following completion of construction, the testing included profilometer, computer reduced to serviceability indeces, photologging and again this year, dynaflecting (1).

Placement procedures and other details have been presented in previous publications. To avoid duplication, this information would generally not be repeated. The reports that present the data in detail are included in the attached bibliography.

I.H. 410, in the vicinity of the Valley Hi Drive undercrossing, was the first section in District 15 where the deep vertical fabric moisture barrier was used (2). In 1978, a one-half mile long section of the northbound lane had the fabric placed 8 ft. deep along the inside and outside shoulders (Figure 3). The existing median ditch remained and the adjacent southbound lane, unprotected by the fabric, was used as a control section. The contractor excavated the trench for the fabric using a backhoe. Some sliding occurred initially. A sliding shoring was developed that held the roll of the Typar T-063 material vertically as well as restraining the movement of the subgrade from filling the excavated trench prior to the placement of the fabric. In this section, moisture sensors, profilometer and photolog testing was conducted.

I.H. 37 from S. Hackberry Street to Pecan Valley Drive, in southeast San Antonio, was in a 2 mile long cut section (Figure 4). A minimum of $50,000 a year had been spent to level-up the concrete pavement distorted by the expansive soils (3). On this rehabilitation project, and which began in 1980, the median ditch was removed, positive drainage was established across the pavement, a rubber asphalt seal was applied to the surface which was leveled-up, a deep vertical fabric moisture barrier was placed along the outside shoulders of both the north and southbound lane and a final pavement finish course was placed (Figure 5). On this contract, the excavation for the placement of 8 ft. depths of fabric was done with a trenching machine. Testing procedures included moisture sensors, profilometer and photologging.

U.S. 281, the southbound lane, just south of I.H. 410 and underpassing the Airport Boulevard entrance connection, exhibited considerable pavement distortion. The subgrade was an expansive clay. In the rehabilitation contract, awarded in 1983, the deep vertical fabric moisture barrier was placed 8 ft. deep along the inside and outside shoulders (Figure 6). A gradall was used to excavate the trench for the fabric placement. A seal coat, level-up and a pavement finish course completed the rehabilitation work (4). Testing to date involved the use of the profilometer and photologging. It is hoped that in the future, moisture sensors will be installed to determine the effectiveness of the fabric barrier reducing the moisture change in the subgrade. The adjacent northbound lane was used as a control.

I.H. 10, between Pine and Amanda Street on San Antonio's eastside, was another rehabilitation project where the deep vertical fabric moisture barrier was used in an effort to control the distortion caused by the expansive soil subgrade. In this project, where work began in November 1983, positive drainage was established across the east and westbound lanes. The fabric was placed along the outside shoulders of the lanes (as in Figure 5). A trenching machine was used to excavate the material. Testing to date has included the use of a profilometer and photologging. It is planned to install moisture sensors on this project also.

A contract was recently let on I.H. 10 from Ackerman Road to Cibolo Creek. Approximately 10 miles of vertical fabric will be placed on this project. Work has not begun. It is also planned to use a fabric on a section of F.M. 725 between I.H. 10 and F.M. 78 in Guadalupe County near Seguin.

OBSERVATIONS

GENERAL McMULLEN DRIVE. Serviceability Indices were developed from the profilometer runs on General McMullen Drive. The indices rate the smoothest riding surface as a 5 with descending values indicating increasing roughness. Usually the fabric protected section, though it was placed over the most active subgrade, provided the smoother riding surface as indicated by the higher serviceability index. With the exception of the first profilometer runs in July 1981, when in 5 out of 6 observations the fabric protected section had the highest index reading, the usual pattern has been that in 4 out of the 6 cases, the pavement section above the fabric protected subgrade had the highest serviceability index (Table 1). Though the usual pattern of decreasing serviceability indices take place with the passage of time, in several cases recent serviceability indices were higher than those recorded initially. This has taken place in three of the March 1985 readings in the northbound lane, south control, on the inside lane, on the south control of the outside lane, on the fabric section of the southbound lane's center lane and on the southbound lanes inside south control. A visual inspection in the field indicated no repair work had been done in these sections. This raises the question of how the passage of four years allows for indications of a smoother riding surface.

However, the bottom line is that in the majority of cases, though the fabric was placed on the more active subgrade, according to potential vertical rise measurements, fabric protected subgrade pavement has the smoother ride.

Dynaflect testing was conducted in August 1973 prior to construction, in January 1981, March 1982 and March 1985. A static tire loading test device is used. Five geophone readings are taken and a curve plotted. Stiffness coefficients, spreadability and maximum deflection are calculated. The stiffness coefficient separates subgrade values from the pavement's total section. The higher the number the greater the strength. The preconstruction subgrade values show a uniformity. In March 1982 the coated fabric protected section subgrade value was slightly lower than the adjacent ones. Pavement values for the coated fabric protected section appears to be slightly higher (Table 2). The January 1981 and March 1982 tests indicated the subgrade under the coated fabric protected section had greater deflection in five of six cases and was possibly weaker (Table 3). This may be related to its potential vertical rise (PVR), its greater expansive capabilities or the holding of moisture under the material. The 1985 test results have not yet been received.

The higher the Spreadability Value, the stiffer the pavement structure. In the January 1981 and March 1982 tests, the coated fabric sections showed the higher indices (Table 4). The higher average stiffness coefficients on the total coated fabric protected section's pavement structure and its higher spreadability indices are significant from its placement on the most active and weaker subgrade section. This substantiates the effectiveness of coated fabrics as a strengthener of total pavement structure reported in other studies (5,6,7).

Photologging indicated that the fabric protected section generally showed less cracking than the unprotected sections. In the first readings of January 1981, the fabric sections had no cracking in four of six lanes and in only one case did it have more than the fabric free section. In the last reported readings, tested in 1983, the fabric sections had less cracking than those without it (Table 5).

I.H. 410. The Serviceability Indices on this project were first taken in June 1978. The southbound lane, without the deep vertical fabric barrier provided the control section, the northbound lane had the barriers (Table 6). In all cases, the serviceability indices decreased with the passage of time during the six year period. In 1981, a rotomilling and level-up was done on both the north and southbound lanes. At that time, twice as much asphaltic concrete was used to level-up the southbound lane than the northbound lane. In all readings, the northbound lane with the deep vertical fabric moisture barrier provided a higher serviceability index indicating a smoother ride than the southbound lane without the fabric. Examining the drop in serviceability index, the southbound lane had a decrease of 1.10 on the outside lane and 1.40 on the inside lane. The drop in serviceability index on the northbound fabric protected lane was 0.51 and on the inside lane 0.50. Indications of a loss of serviceability are a half to third on the fabric protected lane than the control section without the fabric.

Moisture Sensors (MC 374) were placed inside and outside the test sections at depths of 2 through 8 feet. Readings reported in detail in an early report (2) initially indicated greater changes in the unprotected southbound lanes subgrade than under the northbound lane (Table 7). Drying, an increase of resistivity in the cells, appeared outside the fabric along the northbound lane. The irregularity and non-response in many cells led to abandonment of the readings.

Photologging began in August 1980. The northbound lanes had 0.07% and 0.01% frames showing cracking while the southbound lane had 0.28% and 0.21%. By 1983, cracking had increased in the northbound fabric protected lane to 0.19% and 0.37% while the southbound lane increased to 0.75% and 0.45% (Table 8). No results have been received yet from the 1985 photos. Results of the early photologging indicate significantly less pavement cracking in the fabric protected lanes.

I.H. 37. The Serviceability Indices were obtained in November 1979, by profilometer runs made prior to the rehabilitation on I.H 37 between S. Hackberry and Pecan Valley Drive. In each case the control sections indicated a serviceability index higher than the sections to be rehabilitated. They were all above 3.15 while the sections to be reconstructed varied from 2.79 to 2.92 (Table 9). Following the rehabilitation, the first profilometer run took place in December 1980. At that time the fabric protected sections provided the smoother ride as indicated by the higher serviceability indices. Their values were

3.68 and 3.81 as compared to the highest value of 3.30 on the northbound lanes, south control. With the passage of time the serviceability indeces tended to decrease. In August 1983, the northbound lanes, north control had asphalt level-up work between that time and March 1984. Its serviceability indices increased from 3.05 to 4.24, higher than the fabric sections. However, in the southbound lane fabric section, over the period from December 1980 to the latest noted reading, April 1985, there was a decrease of only .07 in the serviceability index and on the northbound lanes fabric section, a decrease of 0.11. This compares to a decrease in a four year period, from November 1979 to March 1984 of 0.26 in the southbound lane, north control and 0.97 in the south control. A decrease occurred in the northbound lanes, north control, prior to its rehabilitation work of 0.10 and in the south control a decrease to April 1985 of 0.64.

Since a new profilometer was used in the readings from March 1984 through the present, there does seem to be the possibility of some distortion in the readings. However, one can conclude that in comparing the fabric protected sections against the control sections prior to the rehabilitation work, the fabric sections were significantly smoother.

Photologging has revealed little surface cracking (Table 10). In this testing, two 1750 ft. sections in both the north and southbound lanes were used to represent the barriered lanes compared to the adjacent controls. The initial photologging in June 1981 indicated cracking only in the northbound lane pavement with 0.15% in the fabric protected section and 0.04% in the control. A year and a half later, only the northbound control pavement had any cracking at all and it was a minimal 0.07%.

Moisture Sensors used on I.H. 37 have proven slightly more reliable than those on Loop 410. Reported fully in a paper by Picornell, Lytton and Steinberg (3), these thermal block sensors were model MCS 6000 of Moisture Control Systems, Incorporated. Ten sensors were installed at four locations. Two of the locations were inside the fabric area and two outside. Periodic readings within a 90 week time period indicated high moisture levels from the time of initial measurement. Sensors placed outside the fabric showed substantial change in later readings. Sensors inside the fabric showed a uniform matrix potential over a two year period. Several of the sensors have become non-operational. The ones still functioning indicated that inside the geomembrane, the subgrade moisture remained relatively uniform while those outside showed more significant changes.

U.S. 281, Serviceability Indices were obtained on the southbound lane which received the geomembrane fabric protection with the adjacent northbound as a control section. Prior to the rehabilitation work on the southbound lane, its serviceability indices varied from 2.42 in its outside lane to 1.31 on the inside lane, compared to the northbound lanes, 2.90 and 2.72 (Table 11). In the first reading on the profilometers following the rehabilitation work, the southbound lanes serviceability indices ranged from 3.08 on the outside lane to 3.00 on the inside lane, compared to the northbound lanes 2.84, 2.91 and 2.55

from the outside to the inside. Though some variation again appears where the serviceability indices increase on the southbound lane, the April 1985 serviceability ranged from 3.18 to 3.00. No signs of addition work on that pavement were visible. Serviceability indices decreased very little on the fabric protected lanes, ranging from 0.04 to 0.08 between March 1984 and April 1985. The northbound control lanes had decreases ranging from 0.29 to 0.10. The southbound lane uniformly remains smoother riding than the adjacent northbound lane.

Profilometer reading taken in July 1985 have not been reported as of this date.

SUMMARY AND CONCLUSION

In analyzing all the results it seems apparent that the fabric protected lanes will provide a smoother riding surface than non-fabric protected ones in expansive soil areas.

Only further observation and testing will provide the answers to how long the fabric will hold up, how long the advantages will remain, and how long they will have to show significant changes to remain economically feasible.

An unresolved question is, how effective is the horizontal seal on the pavement in maintaining equal longevity. If this seal begins to permit the seepage of water through the surface, and if tests conducted by other researchers have indicated that considerable water does come through asphalt as well as Portland Cement concrete pavements, the question then becomes, if we are getting increased distortions, is it because of our inadequate surface seals?

The geomembranes provide a significant improvement in riding surface over expansive soils. Monitoring should continue to observe its economic feasibility.

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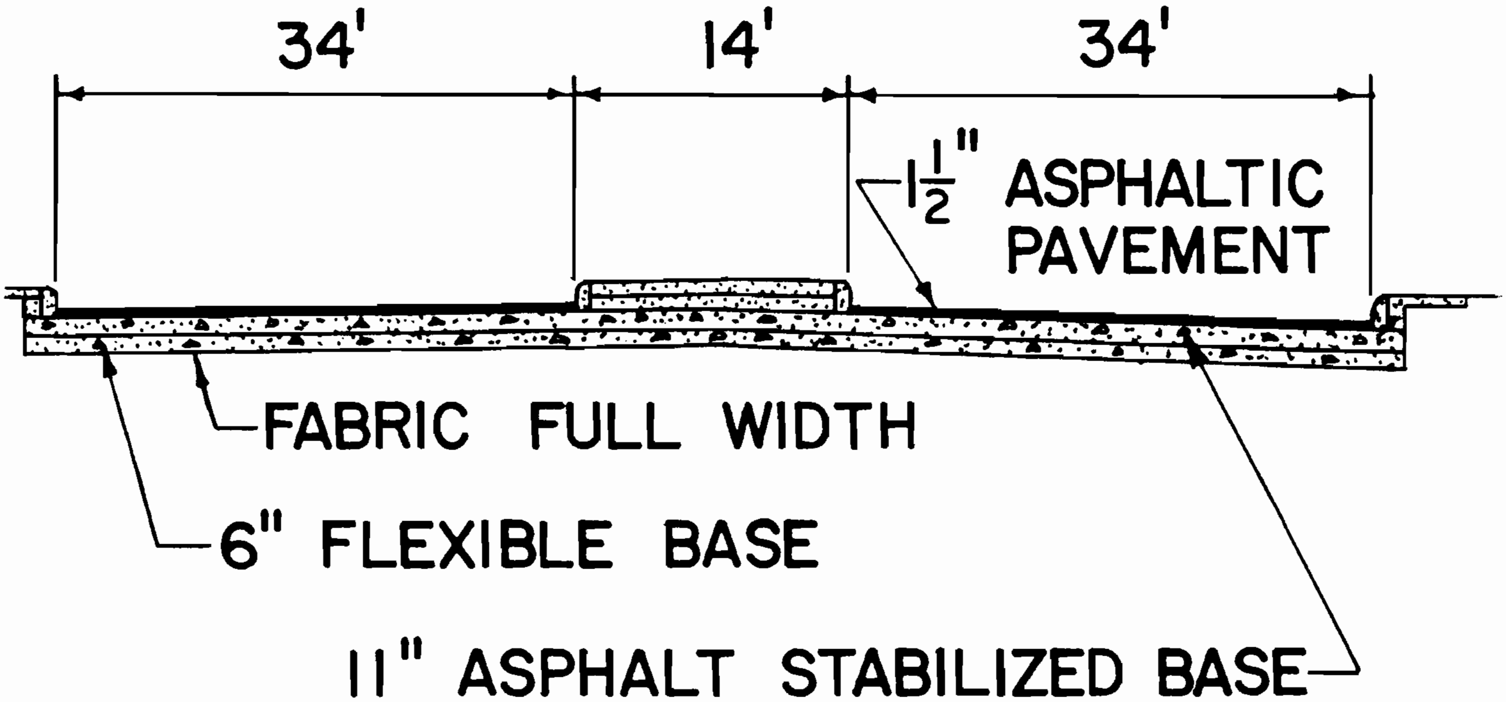
FIGURE 1



TYPICAL SECTION
GENERAL McMULLEN DR.

GENERAL McMULLEN DRIVE

CALCULATED POTENTIAL VERTICAL RISE

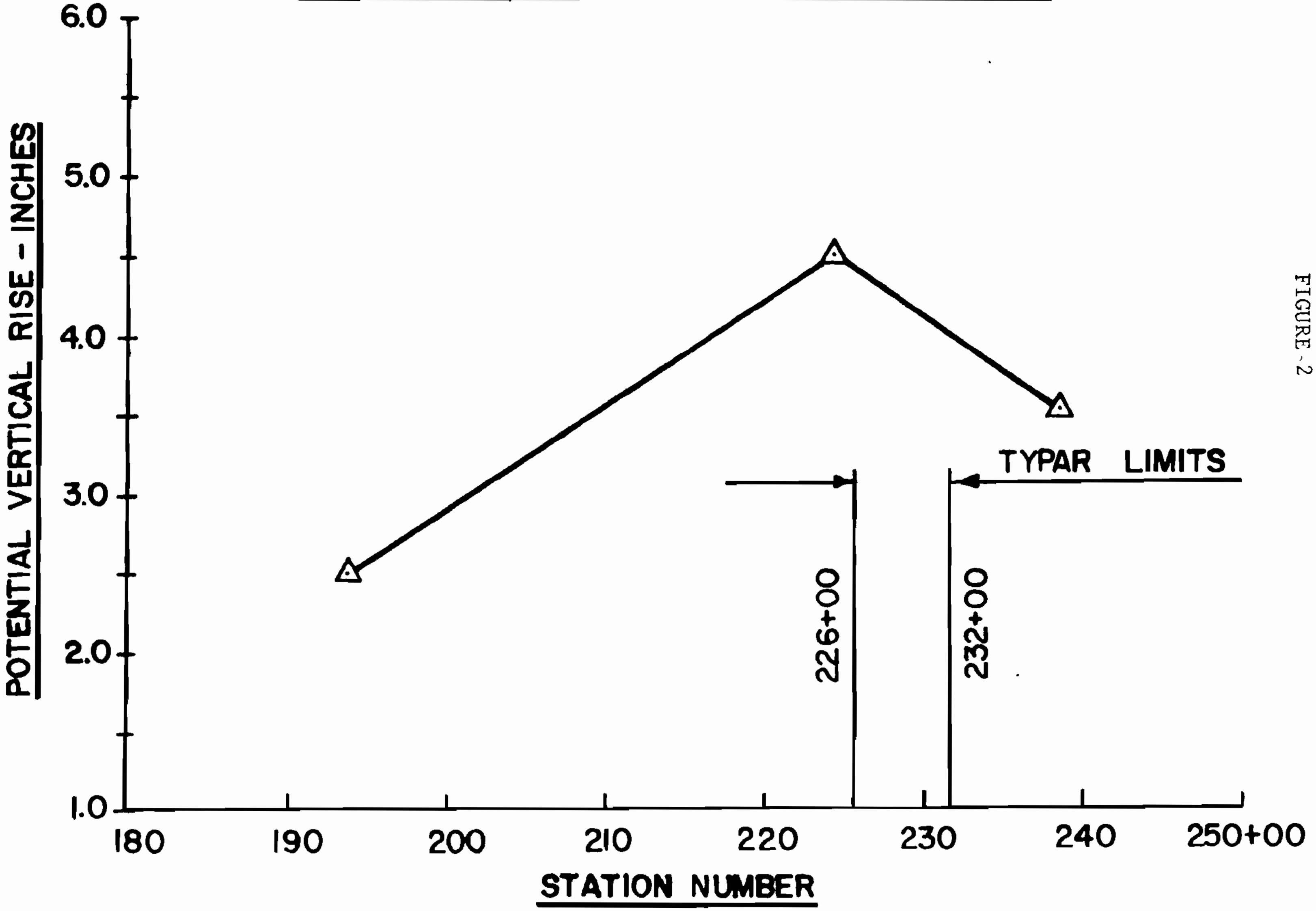
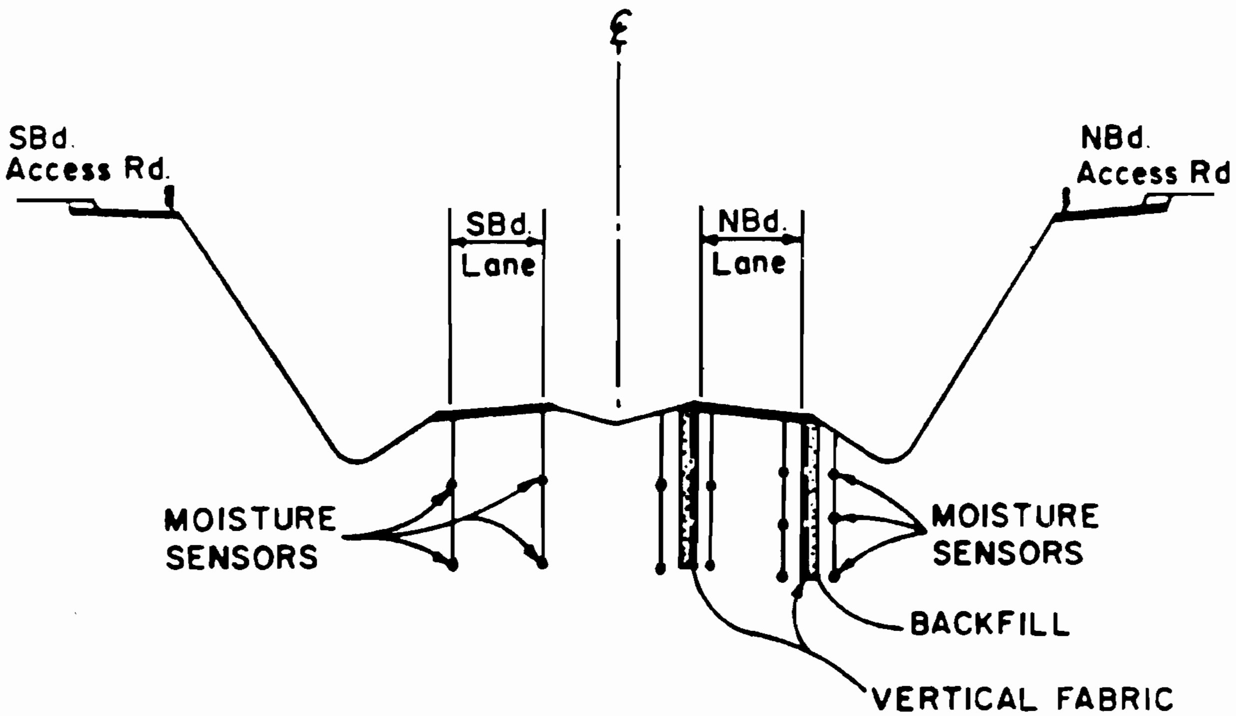


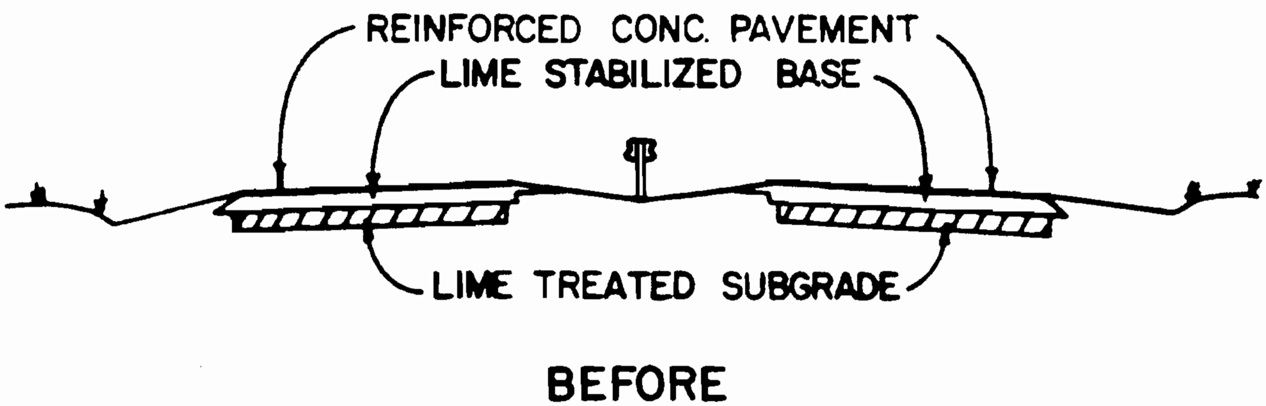
FIGURE 2

FIGURE 3



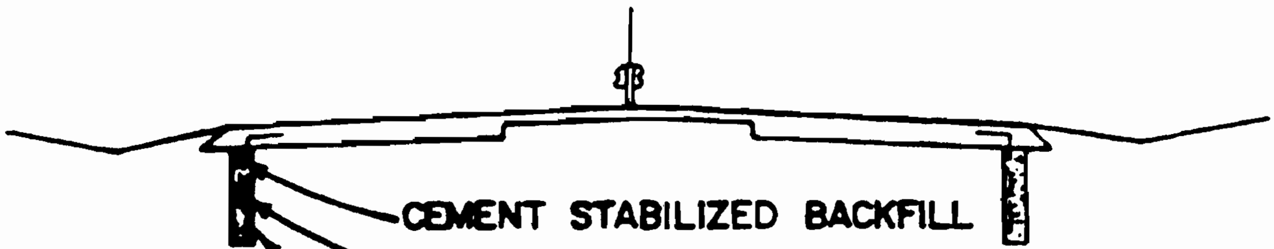
INTERSTATE 410 SECTION

FIGURE 4



INTERSTATE 37

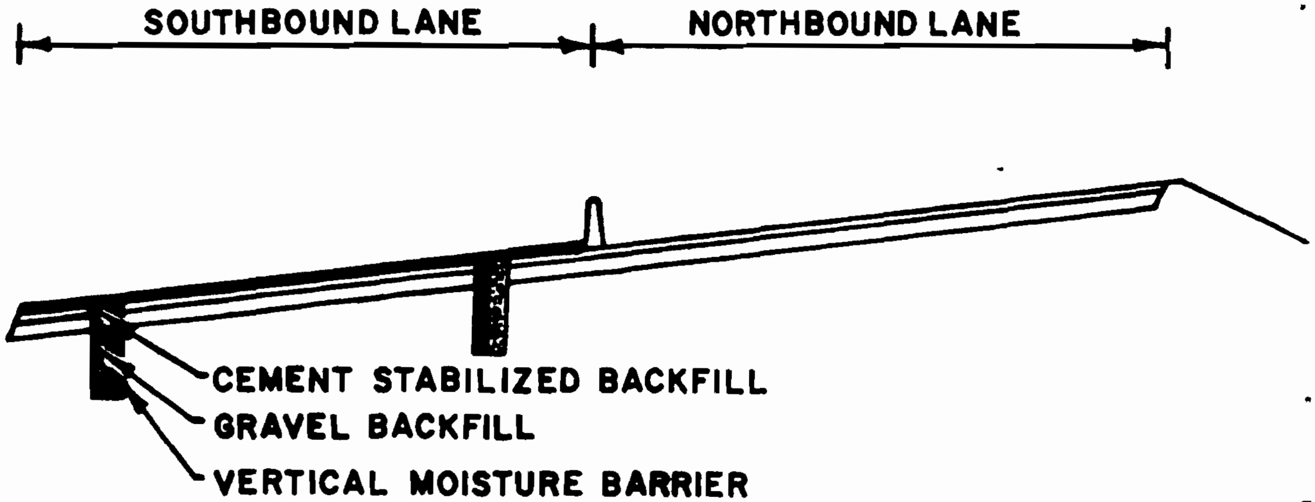
FIGURE 5



AFTER

INTERSTATE 37

FIGURE 6



TYPICAL SECTION
U.S. 281

TABLE 1

GENERAL McMULLEN SERVICEABILITY INDICES

Northbound Lanes

Date	Outside			Center			Inside		
	S.Control	Fabric	N.Control	S.Control	Fabric	N.Control	S.Control	Fabric	N.Control
July '81	2.75	3.63	2.17	3.67	3.86	3.69	3.85	3.41	4.14
Dec. '81	1.73	3.62	2.81	3.54	3.72	3.68	4.11	3.30	3.88
June '82	1.95	3.58	2.92	3.25	3.59	3.67	4.13	3.33	3.87
Feb. '83	2.00	3.58	2.79	3.14	3.52	3.42	4.02	3.26	3.65
Aug. '83	1.54	3.58	2.78	2.91	3.77	3.42	4.07	3.27	3.88
Mar. '84*	1.09	3.62	2.58	2.67	2.84	3.28	4.06	3.36	3.12
Sept.'84*	1.42	3.67	2.59	3.45	3.79	3.43	2.42	3.58	1.96
Mar. '85*	1.90	3.77	2.93	3.46	3.55	3.40	4.05	3.31	3.31

Southbound Lanes

Date	S.Control	Fabric	N.Control	S.Control	Fabric	N.Control	S.Control	Fabric	N.Control
July '81	2.32	2.64	--	3.09	3.83	3.68	3.41	3.86	3.61
Dec. '81	1.95	2.58	2.70	3.01	3.81	3.61	3.34	3.84	3.53
June '82	2.16	2.61	2.60	2.94	3.84	3.64	3.31	3.75	3.56
Feb. '83	2.11	2.64	2.53	2.87	3.81	3.51	3.27	3.81	3.50
Aug. '83	2.09	2.50	2.44	2.78	3.82	3.43	3.27	3.89	3.57
Mar. '84*	1.85	2.56	2.38	2.70	3.88	2.92	3.23	3.82	3.60
Sept.'84*	2.36	2.49	2.36	3.03	3.97	2.33	3.36	3.58	3.53
Mar. '85*	2.75	2.46	2.60	2.72	4.10	3.10	3.50	3.71	3.61

*New Profilometer

TABLE 2

GEN. McMULLEN - STIFFNESS COEFFICIENTS

Date:	Subgrade 8-73*	Subgrade 3-82	Pavement 8-73*	Pavement 3-82
North Control	0.20	0.20	0.60	0.95
Fabric	0.20	0.18	0.72	1.09
South Control	0.21	0.20	0.65	0.98

* Prior to Reconstruction

TABLE 3

GEN. McMULLEN - MAXIMUM DEFLECTIONS

Date:	1-81	3-82	1-81	3-82	1-81	3-82
Southbound Lanes	L		M		N	
Control	.015	.023	.017	.017	.022	.016
Fabric	.018	.022	.015	.017	.023	.019
Control	.012	.016	.013	.014	.016	.013
Northbound Lanes	T		S		R	
Control	.013	.015	.015	.015	.018	.020
Fabric	.019	.021	.019	.020	.025	.026
Control	.017	.017	.015	.017	.020	.023

TABLE 4

GENERAL McMULLEN - SPREADABILITY INDICES

	1-9-81	3-22-82	1-9-81	3-22-82	1-9-81	3-22-82
	R		S		T	
Northbound Lanes						
Control	80	76	79	80	79	79
Horizontal Fabric	84	77	84	82	84	82
Control	80	73	82	81	80	81
	L		M		N	
Southbound Lanes						
Control	81	74	79	79	76	80
Horizontal Fabric	86	78	83	83	83	83
Control	81	75	79	79	74	80

TABLE 5

GENERAL McMULLEN - PHOTOLOGGING TESTS PERCENT AREA CRACKED

DATE	SECTION	L	M	N	T	S	R	Average
1-81	Control	1.08	0.97	0.51	0	0	0.98	.59
	Fabric	1.07	0	0	0	0	0.36	.24
	Control	0	1.05	0.69	0	0	0.54	.38
6-81	Control	1.26	1.6	0	0	0	1.4	.71
	Fabric	1.42	0	0	0	0	0.5	.32
	Control	0	1.8	0.1	0	0	0.7	.43
1-82	Control	0.62	1.25	0	0	0	1.64	.59
	Fabric	0.73	0.03	0	0	0	0.52	.21
	Control	0	1.43	0	0	0	0.16	.27
8-82	Control	1.09	1.65	0	0	0	3.93	1.11
	Fabric	1.64	0	0	0	0	0.53	.36
	Control	2.07	0	0	0	0	0.40	.41

TABLE 6

LOOP 410 - SERVICEABILITY INDICES

Date	Southbound Lane (Control Section)		Northbound Lane (Deep Vertical Fabric)	
	Outside	Inside	Outside	Inside
June '79	4.13	4.02	4.16	4.11
Nov. '79	3.70	3.63	4.03	3.99
Aug. '80	3.39	3.30	3.83	3.83
Dec. '80	3.28	3.15	3.55	3.57
Mar. '81[1]	3.38	3.17	3.72	3.76
July '81[2]	3.43	3.29	3.74	3.61
Dec. '81	3.57	3.56	3.76	3.66
June '82	3.47	3.25	3.66	3.67
Feb. '83	3.28	2.99	3.57	3.55
Sept. '83	3.16	2.89	3.47	3.50
Mar. '84*	3.12	2.87	3.49	3.59
Sept. '84*	2.99	2.81	3.47	3.54
April '85*	3.03	2.62	3.65	3.61

* New Profilometer

1. Rotomilled southbound lane 3/30/81 - 4/2/81.
   Rotomilled northbound lane (isolated spots) 4/3/81 - 4/7/81.

2. Project leveled up 8-81.

TABLE 7

MOISTURE SENSOR READINGS

LOOP 410 - VALLEY HI DRIVE

Hole #	Sensor #	Depth F	Depth M	Fabric Location In	Fabric Location Out	5-30-79	5-31-79	6-28-79	8-15-79	11-14-79 11-15-79	6-6-80	7-17-80	12-18-80 1-16-81	3-19-81	7-13-81	7-7-83
	001	7			X	260K	20K	0	0	0	6K	4K	4K	1K	0	-
	002	5			X	28K	9K	0	0-A	0	4K	4K	53K	00*	3K	58K
1	003	2			X	780K	10K	0	0-A	63K	40K	600K	00*	450K	300K	-
	004	7.5			X	120K	0	0	0-A	0	0	1.5M	0	8K	240K	0
	005	3			X	300K	0	0	0-A	5K	0	1.5M	29K	80K	8K	0
2	006	2			X	165K	0	0	0-A	11K	5K	1M	0	14K	5K	0
	007	8			X	-	-	500K	0	0	0	0	11K	20K	23K	-
3	008	2			X	-	-	45K	0	1500K	0	0	0	16K	0	-
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4	010	2		X		45K	9K	0	0	0	0	0	11K	00*	0	-
	011	7		X		226K	0	0	0	0	0	2K	0	3K	4K	4K
5	012	2		X		352K	0	0	0	0	0	0	8K	0	9K	6K
	013	7			X	-	-	47K	0	0	0	0	0	00*	0	25K
6	014	2			X	-	-	50K	0	0	0	0	0	0	30K	120K
	015	8			X	-	-	70K	0	10K	0	0	9K	13K	70K	-
	016	5			X	-	-	150K	0-A	0	0	0	0	0	0	-
7	017	2			X	-	-	130K	0-A	0	0	0	0	600K	0	-
	018	5		X		0	0	0	0-A	0	0	240K	2K	6K	0	-
	019	4		X		0	0	0	0-A	0	0	10K	0	0	0	-
8	020	2		X		0	0	0	0-A	0	0	0	4K	15K	0	-
	021	7		X		-	0	0	0-A	0	0	0	11K	00*	0	-
	022	5		X		-	0	0	0-A	0	0	9K	6K	220K	22K	-
9	023	2		X		-	0	0	0-A	0	0	0	14K	190K	5K	-

* = Infinity
0-A = Leads inaccessible
K = Thousand
M = Million

TABLE 7

MOISTURE SENSOR READINGS

LOOP 410 – VALLEY HI DRIVE

Hole #	Sensor #	Depth F	Depth M	Fabric Location In	Fabric Location Out	5-30-79	5-31-79	6-28-79	8-15-79	11-14-79 11-15-79	6-6-80	7-17-80	12-18-80 1-16-81	3-19-81	7-13-81	7-7-83
	024	8			X	-	-	0	0-A	0	0	0	0	0	0	-
	025	5			X	-	-	38K	0-A	0	0	0	12K	40K	0	-
10	026	2			X	-	-	196K	0-A	1500K	0	0	9K	35K	0	-
	027	8			X	-	-	300K	0-A	71K	5K	00*	6K	00*	5K	-
	028	5			X	-	-	450K	0-A	0	0	1.5M	00*	31K	0	-
11	029	2			X	-	-	5K	0-A	40K	12K	00*	1.3M-2	00	7K	-
	030	6		X		25K	0	0	0-A	1K	0	2K	2K	00*	00*	-
	031	3		X		175K	0	0	0-A	0	0	0	0	0	0	-
12	032	2		X		200K	6K	0	0-A	4K	4K	2K	3K	0	0	-
	034	4		X		280K	0	0	0-A	0	0	0	11K	0	0	-
13	035	2		X		425K	0	0	0-A	3K	0	0	1K	00*	6K	-
	036	8			X	-	-	282K	0-A	0	0	0	0	0	0	-
	037	5			X	-	-	72K	0-A	0	0	350K	31K	170K	8K	-
14	038	2			X	-	-	775K	0-A	0	0	4K	15K	00*	0	-
	039	8			X	-	-	600K	0	0	0	0	0	0	0	-
15	040	2			X	-	-	450K	0-A	40K	1.5K	55K	5K	0	0	-
	041	7		X		150K	0	0	0	0	0	0	14K	0	0	-
16	042	2		X		800K	80K	0	0-A	2K	3K	2K	3K	2K	0	-
	043	7		X		0	0	0	0-A	0	0	0	4K	00*	0	-
17	044	2		X		0	0	0	0-A	0	0	0	0	0	20K	-
	045	8			X	-	-	0	0	0	0	0	0	0	0	-
18	046	2			X	-	-	260K	0-A	6K	0	49K	11K	0	0	-

* = Infinity
0-A = Leads inaccessible
K = Thousand
M = Million

TABLE 8

I.H. 410 - PHOTOLOGGING

	8/30	12/80	6/81	1/82	8/82	1/83
			NORTHBOUND LANES			
Outside	0.07	0.08	-0-	0.04	0	0.19
Inside	0.01	0.24	0.08	0.34	0.03	0.37
			SOUTHBOUND LANES			
Outside	0.28	0.62	0.11	0.87	0.29	0.75
Inside	0.24	1.01	0.10	0.78	0.51	0.45

TABLE 9

IH 37 - SERVICEABILITY INDICES

Date	Southbound Lane			Northbound Lane		
	N. Control	Fabric Section	S. Control	N. Control	Fabric Section	S. Control
Nov. '79	3.22	2.79#	3.33	3.15	2.92#	3.24
Dec. '80	2.97	3.68	3.18	3.09	3.81	3.30
July '81	2.79	3.72	3.20	3.02	3.84	3.30
Dec. '81	2.99	3.67	3.22	2.93	3.75	3.28
June '82	3.04	3.69	3.22	3.12	3.80	3.33
Feb. '83	3.09	3.61	3.19	3.01	3.68	3.29
Aug. '83	3.04	3.64	3.19	3.05#	3.72	3.26
March '84*	2.96#	3.75	2.36	4.24	3.83	2.31
Sept. '84*	4.05	3.68	2.29	4.17	3.71	2.28
April '85*	4.16	3.61	2.84	4.07	3.70	2.80

*New Profilometer

#Before Level-up

TABLE 10

I.H. 37 - PHOTOLOGGING

Lane	Treatment	6/81	4/82	8/82	1/83
L	Control	0.00%	0.00%	0.00%	0.00%
	Treat #1	0.00%	0.00%	0.00%	0.00%
	Treat #2	0.00%	0.00%	0.00%	0.00%
M	Control	0.00%	0.00%	0.00%	0.00%
	Treat #1	0.00%	0.00%	0.00%	0.00%
	Treat #2	0.00%	0.00%	0.00%	0.00%
N	Control	0.00%	0.00%	0.00%	0.00%
	Treat #1	0.00%	0.00%	0.00%	0.00%
	Treat #2	0.00%	0.00%	0.00%	0.00%
R	Control	0.04%	0.00%	0.00%	0.07%
	Treat #1	0.03%	0.00%	0.06%	0.00%
	Treat #2	0.00%	0.30%	0.00%	0.00%
S	Control	0.00%	0.00%	0.00%	0.00%
	Treat #1	0.00%	0.00%	0.00%	0.00%
	Treat #2	0.00%	0.00%	0.00%	0.00%
T	Control	0.00%	0.00%	0.00%	0.00%
	Treat #1	0.01%	0.00%	0.00%	0.00%
	Treat #2	0.15%	0.00%	0.00%	0.00%
Off Ramp	Treat	0.00%	0.10%	0.00%	0.00%

TABLE 11

U.S. 281 - SERVICEABILITY INDICES

Date	Southbound Lane (Deep Vertical fabric) Outside	Center	Inside	Northbound Lane (Control) Outside	Center	Inside
July '83#	2.42	2.35	1.31	2.90	2.86	2.72
March '84*	3.08	3.07	3.00	2.84	2.91	2.55
Sept. '84*	3.21	3.18	2.92	2.74	2.78	2.45
April '85*	3.04	2.99	3.18	2.55	2.77	2.45

* New Profilometer
# Before Level up

APPENDIX

POOLED ESTIMATE OF THE STANDARD DEVIATION

STUDENT'S t-DISTRIBUTION TWO-TAILED TEST

Are the two means significantly different (5% level)?

Table 1. Northbound

Outside Fabric vs. S. Control

$x = 3.63$ $\quad$ $y = 1.80$

$s = 0.0642$ $\quad$ $s = 0.4922$

$$s = \sqrt{\frac{(0.0642)^2(8) - (.4922)^2(8)}{14}} = 0.375$$

$$sx = \frac{s}{n} = \frac{.375}{8} = 0.133$$

$$sy = \frac{s}{n} = \frac{.375}{8} = 0.133$$

$$sx\text{-}y = \sqrt{(.133)^2 + (.133)^2} = 0.188$$

$$t = \frac{(3.63 - 1.80)}{0.188} = 9.73$$

For $v = 14$, $t_{0.05} = 2.145$

Since $9.73 > 2.145$

Therefore, the fabric performs significantly better than control.

Table 1. Northbound

Outside Fabric vs. N. Control

$x = 3.63 \qquad y = 2.70$

$s = 0.0642 \qquad s = 0.249$

$$s = \sqrt{\frac{(.0642)^2(8) + (.249)^2(8)}{14}} = 0.194$$

$$sx = \frac{s}{n} = \frac{.194}{8} = 0.0686 \qquad sy = .0686$$

$$sx\text{-}y = \sqrt{(.0686)^2 + (.0686)^2} = 0.0970$$

$$t = \frac{(3.63 - 2.70)}{0.0970} = 9.59$$

For $v = 14$, $t_{0.05} = 2.145$

Since $9.59 > 2.145$

Therefore, the fabric performs significantly better than the control.

Table 1. Northbound

Center Fabric vs. S. Control

$x = 3.58 \qquad y = 3.26$
$s = 0.323 \qquad s = 0.340$

$$s = \sqrt{\frac{(0.323)^2(8) + (.340)^2(8)}{14}} = 0.355$$

$$sx = \frac{s}{n} = \frac{.355}{8} = 0.126 \qquad sy = \frac{s}{n} = \frac{.355}{8} = 0.126$$

$$sx - y = \sqrt{(.126)^2 - (.126)^2} = 0.178$$

$$t = \frac{(3.58 - 3.26)}{0.178} = 1.80$$

For $v = 14$, $t_{0.05} = 2.145$

Since 1.80 < 2.145, the fabric does not perform significantly differently than the control.

Table 1. Northbound

Center Fabric vs. N. Control

$x = 3.58 \qquad y = 3.50$

$s = 0.323 \qquad s = 0.157$

$$s = \sqrt{\frac{(0.323)^2(8) + (.157)^2(8)}{16 - 2}} = 0.271$$

$$sx = \frac{s}{n} = \frac{.271}{8} = 0.0958 \qquad sy = \frac{s}{n} = \frac{.271}{8} = 0.0958$$

$$sx - y = \sqrt{(.0958)^2 + (.0958)^2} = 0.135$$

$$t = \frac{(3.58 - 3.50)}{0.135} = 0.59$$

For $v = 14$, $t_{0.05} = 2.145$

Since $0.59 < 2.145$, the fabric does not perform significantly differently than the control.

Table 1. Northbound

Inside Fabric vs. S. Control

$x = 3.35$ $y = 3.83$

$s = 0.104$ $s = 0.580$

$$s = \sqrt{\frac{(0.104)^2(8) + (0.580)^2(8)}{14}} = 0.445$$

$$sx = \frac{s}{n} = \frac{0.445}{8} = 0.157 \qquad sy = \frac{s}{n} = \frac{0.445}{8} = 0.157$$

$$sx - y = \sqrt{(0.157)^2 + (0.157)^2} = .222$$

$$t = \frac{(3.35 - 3.83)}{.222} = 2.16$$

For $v = 14$, $t_{0.05} = 2.145$

Since 2.16 > 2.145, the control performs significantly better than the fabric.

Table 1. Northbound

Inside Fabric vs. N. Control

$x = 3.35 \qquad y = 3.48$

$s = 0.104 \qquad s = .697$

$$s = \sqrt{\frac{(.104)^2(8) + (.697)^2(8)}{14}} = 0.533$$

$$sx = \frac{s}{n} = \frac{.533}{8} = .188 \qquad sy = \frac{s}{n} = \frac{.533}{8} = .188$$

$$sx - y = \sqrt{(.188)^2 + (.188)^2} = 0.266$$

$$t = \frac{(3.35 - 3.48)}{.266} = 0.489$$

For $v = 14$, $t_{0.05} = 2.145$

Since $.489 < 2.145$, the fabric does not perform significantly differently than the control.

Table 1. Southbound

Outside Fabric vs. S. Control

$x = 2.56$ $\quad$ $y = 2.20$

$s = 0.0699$ $\quad$ $s = .280$

$$s = \sqrt{\frac{(.0699)^2 + (.280)^2(8)}{14}} = 0.218$$

$$sx = \frac{s}{n} = \frac{.218}{8} = 0.0771 \qquad sy = \frac{s}{n} = \frac{.218}{8} = 0.0771$$

$$sx - y = \sqrt{(.0771)^2 - (.0771)^2} = 0.109$$

$$t = \frac{2.56 - 2.20}{0.109} = 3.30$$

For $v = 14$, $t_{0.05} = 2.145$

Since 3.30 > 2.145, the fabric performs significantly better than the control.

Table 1. Southbound

Outside Fabric vs. N. Control

$x = 2.56 \qquad y = 2.52$
$s = 0.0699 \qquad s = .127$

$$s = \sqrt{\frac{(.0699)^2 - (.127)^2(7)}{13}} = 0.108$$

$$sx = \frac{s}{n} = \frac{.108}{8} = 0.0382 \qquad sy = \frac{.108}{7} = 0.0409$$

$$sx - y = \sqrt{(0.382)^2 + (.0409)^2} = 0.0560$$

$$t = \frac{2.56 - 2.52}{.0560} = 0.71$$

For $v = 13$, $t_{0.005} = 2.179$

Since $0.71 < 2.179$, the fabric does not perform significantly differently than the control.

Table 1. Southbound

Center Fabric vs. S. Control

$x = 3.88 \qquad y = 2.89$

$s = .103 \qquad s = .148$

$$s = \sqrt{\frac{(.103)^2(8) + (.148)^2(8)}{14}} = 0.136$$

$$sx = \frac{s}{n} = \frac{.136}{8} = 0.0481 \qquad sy = \frac{s}{n} = \frac{.136}{8} = 0.0481$$

$$sx - y = \sqrt{(.0481)^2 + (.0481)^2} = 0.0680$$

$$t = \frac{3.88 - 2.89}{.0680} = 14.6$$

For $v = 14$, $t_{0.05} = 2.145$

Since $14.6 > 2.145$, the fabric performs significantly better than the control.

Table 1. Southbound

Center Fabric vs. N. Control

$x = 3.88 \qquad y = 3.28$

$s = .103 \qquad s = .469$

$$s = \sqrt{\frac{(.103)^2 + (.469)^2 (8)}{14}} = 0.363$$

$$sx = \frac{s}{n} = \frac{.363}{8} = 0.128 \qquad sy = \frac{s}{n} = \frac{.363}{8} = 0.128$$

$$sx - y = \sqrt{(.128)^2 - (.128)^2} = 0.181$$

$$t = \frac{3.88 - 3.28}{.181} = 3.31$$

For $v = 14$, $t_{0.05} = 2.145$

Since 3.31 > 2.145, the fabric performs significantly better than the control.

Table 1. Southbound

Inside Fabric vs. S. Control

$x = 3.79 \qquad y = 3.34$
$s = 0.104 \qquad s = 0.087$

$$s = \sqrt{\frac{(.104)^2(8) + (.087)^2(8)}{14}} = 0.102$$

$$sx = \frac{s}{n} = \frac{0.102}{8} = 0.0361 \qquad sy = \frac{s}{n} = \frac{0.102}{8} = 0.0361$$

$$sx - y = \sqrt{(.361)^2 + (.0361)^2} = 0.0511$$

$$t = \frac{3.79 - 3.34}{0.0511} = 8.81$$

For $v = 14$, $t_{0.005} = 2.145$

Since 8.81 > 2.145, the fabric performs significantly better than the control.

Table 1. Southbound

Inside Fabric vs. N. Control

$x = 3.79$ $\quad$ $x = 3.557$

$s = 0.104$ $\quad$ $s = 0.0399$

$$s = \sqrt{\frac{(.104)^2(8) + (.0399)^2(8)}{14}} = 0.0842$$

$$sx = \frac{s}{n} = \frac{.0842}{8} = .0298 \qquad sy = \frac{.0842}{8} = .0298$$

$$sx - y = \sqrt{(.0298)^2 + (.0298)^2} = 0.0421$$

$$t = \frac{3.79 - 3.56}{.0421} = 5.46$$

For $v = 14$, $t_{0.05} = 2.145$

Since 5.46 > 2.145, the fabric performs significantly better than the control.

Table 6. Outside

Control Fabric

$x = 3.38$ $x = 3.70$
$s = 0.306$ $x = 0.211$

$$s = \sqrt{\frac{(.306)^2 + (.211)^2(13)}{24}} = 0.274$$

$$sx = \frac{s}{n} = \frac{.274}{13} = 0.760 \qquad sy = \frac{s}{n} = \frac{.274}{13} = .0760$$

$$sx - y = \sqrt{(.0760)^2 - (.0760)^2} = 0.107$$

$$t = \frac{3.70 - 3.38}{0.107} = 2.99$$

For $v = 24$, $t_{0.05} = 2.064$

Since 2.99 > 2.064, the fabric performs significantly better than the control.

Table 6. Inside

Control	Fabric
x = 3.20	x = 3.69
s = .382	s = .184

$$s = \sqrt{\frac{(.382)^2(13) + (.184)^2(13)}{24}} = 0.312$$

$$sx = \frac{s}{n} = \frac{.312}{13} = .0865 \qquad sy = \frac{s}{n} = \frac{.312}{13} = .0865$$

$$sx - y = \sqrt{(.0865)^2 + (.0865)^2} = .122$$

$$t = \frac{3.69 - 3.20}{.122} = 4.02$$

For $v = 24$, $t_{0.05} = 2.064$

Since 4.02 > 2.064, the fabric performs significantly better than the control.

Table 9. Southbound

Fabric vs. N. Control

$x = 3.67 \qquad y = 3.26$

$s = .0468 \qquad s = 0.492$

$$s = \sqrt{\frac{(.0468)^2(9) + (.492)^2(9)}{16}} = 0.371$$

$$sx = \frac{s}{n} = \frac{.371}{9} = .124 \qquad sy = \frac{s}{n} = \frac{.371}{9} = .124$$

$$sx - y = \sqrt{(.124)^2 - (.124)^2} = 0.175$$

$$t = \frac{(3.67 - 3.26)}{.175} = 2.34$$

For $v = 16$, $t_{0.05} = 2.12$

Since 2.34 > 2.12, the fabric performs significantly better than the control.

Table 9. Southbound

Fabric vs. S. Control

$x = 3.67 \qquad y = 3.00$

$s = .0468 \qquad s = .379$

$$s = \sqrt{\frac{(.0468)^2 + (.379)^2(10)}{17}} = 0.293$$

$$sx = \frac{s}{n} = \frac{.293}{9} = .0977 \qquad sy = \frac{s}{n} = \frac{.293}{10} = .0927$$

$$sx - y = \sqrt{(.0977)^2 + (.0927)^2} = 0.1347$$

$$t = \frac{3.67 - 3.00}{.1347} = 4.97$$

For $v = 17$, $t_{0.05} = 2.110$

Since 4.97 > 2.110, the fabric performs significantly better than the control.

Table 9. Northbound

Fabric vs. N. Control

$x = 3.76$ $y = 3.42$

$s = .0608$ $s = 0.559$

$$s = \sqrt{\frac{(.0608)^2 + (.559)^2(9)}{16}} = 0.422$$

$$sx = \frac{s}{n} = \frac{.422}{9} = .141 \qquad sy = \frac{s}{n} = \frac{.422}{9} = .141$$

$$sx - y = \sqrt{(.141)^2 - (.141)^2} = .199$$

$$t = \frac{3.76 - 3.42}{.199} = 1.71$$

For $v = 16$, $t_{0.05} = 2.12$

Since $1.71 < 2.12$, the fabric does not perform significantly differently than the control.

Table 9, Northbound

Fabric vs. S. Control

$x = 3.76 \qquad y = 3.04$
$s = 0.0608 \qquad s = 0.421$

$$s = \sqrt{\frac{(.0608)^2(9) + (.421)^2(10)}{17}} = .326$$

$$sx = \frac{s}{n} = \frac{.326}{9} = .109 \qquad sy = \frac{s}{n} = \frac{.326}{10} = .103$$

$$sx - y = \sqrt{(.109)^2 + (.103)^2} = .150$$

$$t = \frac{3.76 - 3.04}{.150} = 4.80$$

For $v = 17$, $t_{0.05} = 2.110$

Since 4.80 > 2.11, the fabric performs significantly better than the control.

Table 11. Outside

Fabric vs. Control

$x = 2.94$ $y = 2.758$
$s = .353$ $s = .153$

$$s = \sqrt{\frac{(.353)^2(4) + (.153)^2(4)}{6}} = .314$$

$$sx = \frac{s}{n} = \frac{.314}{4} = .157 \quad sy = \frac{s}{n} = \frac{.314}{4} = .157$$

$$sx - y = \sqrt{(.157)^2 + (.157)^2} = 0.222$$

$$t = \frac{2.94 - 2.76}{.222} = 0.81$$

For $v = 6$, $t_{0.05} = 2.45$

Since $0.81 < 2.45$, the fabric does not perform significantly differently than the control.

Table 11. Center

Fabric vs. Control

$x = 2.90$ $y = 2.83$
$s = .373$ $s = .0668$

$$s = \sqrt{\frac{(.373)^2(4) + (.0668)^2(4)}{6}} = 0.309$$

$$s_x = \frac{s}{n} = \frac{.309}{4} = .155 \qquad s_y = \frac{.309}{4} = .155$$

$$s_{x-y} = \sqrt{(.155)^2 + (.155)^2} = 0.219$$

$$t = \frac{2.9 - 2.83}{.219} = .32$$

For $v = 6$, $t_{0.05} = 2.45$

Since $0.32 < 2.45$, the fabric does not perform significantly differently than the control.

Table 11. Inside

Fabric vs. Control

$x = 2.60 \qquad y = 2.54$

$s = .868 \qquad s = .127$

$$s = \sqrt{\frac{(.868)^2(4) + (.127)^2(4)}{6}} = 0.716$$

$$sx = \frac{.716}{4} = .358 \qquad sy = \frac{s}{n} = \frac{.716}{4} = .358$$

$$sx - y = \sqrt{(.358)^2 + (.358)^2} = .506$$

$$t = \frac{2.60 - 2.54}{.506} = 0.12$$

For $v = 6$, $t_{0.05} = 2.45$

Since $0.12 < 2.45$, the fabric does not perform significantly differently than the control.