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POROUS PAVEMENT FOR CONTROL OF HIGHWAY RUN-OFF

Final Report

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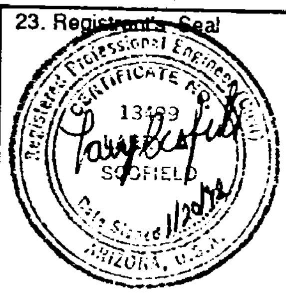
16. Abstract

In 1986, the Arizona Department of Transportation (ADOT) constructed a 3500-foot porous pavement experimental section on SR-87 in the Phoenix metropolitan area. The objectives of this project were to determine the constructibility and subsequent performance of porous pavement as a drainage system and pavement structure in an urban area and a desert environment.

The porous pavement test section has performed satisfactorily for five years. Although a slight decrease in the infiltration rate has occurred, both the infiltration rate and the storage capacity are above the design values. Visual observation during storm events has shown that the surface of the porous pavement section does not include sheet flow. This provides a marked difference in stripe delineation and pavement glare during night time inclement weather driving when compared to conventional pavement. However, Mu-meter skid test results for the porous pavement section are comparable to those of conventional pavements (control).

Material tests conducted on the pavement components indicate that the Marshall stability, resilient modulus, and asphalt cement viscosity of the open graded asphalt concrete have increased with time. No cracking or significant surface deformation has occurred during the five years of service. Annual FWD testing was conducted to establish the changes in layer properties. To date, little change has occurred in the layer moduli except for the open graded subbase whose modulus has decreased with time. This phenomenon is unexplained at present. No unusual presence of moisture was detected in any layer of the pavement system. The subgrade moisture content has achieved equilibrium at less than the optimum content determined during the design process.

23. Registrant's Seal



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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	2.54	centimeters	cm
ft	feet	0.3048	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	6.452	centimeters squared	cm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.395	hectares	ha
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		VOLUME		
fl oz	fluid ounces	29.57	millimeters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.0328	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3

Note: Volumes greater than 1000 L shall be shown in m^3.

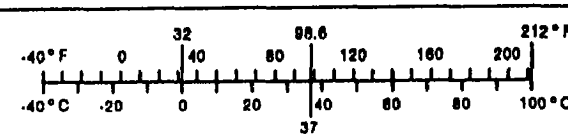
Symbol	When You Know	Multiply By	To Find	Symbol
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

These factors conform to the requirement of FHWA Order 5190.1A

*SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
yd	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
yd^2	kilometers squared	0.39	square miles	mi^2
ha	hectares (10,000 m^2)	2.53	acres	ac
		MASS (weight)		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
mL	millimeters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

Background

Paved surfaces increase surface run-off and overload the existing sewer systems if alternative drainage is not provided. Rainfall is the only source of surface run-off in the Phoenix area. Typical summer storms have high intensity and short duration while typical winter storms have low intensity but longer duration (1,2). This creates a large volume of run-off requiring costly highway drainage systems. Up to 35% of the total cost of highway construction projects in Arizona's urban area is expended on drainage structures (3).

In an attempt to reduce the need for extensive drainage systems, porous pavements have been suggested as an alternative to conventional pavement (4,5). The basic concept of porous pavement design is that in addition to carrying traffic, the porous pavement will also serve as a drainage system by absorbing, storing and dissipating storm waters into the ground.

In 1986, the Arizona Department of Transportation (ADOT) constructed a 3500 ft long porous pavement experimental test section as part of construction project F045-1(4). The objectives of the project were to determine the constructibility and subsequent performance of porous pavement as a drainage system and pavement structure in an urban area and a desert environment.

PROJECT LOCATION AND LAYOUT

Location

The test section is located in the three north bound lanes of State Route (SR) 87 (Arizona Avenue) between Station 105+00 and 140+00 in the city of Chandler between Elliot and Warner Roads. Chandler is a rapidly growing and developing suburban city approximately 20 miles southeast of Phoenix. SR 87 is heavily traveled by commuter traffic going to and from the Superstition freeway which is approximately 2.5 miles north of the project. Currently, the project carries approximately 30,000 ADT with 27% commercial traffic. FIGURE 1 shows the traffic loadings on this project since the construction. FIGURE 2 shows the layout of the porous pavement section and the control section.

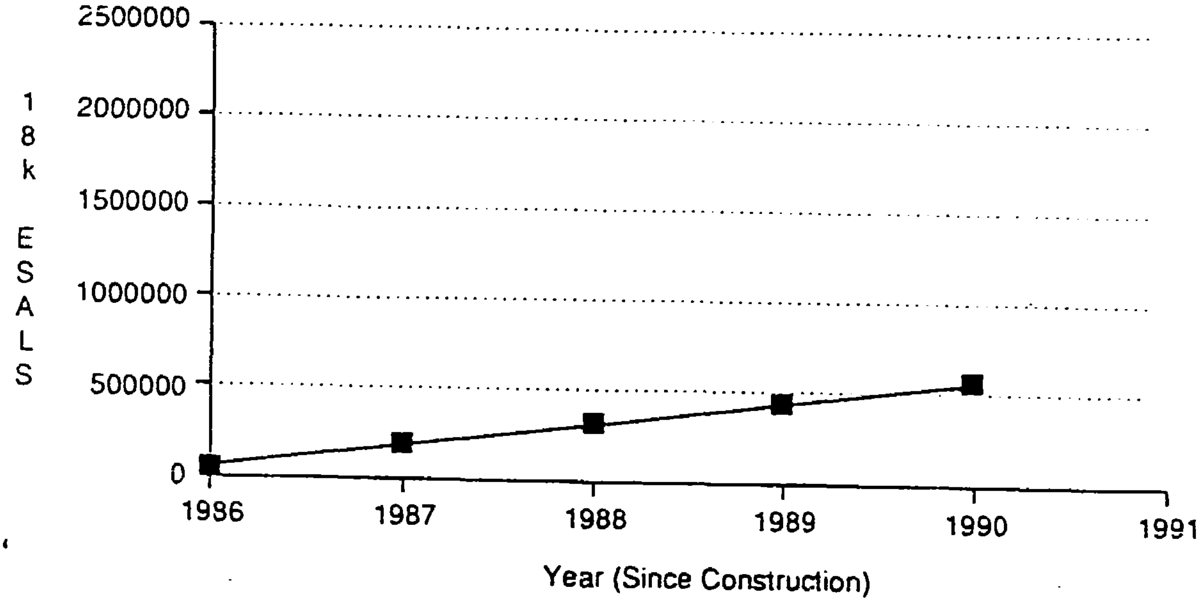


FIGURE 1 TRAFFIC HISTORY OF POROUS PAVEMENT

DESIGN CONSIDERATIONS

Porous Pavement Section

The porous pavement section consists of 6" Open Graded Hot Mix Asphalt Concrete, 6" Open Graded Asphalt Treated Base (ATB) and 8" Open Graded Subbase. The pavement structure was designed equivalent to the control section of conventional dense graded pavement. This pavement was designed using the AASHTO design equation to carry the design traffic loading of 2,270,653 single-axle, equivalent 18-kip loads for a 20-year design period (6).

A woven filter fabric was placed for separation of the subbase and subgrade. The open graded layers of the pavement drain into a trench at the edge of the pavement which is filled with open graded aggregate. The water from the drainage trench was expected to dissipate into the natural ground. An alternative drainage system was also provided for the experimental section. This was intended for use as a backup system in the event of failure of the designed experimental drainage system. The pavement structure designed was found to have adequate water-holding capacity to temporarily store run-off from the 10-year 24-hour design storm. The intensity of this rain storm was found to be 0.11 inch/hour. The design

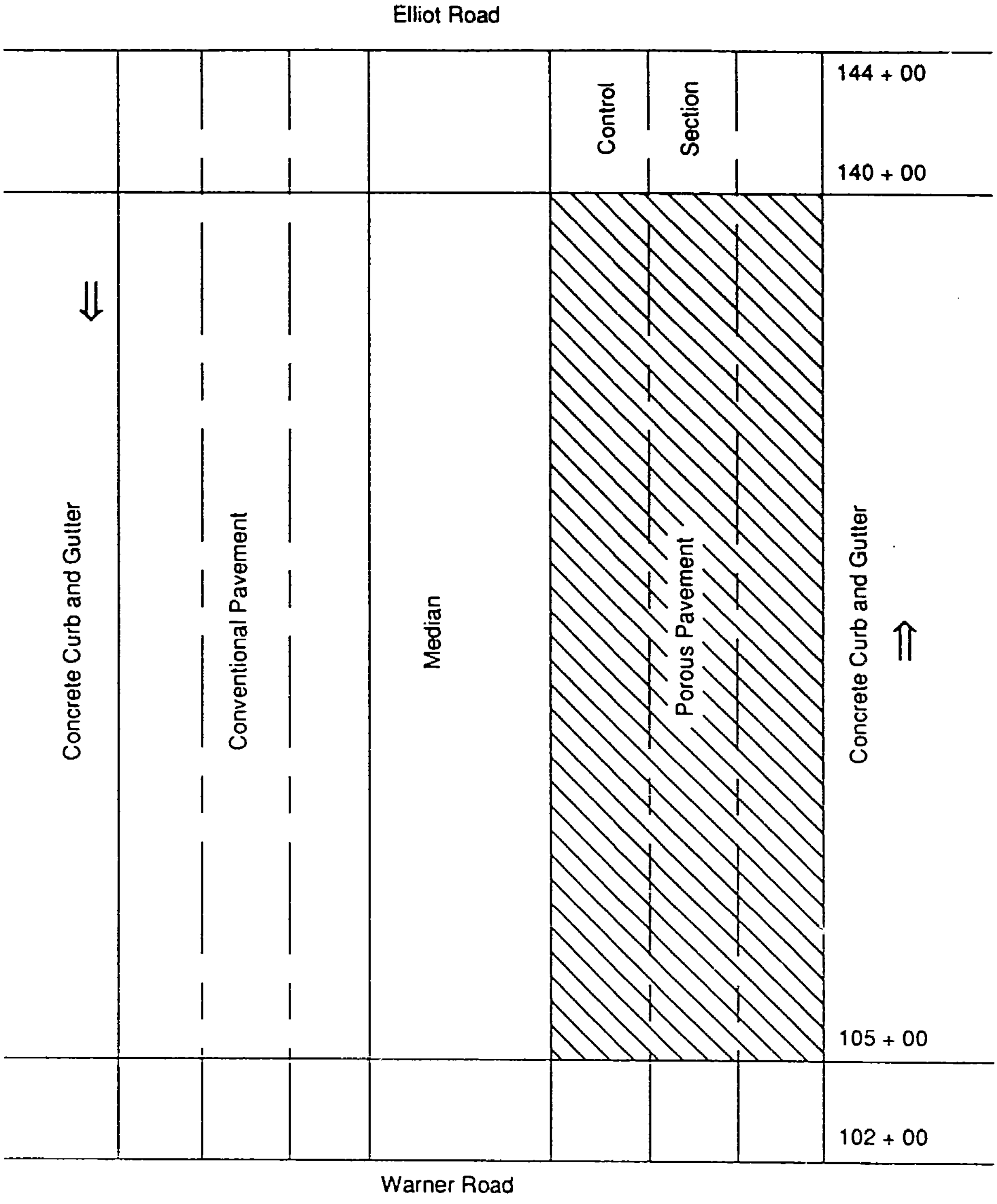


FIGURE 2 LAYOUT OF POROUS PAVEMENT TEST SECTION

rainfall intensity for percolation of water through the surface course was based upon the 10-year frequency 10- minute duration storm. This intensity was estimated at 5.20 inch/hour during the 10-minute storm (7).

Control Pavement Section

The control section of the project is located at the north end of the porous pavement section and consists of 8 inches of asphalt concrete over 7 inches of aggregate base. The same design was used for the three south bound lanes. The south-bound lanes were used as control section for Mays roughness and Mu-meter testing. FIGURE 3 shows the structural section of the porous pavement and the control section.

The specific design data appears in TABLE 1. A design structural number of 4.5 was selected for both sections. The thicknesses of different layers were calculated based on this structural number. A structural layer coefficient of 0.40 was assumed for the open graded asphalt concrete,

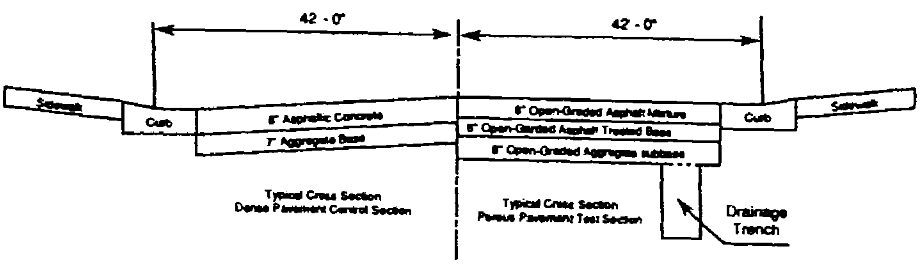


FIGURE 3 TYPICAL CROSS SECTIONS OF POROUS AND CONVENTIONAL PAVEMENT

TABLE 1- SUMMARY OF STRUCTURAL DESIGN DATA

Material	Thickness (in)	Layer Coefficient	Structural Number
	CONTROL SECTION		
AC (1/2") (Control)	2	0.44	0.88
AC (3/4") (Control)	6	0.44	2.64
AB (Control)	7	0.14	<u>0.98</u>
			4.50
	POROUS PAVEMENT		
AC (Open Graded)	6	0.40	2.40
ATB (Open Graded)	6	0.20	1.20
Subbase (Open Graded)	8	0.11	<u>0.88</u>
			4.48

Other data: Design R-value=15, 20-year 18K ESALs=2,270,653, Regional Factor =1.0, Terminal Serviceability =2.5.

DESIGN EVALUATION

Material Characterization

Subgrade

The subgrade characteristics of the soil were studied in detail. Several soil samples were taken at different depths and tested. The soils were generally sandy clays with low to medium plasticity. TABLE 2 summarizes the soil data at different locations. As evident from the test results, the subgrade characteristics are quite variable over the project. An R-value of 15 was chosen for the structural design of the pavement.

TABLE 2- SUBGRADE TEST RESULTS

Station Location	Depth (ft)	P.I.	%Passing #200	Moisture Content (%)	R-value*
107 SB	2.4-7.0	NP	6.4	-	-
	7.0-11.4	NP	5.2	-	
	11.4-25.4	15	32.1	-	-
110 --	2.0-10.0	19	55.0	13.5	-
117 NB	2.7-6.0	NP	6.1	-	-
	6.0-11.5	NP	7.6	-	-
	11.5-25.0	13	52.4	-	-
126 SB	2.7-7.5	NP	6.3	-	-
	7.5-15.8	NP	8.3	-	-
	15.8-25.0	11	50.6	-	-
130 ---	2.0-10.0	24	34.0	14.9	32
137 NB	3.2-5.7	NP	6.2	-	-
	5.7-12.0	NP	6.7	-	-
	12.0-25.0	6	41.5	-	57
140 SB	2.0-5.0	1	39.0	6.6	-
	5.0-10.0	9	43.0	9.4	28

*at 300 psi exudation pressure.

The drainage characteristics of the soil were studied during the design phase. Permeability tests performed on compacted samples of the cohesive subgrade soils yielded coefficients of permeability ranging from 0.0002 to 0.005 ft/day. TABLE 3 summarizes the permeability test results. A special percolation test was also run to determine the rate of percolation of water through the subgrade. By using this percolation test results and the principles of water flow through soils, an expression was developed relating time to the volume of water percolated from the drainage trench as follows:

$t = 435.25 - 22.64h + 0.294h^2$, where h is the depth of water in the trench at time t.

Based on the time needed for dissipation of water, the size of the drainage trench was designed (8).

TABLE 3- SUBGRADE PERMEABILITY TEST RESULTS

Station Location	Moisture Content (%)	Unit Wt. (pcf)	Coefficient of Permeability (cm/sec)
110+00 --	13.5	-	7.1×10^{-8}
130+00 --	14.9	105	1.3×10^{-7}
140+00 SB	9.4	110	1.8×10^{-6}
140+00 SB*	6.6	110	1.7×10^{-6}

* at 5-10 ft depth.

Open Graded Asphalt Concrete Mix Design

The mix design for open graded asphalt concrete was based on Arizona Method 814a: Design of Asphaltic Concrete Friction Course (9). The method is primarily used by ADOT for designing open graded wearing courses on dense graded pavements. This method determines the bitumen content and density of an asphaltic concrete course. The design bitumen content was found from the following equation:

$$B = (1.5\ Kc + 3.5) \times 2.65 / Gag$$

Where: B = bitumen content expressed as a percent of total mix

Kc = K-factor for coarse material which represents the total effect of superficial, the aggregate's absorptive properties, and surface roughness, and

Gag = Combined oven dry specific gravities of the aggregates retained and passing #4 sieve.

The design bitumen content for the porous asphalt concrete was 5.5% by weight of the total mix.

Drainage Characteristics of Different Layer Materials

Samples of the pavement layer materials were tested in the laboratory for void content and coefficient of permeability. The results are summarized in TABLE 4. The coefficients of permeability were used to estimate the rate at which the porous pavement could drain water from the surface. The air voids allowed a measurement of the water holding capacity of the materials used (8).

TABLE 4- VOID CONTENTS AND COEFFICIENTS OF PERMEABILITY OF DIFFERENT LAYER MATERIALS

Material Type	Asphalt Content (%)	Air Voids. (%)	Coefficient of Permeability (ft/day)
Asphalt Concrete Pavement	5.5	22	200
Asphalt Treated Base	1.8	40	16,000
Aggregate Subbase	0.0	40	23,000

Drainage Trench Design

A parallel drainage trench was designed along the edge of the roadway. This was connected to the open-graded subbase such that run-off entering the pavement could readily flow into the trench. The trench was designed to drain the 10-year, 24-hour design storm from the subbase within 26 hours. A trench 2 feet wide by 4 feet deep was found to be adequate to drain one-half the road plus the sidewalk and shoulder. A width of approximately 50 feet would receive 9 cubic feet of runoff in one linear foot length of the project during 10-year 24-hour storm. The trenches were designed to be filled with the open-graded aggregate specified for the pavement subbase. The aggregate in the drainage trench and the subabse were designed to be isolated from the subgrade soil by a permeable geotextile at the soil-aggregate interface (8).

CONSTRUCTION FEATURES

Subgrade and Drainage Trench

The pavement subgrade was constructed by removing the existing pavement layers and adjusting the subgrade to design elevation. The drainage trench was excavated with a backhoe. A geotextile filter fabric, Supac 4WS, was hand placed in the drainage trench and temporarily held in place by nailing it to the underlying soil. The trench was filled with open-graded subbase aggregate and compacted in two 24-inch thick lifts with mechanical hand compactors. The roadway subgrade was covered with the same geotextile as placed within the drainage trenches.

Subbase

Open graded aggregate subbase material was placed 8-inch thick and compacted with a steel drum roller. Specifications required that the aggregate subbase be placed on the geotextile before traffic could be carried over it. However, hauling units had such difficulty moving on the open graded material, even when compacted, and traveling on the fabric while depositing aggregate was permitted. The smooth subgrade and care taken by the hauling units allowed this procedure with no apparent damage to the fabric.

Asphalt Treated Base (ATB)

The asphalt treated base was designed for a 6 inch thickness using an open-graded aggregate and 1.8 percent asphalt cement. The specifications allowed the first lift of the ATB to be placed by means other than a paver as equipment operations on top of the open-graded, untreated aggregate subbase was anticipated to be difficult. The contractor elected to place the material into windrows with bottom dump trucks. The windrowed material was leveled with motor graders and compacted with steel drum rollers. The hauling units were pushed with motor graders while traveling on the subbase to avoid getting stuck. The compacted subbase was displaced during this process. This resulted in variation of thicknesses of the ATB from wheel ruts and ridges in the subbase. The second course of ATB was placed using a pickup machine and a conventional self-propelled paver. This operation had little difficulty other than the paver broke occasionally through the first lift of ATB caused by ridges in the subbase. The material was compacted by static rolling with a steel drum roller (10).

Open Graded Asphalt Concrete

Two 3-inch thick lifts of open-graded asphalt concrete were placed. Construction was completed by a conventional self-propelled paver with a pick-up machine. Compaction was done with static steel wheeled rollers. The compacted pavement retained a somewhat tender, unstable condition for a day or two after placement. Very high ambient day time temperatures and low Marshall stability values of the mix were thought to have contributed to this condition.

CONSTRUCTION PROBLEMS

It was previously mentioned that construction of the open graded subbase and base had minor difficulties. The major problem occurred while carrying traffic on the east half of the open graded asphalt concrete while the west half was being constructed. Within 3 weeks, severe vertical deformation was noticed. Surface deformations were measured with a straightedge placed on the pavement. Vertical displacements from the straight edge varied from 1/8 inch to 1 inch. The average depth was 3/8 inch with 139 of the 144 readings taken being 5/8 inch or less. Nuclear gage densities and cores were taken along wheel paths and between lanes in an effort to determine whether compaction of the pavement had occurred under traffic. Average unit weights of porous pavement within the wheel paths were slightly higher than between lanes but not by a significant amount. The difference was not suspected to be nearly the amount that would account for the deformations noted. It was further observed that the deformation was not confined to the wheel paths but appeared as a wide depression generally extending from wheel path to wheel path. However, the condition of plastic flow where material is pushed down in the wheel paths and up between them was not evident. To further investigate the source of these large vertical deformations, a trench was excavated down to the subgrade at a location of one inch vertical deformation. Observation of the pavement layers indicated that the top course of asphalt concrete was of uniform thickness but displaced vertically along both bottom and top surfaces. As a result of intermingling of the asphalt treated base and the aggregate subbase, it was not possible to observe where the vertical deformation had occurred. However, it was concluded that as the hauling units deposited asphalt treated base material, decompaction of the untreated subbase occurred resulting in an increase volume of the open graded subbase. The volume of this subbase was decreased by recompaction of this course during subsequent construction and traffic. This change in volume of the untreated subbase is the most probable cause of vertical deformation of the pavement structure. The entire section was subsequently rolled with a steel vibratory roller for three or four coverages. This produced some levelling of the surface. An additional thin lift of open graded asphalt concrete was placed to produce a surface at the proper elevation and cross slope. The project was finally opened to traffic in July of 1986 (10).

INSTRUMENTATION

Rain Gage

In order to obtain rainfall data, a continuous recording rain gage was placed just beyond the west right-of-way line at station 139+10. In August of 1987, at the request of the property owner, the rain gage was moved 385 feet to the west. Continuous rainfall readings were taken from June, 1986 to July, 1989.

Moisture Monitors

Soil moisture monitoring devices were placed in the subgrade at two locations within the porous pavement and three locations in the control pavement. Six positions were monitored at each location. Moisture monitoring locations were at Stations 97+40, 138+00, and 143+25 in the southbound lanes and Stations 108+00 and 138+00 in the northbound lanes. Soil cells were placed at depths of 1 and 3 feet below top of the subgrade at distances of approximately 5, 10 and 20 feet from the front face of the curb and gutter.

Well Point

A well point was placed within the drainage trench located in the east concrete gutter at station 130+00. A device installed in the well point in February 1987 recorded the highest water level reached in the trench.

FIELD INVESTIGATION SINCE CONSTRUCTION

Visual Pavement Distress Surveys

The porous pavement section was visually reviewed several times between July, 1986 to April, 1990. These reviews included observing both the conventional and porous pavement sections for cracking, distortion, disintegration, and frictional characteristics. However, no such distresses were observed during these reviews. Part of the outermost lane was flushed in summer of 1989. This flushing was inadvertently performed by maintenance personnel flushing an adjoining project.

Rut Depth Measurements

Rut depth measurements were taken on all three lanes during 1986, 1987, 1988 and on the outermost lane in 1989 and 1990. TABLE 5 shows the summary of rut depth measurements. From the table, it is evident that the average rut depth on the porous pavement section is higher than on the conventional pavement. TABLE A.1 in the Appendix A shows the measurements station by station. The stations 118+00 and 108+00 display higher rut depths than any other station location on the porous pavement. However, the average rut depth on the porous pavement section is within an acceptable limit. FIGURE 4 shows the average rut depth for the two types of pavement the last five years.

TABLE 5 SUMMARY OF RUT DEPTH (IN) MEASUREMENTS

Type	1986	1987	1988	1989	1990
Porous	0.17	.11	0.13	0.12	0.20
Conventional	0.13	0.02	0.02	0.13	0.07

NON DESTRUCTIVE TESTING

Purpose and Background

Non destructive testing (NDT) was conducted every year since 1988 and consisted of deflection testing using a falling weight deflectometer (FWD). The FWD testing was performed with a Dynatest model 8002 with sensor locations of 0, 12, 24, 36, 48, 60, and 72 inches from the center load at load levels of 6,000, 9,000, and 12,000 pounds. The testing was performed at 15 locations in 1988, 27 locations in 1989 and 90 and 21 locations in 1991. Testing was conducted in early Fall of every year. In 1989, testing was also done in the Winter. These tests were performed on the outer wheel path of the outside lane generally 2-3 feet from the edge of the pavement. In the years 1989 and 1990, FWD testing was also done in 3 locations on both porous and conventional pavements at between wheel path and inner wheel path locations. This was done to assess lateral variation of layer moduli (if any). In addition, tests were also done in January of 1989 to find the seasonal variation of layer moduli. FWD test location mileposts are shown in Appendix B.

The FWD testing was performed to detect the structural deterioration of porous pavements as well as dense graded pavements. This was to be monitored through the change in backcalculated moduli of the layers. The moduli at wheel path and between wheel path locations would be helpful to determine the difference in structural performance at these locations.

Analysis Methodology

The FWD deflection data were analyzed using the BKCHEVM elastic layer computer program to backcalculate the layer moduli (11). The porous pavement was assumed to be a 4-layer flexible pavement system. Layer 1 was the open graded AC, layer 2 was the open graded asphalt treated base, layer 3 was the open graded subbase and layer 4 was the subgrade which was assumed to be semi-infinite. The conventional pavement was a 3-layer system. Layer 1 was the dense graded AC, layer 2 was the aggregate base (AB) and layer 3 was the subgrade which was assumed to be semi-infinite. However, the BKCHEVM automatically assumes a finite subgrade thickness of 240 inches whenever a rigid layer is detected by it using the seventh sensor deflection. The deflection values corresponding to the load level closest to 9000 pounds were used for backcalculation of layer moduli.

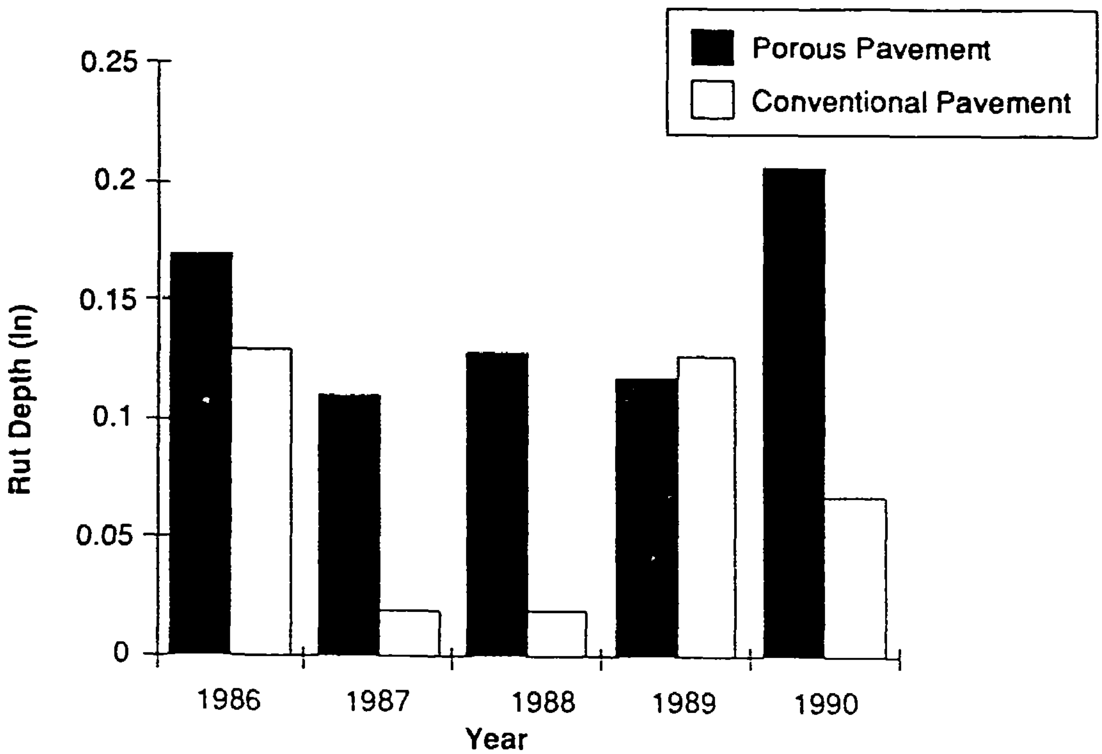


FIGURE 4 AVERAGE RUT DEPTH

Backcalculation Results

The results of the backcalculation analysis are summarized in TABLE 6 for porous pavement and TABLE 7 for conventional dense graded pavement. The average open graded asphalt concrete moduli typically ranged between 374 and 450 ksi. Individual test results ranged from a low of 205 ksi to a high of 751 ksi. The average asphalt concrete moduli for the dense graded pavement is almost two times that for open graded asphalt concrete. The subbase moduli for porous pavement and aggregate base moduli for dense graded pavement tend to decrease with time. No suitable explanation of this trend can be offered at this time. Although there is fluctuation of asphalt concrete moduli for both types of pavement, this variation may be a function of the backcalculation procedure. The subgrade moduli values for both types of pavement are relatively constant over the period of time studied. FIGURES 5, 6, 7, 8 and 9 show the comparison of backcalculated layer moduli over the past five years.

TABLE 6 - POROUS PAVEMENT BACKCALCULATED LAYER MODULI SUMMARY STATISTICS

		Backcalculated Layer Moduli (ksi)		
Layer	Year	Mean	Std. Dev.	Coeff. of Var.(%)
Asphalt* Concrete	1988	726	244	39
	1989	688	433	63
	1990	1110	414	37
	1991	527	221	42
Asphalt Treated Base	1988	302	180	60
	1989	624	239	38
	1990	589	227	39
	1991	232	175	76
Subbase	1988	20	19	95
	1989	15	19	130
	1990	13	18	138
	1991	9	6	67
Subgrade	1988	21	4	19
	1989	20	3	15
	1990	19	3	16
	1991	19	2	11

* Temperature adjusted at 77°F

TABLE 7 - CONVENTIONAL PAVEMENT BACKCALCULATED LAYER MODULI SUMMARY STATISTICS

		Backcalculated Layer Moduli (ksi)		
Layer	Year	Mean	Std. Dev.	Coeff. of Var.(%)
Asphalt *	1988	1245	15	
1				
Concrete	1989	2163	328	15
	1990	2556	30	1
	1991	780	145	19
Aggregate	1988	71	26	37
Base	1989	46	1	2
	1990	30	8	27
	1991	23	18	78
Subgrade	1988	27	3	11
	1989	26	1	3
	1990	24	1	6
	1991	23	1	3

* Temperature adjusted at 77°F

Seasonal Variation of Layer Moduli

As mentioned earlier, FWD testing was also done in January of 1989 to compare the moduli obtained during early Fall. TABLE 8 summarizes the test results. The moduli obtained for asphalt concrete and ATB layer were not remarkably different than those obtained in the previous Fall. The subgrade layer moduli were the same for the consecutive time periods. Since Phoenix area is relatively dry, the season does not appear to affect the moduli of the subgrade. It is to be noted that the asphalt concrete moduli have been adjusted to 77°F.

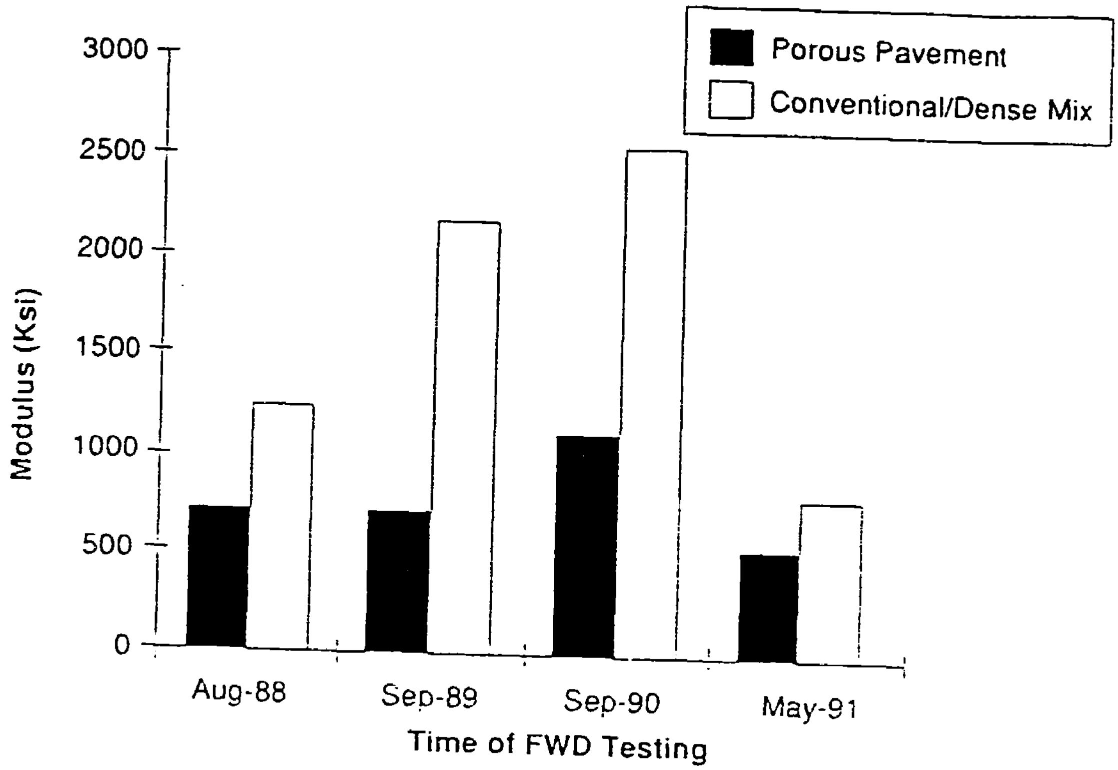


FIGURE 5 BACKCALCULATED AC MODULI

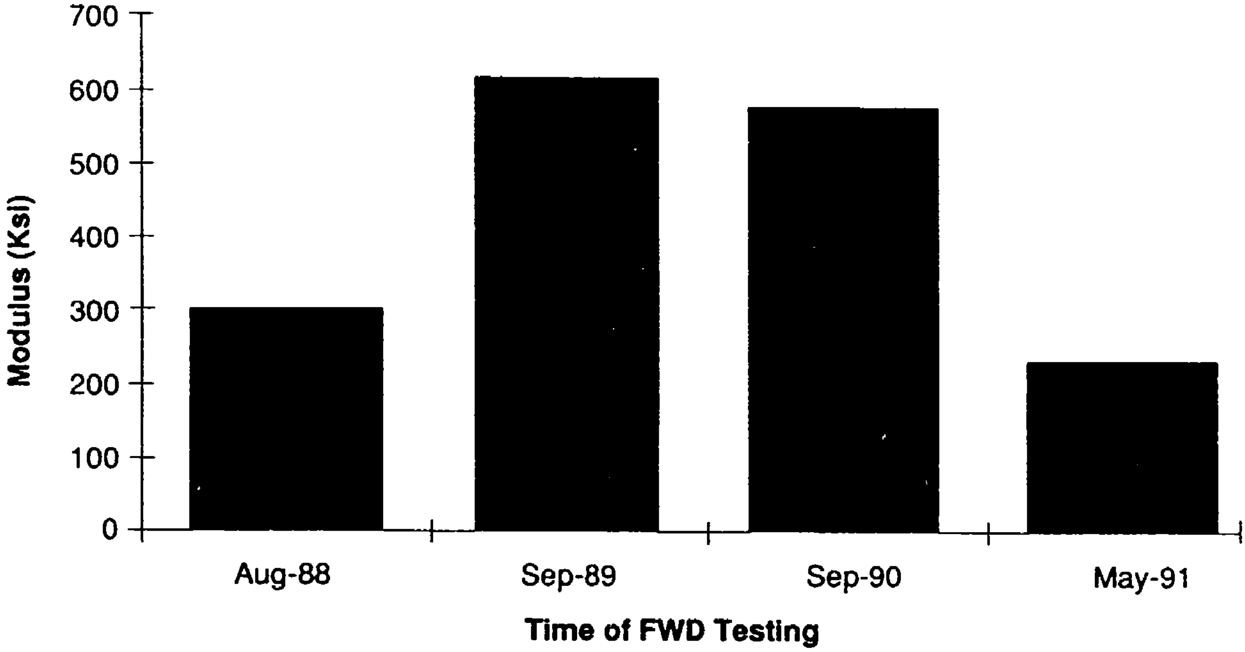


FIGURE 6 BACKCALCULATED ATB MODULI

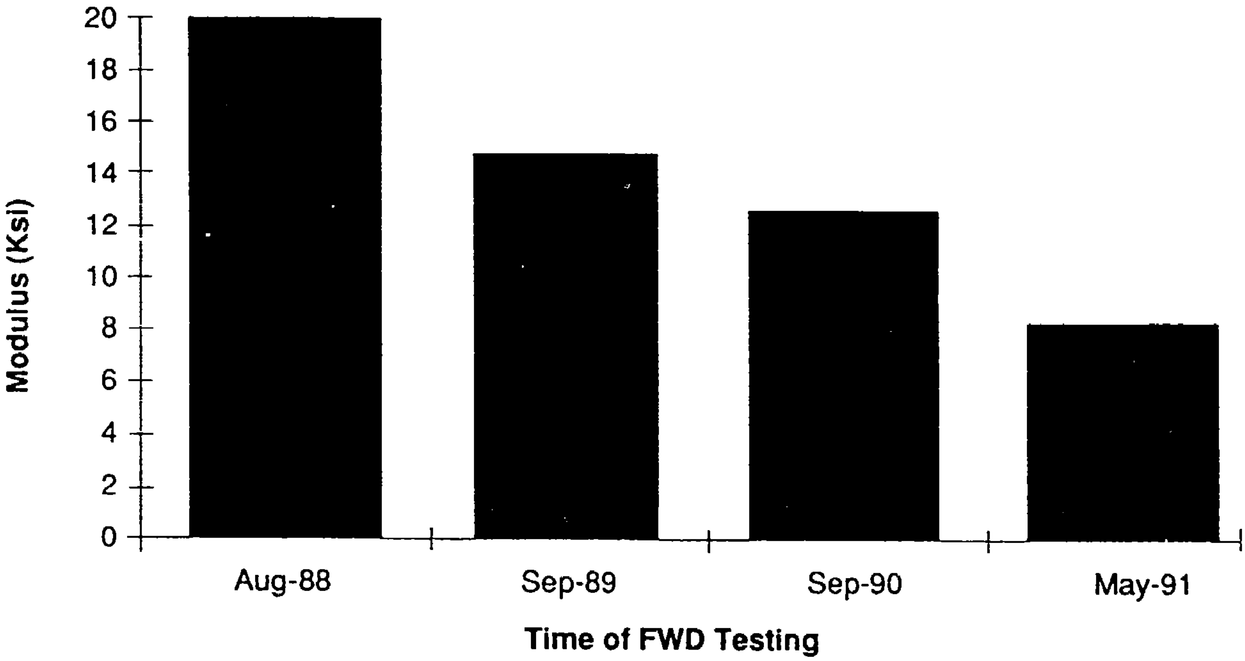


FIGURE7 BACKCALCULATED SUB BASE MODULI

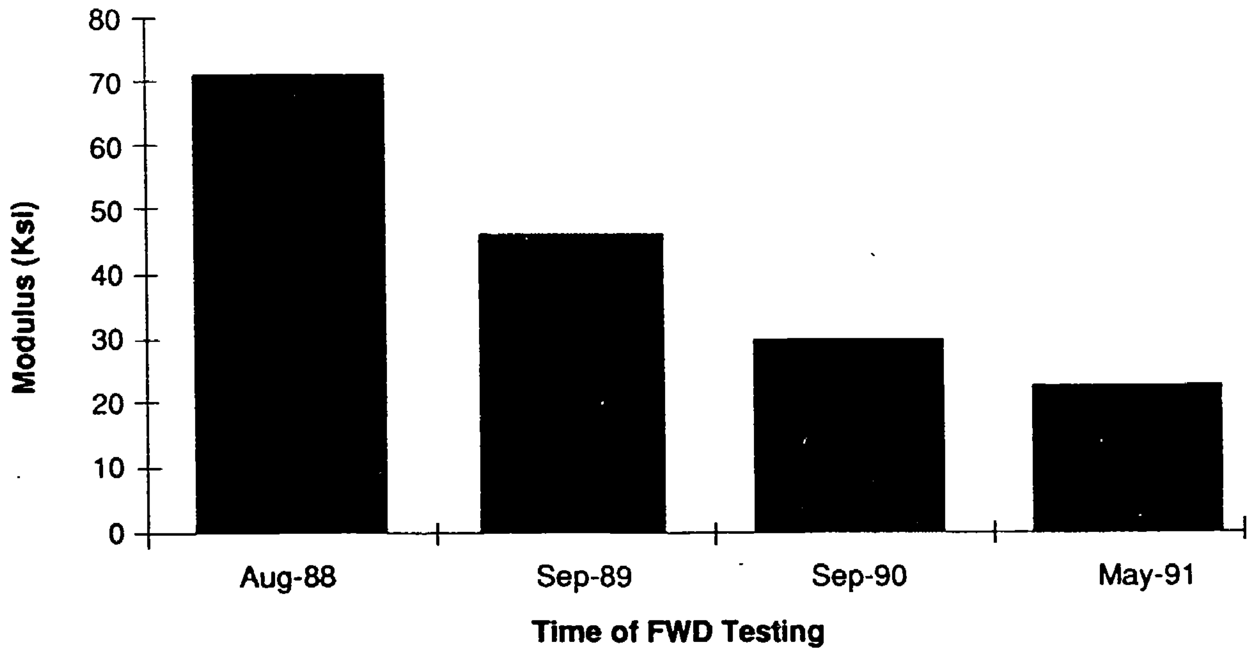


FIGURE 8 BACKCALCULATED AGGREGATE BASE MODULI

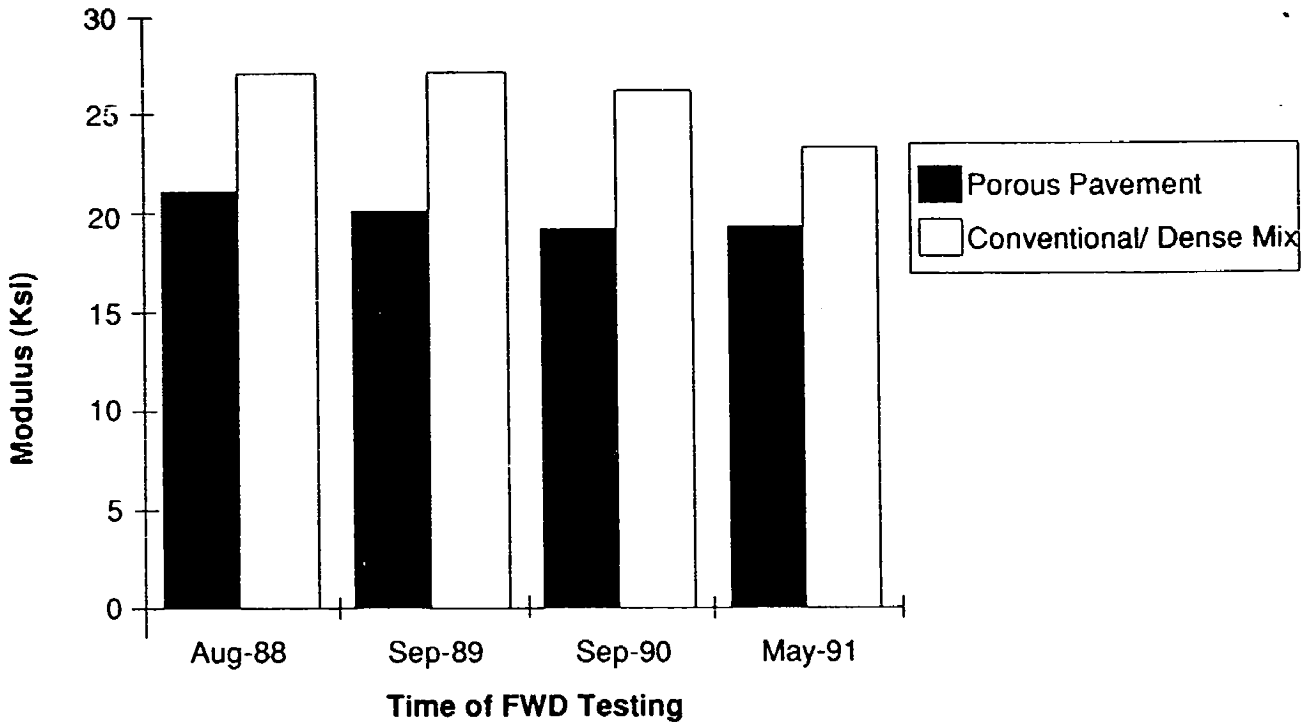


FIGURE 9 BACKCALCULATED SUBGRADE MODULI

TABLE 8 - SEASONAL VARIATION OF POROUS PAVEMENT BACKCALCULATED LAYER MODULI

SUMMARY STATISTICS

Layer	Year	Backcalculated Layer Moduli (ksi)		
		Mean	Std. Dev.	C.V.(%)
Asphalt* Concrete	Fall, 1988	726	244	39
	Winter, 1989	430	153	36
	Fall, 1989	688	433	63
Asphalt Treated Base	Fall, 1988	302	180	60
	Winter, 1989	624	117	19
	Fall, 1989	624	239	38
Subbase	Fall, 1988	20	19	95
	Winter, 1989	19	18	92
	Fall, 1989	15	19	130
Subgrade	Fall, 1988	21	4	19
	Winter, 1989	20	3	6
	Fall, 1989	20	3	15

* Temperature adjusted at 77°F

Lateral Variation of Layer Moduli

The backcalculated layer moduli for all the layers for both conventional/dense graded and porous pavement were compared. The deflection data collected in 1989 and 1990 on the outer wheel path, between wheel path and inner wheel path at three locations were used in the backcalculation analysis. TABLE 9 shows the summary statistics of the backcalculated layer moduli at theses locations. A one way analysis of variance (ANOVA) was conducted to detect any difference between the means of backcalculated layer moduli for all the layers. No significant difference was observed at 5% level of significance for any layer except subgrade layer. The sampling of subgrade in 1990 has shown higher moisture content at the outer wheel path locations than at the between wheel path locations. These higher moisture contents on the outer wheel path locations may be responsible for lower subgrade moduli.

TABLE 9- SUMMARY STATISTICS OF POROUS PAVEMENT BACKCALCULATED LAYER MODULI FOR LATERAL VARIATION

1989 Backcalculated Moduli (ksi)												
Statistic	Outer W.P.				Between W.P.				Inner W.P.			
	AC	ATB	SB	SG	AC	ATB	SB	SG	AC	ATB	SB	SG
Mean	1119	568	20	16	527	780	20	77	879	435	11	25
Std. Dev.	1106	367	22	4	123	0	25	1	309	308	9	0
C.V.(%)	99	65	110	25	23	0	125	3	35	71	80	0

1990 Backcalculated Layer Moduli (ksi)												
Statistic	Outer W.P.				Between W.P.				Inner W.P.			
	AC	ATB	SB	SG	AC	ATB	SB	SG	AC	ATB	SB	SG
Mean	1326	427	16	22	997	625	12	26	1238	401	8	27
Std. Dev.	395	310	17	6	307	268	10	5	438	176	2	3
C.V.(%)	99	65	110	25	23	0	125	3	35	71	80	0

TABLE 10- SUMMARY STATISTICS OF CONVENTIONAL PAVEMENT BACKCALCULATED LAYER MODULI FOR LATERAL VARIATION

1989 Backcalculated Layer Moduli									
Statistic	Outer W.P.			Between W.P.			Inner W.P.		
	AC	AB	SG	AC	AB	SG	AC	AB	SG
Mean	2175	31	20	2163	59	26	1905	45	27
Std. Dev.	379	0	3	236	49	5	427	24	3
C.V.(%)	17	0	15	11	83	19	22	53	11

1990 Backcalculated Layer Moduli									
Statistic	Outer W.P.			Between W.P.			Inner W.P.		
	AC	AB	SG	AC	AB	SG	AC	AB	SG
Mean	2408	32	22	2373	48	26	2228	44	27
Std. Dev.	159	13	6	340	26	5	389	25	3
C.V.(%)	7	41	27	14	54	19	18	57	11

PAVEMENT PERFORMANCE SINCE CONSTRUCTION

Functional Performance

Roughness

Mays meter runs were made on all three lanes of porous pavement immediately after construction. The runs were repeated in 1989 in two consecutive months. At that time, the three south-bound lanes of the conventional pavements were tested for comparison. In April, 1991 the measurements were repeated on the outer lanes of the porous pavement and the conventional pavement in the southbound direction. TABLE 11 shows the mays roughness in inches/mile. It is evident that the as-built roughness of the porous pavement is somewhat higher. The 3-year and 5-year roughness measurements show that the roughness values for the porous pavement are higher than the conventional pavement. Neither type of pavement has shown significant increase in roughness with time and usage. FIGURE 10 shows the Mays meter values on both types of pavements over the last five years.

TABLE 11 - MAYS ROUGHNESS FOR POROUS AND CONVENTIONAL PAVEMENTS

	Mays Roughness (ins/mile)			
Month/Year	Lane 1	Lane 2	Lane 3	Average
POROUS PAVEMENT:				
August, 1986	161	147	199	169
June, 1989	166	140	215	174
July, 1989	165	135	205	168
May, 1991	174	81	148	135
CONVENTIONAL PAVEMENT:				
June, 1989	166	119	148	145
July, 1989	175	116	147	146
May, 1991	84	53	163	100

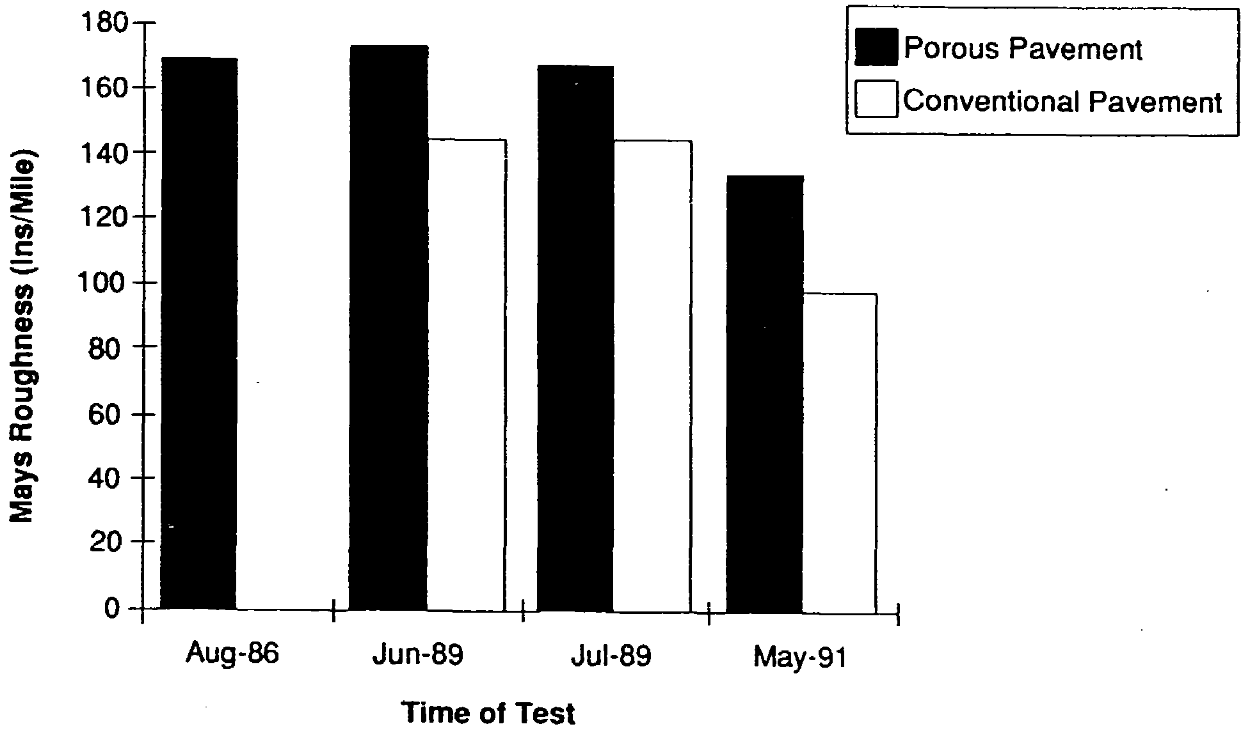


FIGURE 10 MAYS ROUGHNESS HISTORY

Skid

Skid measurements were not available for this project immediately after construction. The measurements were taken on all three lanes of the porous pavement in April, 1988 and repeated in December, 1989 and February, 1990. The later measurements also included all three lanes of the conventional pavement in the south-bound direction. A Mu-meter was used for the skid testing. TABLE 12 shows the Mu-meter values resulting from each test.. The measurements of 1990 shows a slight decrease of skid resistance as expressed by Mu-meter values compared to 1988 measurements but the Mu-meter values on the porous pavement and conventional pavement are comparable. The 1991 measurements show that Mu-meter values on both sections are comparable. FIGURE 11 compares the Mu-meter values on porous and conventional pavements.

TABLE 12 - MU METER VALUES FOR POROUS AND CONVENTIONAL PAVEMENTS

	Mu-meter Values			
Month/Year	Lane 1	Lane 2	Lane 3	Average
POROUS PAVEMENT:				
April, 1988	53	51	53	52
December, 1989	41	42	45	43
February, 1990	49	44	46	43
May, 1991	52	52	54	53
CONVENTIONAL PAVEMENT:				
December, 1989	46	49	44	46
February, 1990	50	52	45	49
May, 1991	-	49	52	51

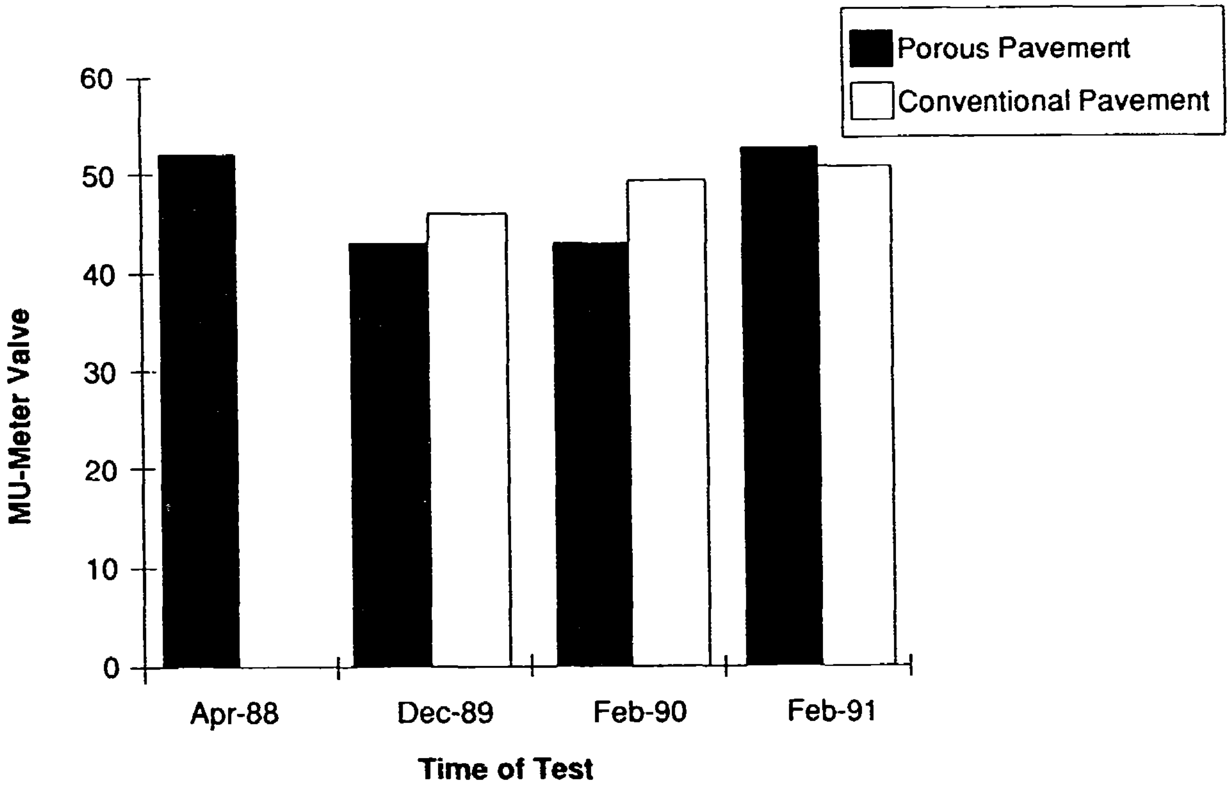


FIGURE 11 SKID HISTORY

Hydraulic Performance

Analysis of Rainfall Data

The rain gage data collected by the continuous recording rain gage were analyzed over a 3-year period from 1987 to 1989. During the one-year period in 1986-87 , the highest amount of rainfall over a 24-hour period was recorded at 0.82 inch on February 24, 1987. The total rainfall for this one-year period of time was 7.07 inches. The highest estimated rainfall intensity occurred on February 26, 1987. On this day, 0.42 inch of rain fell in an estimated time period of one-half hour giving an estimated rainfall intensity of 0.84 in/hr. In 1987-88, the greatest amount of rainfall (1.15 inch) over a 24-hour period occurred on December 17, 1987. The highest estimated rainfall intensity (1.0 in/hr) occurred on April 15, 1988. The design rainfall intensities for a 10-year 10-minute storm and a 10-year, 24-hour storm are 5.20 and 0.11 in/hr, respectively.

The rainfall intensity of April, 1988 is one-fifth the amount of a 10-year 10-minute storm. The rainfall intensity of December was slightly less than one half of that for a 10-year, 24-hour storm.

In 1988-89, the greatest amount of rainfall (1.35 inch) over a 24-hour period occurred in September 22, 1988. The highest estimated rainfall intensity was 1.23 in/hour on July 29, 1988. This intensity is again much lower than the design 10-year 10-minute storm. The last highest amount of rain was recorded on January 4, 1989. A total of 1.24 inch was recorded over a 24-hour period.

FIGURES 12 and 13 compare design rainfall intensities for 10-year 24-hour storm and 10-hour 10-minute storm with actual rainfall on the project in years 1987-89.

The surface of both pavements were observed after rain storms in October, 1986 and February, 1987. It was visually observed that the surface of the porous pavement, although wet, did not have any standing or excess water on its surface. The surface of the conventional pavement was also wet, but, sheets of water could be seen on the surface along with water flowing in the curbs. It appeared that the porous pavement was draining water faster than the conventional pavement. Also the lane stripe delineation was more visible on porous pavement than on conventional pavement. During night driving, reduced headlight glare was also observed.

Analysis of Well Point Data

The highest water level recorded in the trench during the first and the second years in the trench was 3-1/2 inches and 9 inches respectively. The water levels were recorded with respect to the bottom of the trench. The readings indicated that the capacity of drainage trench had not been exceeded. No recording is available for the third year.

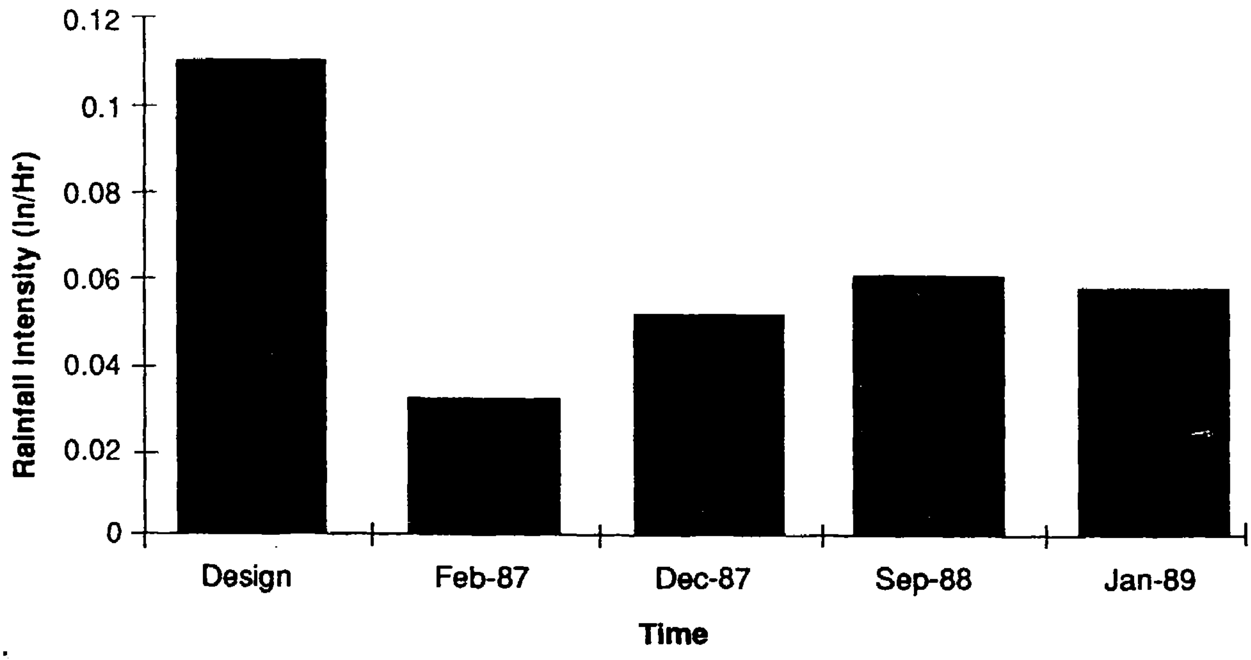


FIGURE 12 COMPARISON OF DESIGN AND (FOUR HIGHEST) ACTUAL RAINFALL FOR 10-YEAR 24-HOUR STORM

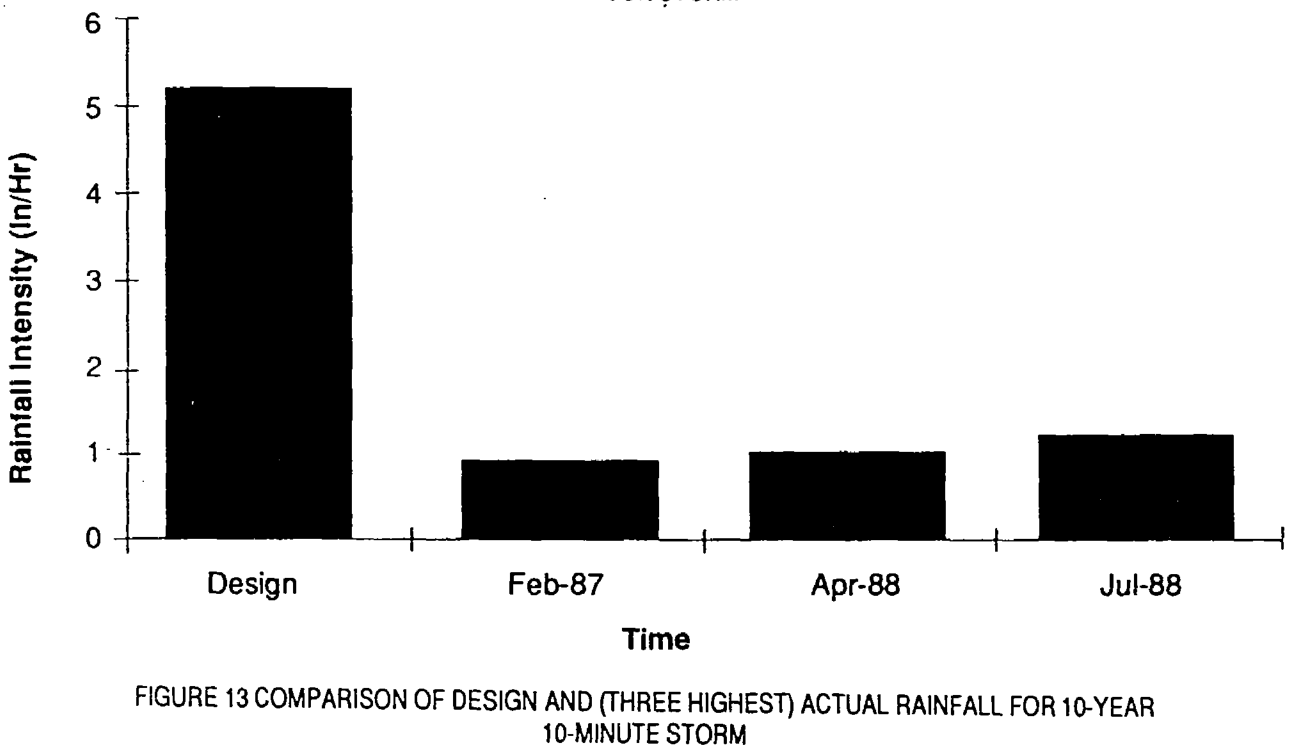


FIGURE 13 COMPARISON OF DESIGN AND (THREE HIGHEST) ACTUAL RAINFALL FOR 10-YEAR 10-MINUTE STORM

Subgrade Moisture Content

All moisture monitors were initially read on June 7, 1986. The majority of the monitors underwent a significant decrease in resistance between then and the next reading on August 11, 1986. A substantial portion of this change appeared to be stabilization of the monitors or moisture contents within the subgrade in the vicinity of the gages. Readings were taken several times during the first year. The moisture readings from monitoring devices located at Station 97+40 Lt and 138+00 Lt remained approximately the same when read in August, 1986, July, 1987 and June, 1988. After the first year, the estimated moisture content of the subgrade at Station 108 Rt increased approximately 2.3 percent. After two years Station 108 Rt had an estimated increase in moisture content of 1.5 percent. The moisture content in the subgrade increased more for gages 5 and 6 which are located nearest to the trench excavation.

The moisture content of the subgrade has decreased approximately 1 percent at Station 138+00 Rt. in 1988. This change was significant at gage 5 where the decrease was estimated to be 4.7 percent. The change in the moisture content at gage 5 may be caused by the stabilization of the subgrade moisture at this location.

Moisture monitor gages located at Station 143+25 Lt indicate a fairly insignificant change in subgrade moisture except for gage 5. During the first year monitoring period, gage 5 indicated a subgrade moisture increase of 9.2 percent. After two years of monitoring, the increase was 8.7 percent. This small change in moisture content would indicate that the moisture content in this area of the subgrade has stabilized.

At all Stations except for 138+00 RT some gages read 2000 or infinity. This would indicate that the soil has dried out or that the monitoring gage has malfunctioned (7).

Structural Performance

No cracking has been observed in the porous pavement to date. Some ravelling was suspected in 1988, but did not turn out to be serious. The rutting in the porous pavement though higher than conventional pavement is within acceptable limits.

SAMPLING AND TESTING POROUS PAVEMENT MATERIALS

In 1990, an extensive sampling and laboratory testing of porous pavement materials was conducted. The objective of this testing program was to find out characteristics of in-service porous pavement materials. The test results were planned to be correlated with the functional and structural performance of the porous pavement. The test results would also serve as a datum for future comparison of material properties.

Sampling

The sampling was done according to the work plan attached in Appendix C. The number of samples required to characterize the porous pavement materials was based on the statistical analysis of as-built porous pavement core properties. Thirty open graded asphalt concrete cores were retrieved by dry coring. Nuclear density gage readings were obtained at each coring location to measure the in-situ density of porous asphalt concrete. The asphalt treated base material samples were collected at each location. Subbase samples were collected at twelve locations. The subgrade was sampled at six locations.

TESTING AND RESULTS

Open Graded Asphalt Concrete

Bulk Density

Thirty cores were prepared for bulk density testing by saw cutting at the lift line between the AC and ATB layers. Bulk density tests were performed by measuring the length, diameter and mass of each core, as described in procedure 6.2 of ASTM method D3203 (12). As mentioned earlier, nuclear density gage measurements were taken at the core locations. TABLE 13 shows the summary statistics of the density measurements of the cores as well as nuclear density gage measurements. The table shows the measurements in 1986 (as-built) and also in 1990 (4 years after construction). The small coefficient of variation of the measurements indicate somewhat the homogenity of the porous pavement materials. Students t-tests were performed to find the difference of means of each measurement. Appendix D shows the test results.The p-values of the tests were included to judge significance of difference. It is to be noted that the p-value is the smallest level o at which the difference in means are statistically significant (13). At 5% level of significance, significant differences were observed between all sets of data. From the table it is evident that on the average, there is a 2 to 3 pcf increase in the density of porous pavement asphalt concrete after 4 years in service. Although the average unit weight in 1990 was similar for both the outer wheel path and between wheel path locations, the range in values suggest that some densification has occurred in the wheel paths.

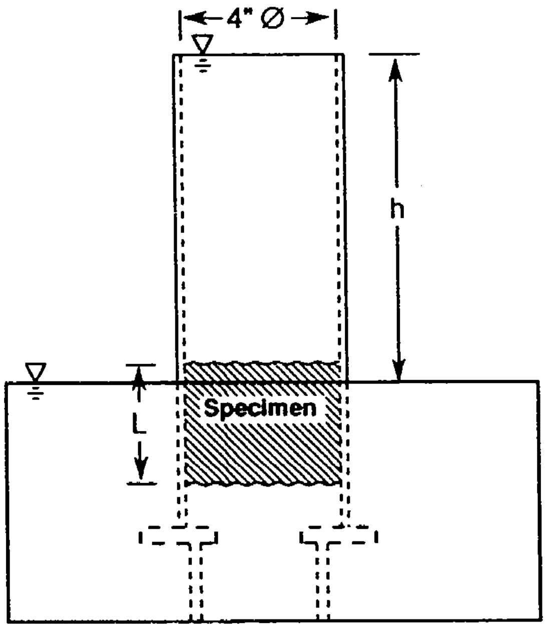
TABLE 13- NUCLEAR AND LABORATORY DENSITIES OF POROUS ASPHALT CONCRETE

Statistic	AS BUILT (1986)				IN-SERVICE (1990)			
	Nuclear		Laboratory		Nuclear		Laboratory	
	OWP	BWP	OWP	BWP	OWP	BWP	OWP	BWP
X	118.5	116.3	116.9	113.6	122.4	121.9	120.1	119.8
o	0.8	1.1	0.35	0.35	2.0	1.7	2.0	1.9
CV	0.68	0.95	0.30	0.30	1.63	1.40	1.67	1.6
n	4	4	4	4	18	18	13	15

Note: CV: Coefficient of Variation (%)

Permeability

Permeability tests were conducted on the cores using a constant head water permeability test procedure. The test set up has been shown in FIGURE 14. Specimens were soaked in water for 24 hours prior to being placed into the test apparatus. The water flow rate was then adjusted to achieve a constant head over the specimen. The flow rate was determined by measuring the volume of water that passed through the specimen in 60 seconds. The average of two repetitions of this measurement was recorded. TABLE 14 tabulates the summary of these test results with the core unit weights. The coefficient of permeability during the mix design formulation was 200 ft/day. From TABLE 14, it is evident the permeability/porosity of the in-service porous pavement has decreased. But the values are well above 26 ft/day required by design. It is to be noted that the average coefficient of permeability in the wheel paths is less than that between the wheel locations.



$$K = \frac{QL}{hAt}$$

Where:

K = Coefficient of Permeability, cm / sec
Q = Quantity of Water, cc
L = Length of Speciman, cm
h = Water Head, cm
A = Surface Area, cm^2
t = Time, sec.

FIGURE 14 CONSTANT HEAD WATER PERMEABILITY TEST SET UP

TABLE 14- PERMEABILITY TEST RESULTS

	1986 (After Construction)		1990 (In service)	
Station	Unit Weight (pcf)	K (ft/day)	Unit Weight (pcf)	K (ft/day)
OUTER WHEEL PATH:				
Mean	123	154	120.0	76.0
Std. Dev.	-	-	1.93	44.1
C.V. (%)-		-	1.60	58.3
Range			117-125	27-166
BETWEEN WHEEL PATH::				
Mean			119.7	80.5
Std. Dev.			1.82	61.2
C.V. (%)			1.50	76.1
Range			116-122.6	14-264

Moisture Susceptibility

Twenty-four porous asphalt concrete specimens were tested for moisture susceptibility according to applicable sections of the Root-Tunnicliff procedure (14). The cores were sliced into top and bottom halves and grouped separately to eliminate the variability due to different lifts in construction in the test data. Although the porous asphalt concrete was designed to be moisture resistance, any potential problem would be diagnosed by this test. TABLE 15 shows the test results. From the Table, it is evident that the tensile strength ratio (TSR) of the samples are reasonable with the top lift samples showing higher TSR than the bottom lift samples. It is to be noted that no antistripping additive was used in the open graded asphalt mix.

TABLE 15- ROOT-TUNNICLIFF TEST RESULTS

	Bottom Lift		Top Lift	
	OWP	BWP	OWP	BWP
S_{td}	152.2	166.4	161.8	158.6
S_{tm}	84.1	98.9	104.0	120.3
T.S.R.(%)	55.3	59.4	64.3	75.9

Note:

S_{td}: Tensile strength of dry specimen (psi)

S_{tm}: Tensile strength of wet specimen (psi)

T.S.R (%) = S_{td}/S_{tm} X 100

Marshall Stability and Flow

Marshall Stability and Flow values were determined on 4 cores from an outer wheel path (OWP) in 1986 immediately after construction. In 1990, 5 cores from an outer wheel path (OWP) and 7 cores from between wheel paths (BWP) were tested. TABLE 16 shows the summary statistics of the test results. From the table it is evident that Marshall stability value has increased significantly since construction. There has also been an increase in flow value. The increase in flow value may be attributed to the flushing done in the summer of 1989.

TABLE 16- MARSHALL STABILITY AND FLOW TEST RESULTS

	1986/after construction				1990/ 4 years in service			
Stat.	Stability		Flow		Stability		Flow	
	OWP	BWP	OWP	BWP	OWP	BWP	OWP	BWP
Mean	272	-	16	-	1070	978	18	18
St. Dev	73	-	1.4	-	109	139	1.9	2.8
CV	27	-	11	-	10.2	14.2	10.7	15.3
n	4	-	4	-	5	7	5	7

Note: 1) OWP: Outer Wheel Path

2) BWP: Between Wheel Paths

3) CV: Coefficient of Variation (%)

4) Stability in lbs, Flow in hundredths of an inch.

Resilient Modulus

The resilient modulus test was performed on cores from 14 locations in the outer wheel path and from 16 locations between the wheel path. Each specimen was sliced into two samples of approximate size of 4-inch diameter and 2.5-inch high to represent the two different lifts used in placing porous asphalt concrete. The resilient modulus test was performed on these samples at 77^{O}F according to ASTM D4123 procedure. Each specimen was tested in two positions (90^{O} apart) and at 3 different loading frequencies (1, 0.5 and 0.3 Hz) with a load duration of 0.1 second in all cases. The applied load was between 85-130 lbs with the majority around 100 lbs. The horizontal deformation was measured and the modulus was computed by assuming a Poissson's ratio of 0.35. The instantaneous resilient modulus was the same as the total resilient modulus in about 95% of the cases. Therefore, only total resilient modulus was used in the analysis. TABLE 17 shows the summary of the test results. From the table it is evident that

TABLE 17- SUMMARY OF RESILIENT MODULUS TEST (at 77^{o}F and 1 Hz) RESULTS

	1986 Test	1990 Test			
Statistic	OWP	OWP		BWP	
		Top	Bottom	Top	Bottom
Mean	162	1004	888	962	986
Std. Dev.	38	271	287	232	359
C.V.(%)	237	27	32	24	36
n	6	14	14	16	16

the resilient modulus of the porous asphalt concrete mix has increased significantly. The average resilient response of the porous asphalt mix at the outer wheel path and between wheel path locations are the same as indicated by the similar average resilient moduli values at these locations.

Correlation between Laboratory and Backcalculated Layer Moduli

Porous asphalt concrete cores were retrieved from the FWD test locations at four points within an outer wheel path and at three points between wheel paths. TABLE 18 shows the locations, test values. and ratios of the laboratory determined resilient modulus and backcalculated layer moduli. The backcalculated layer moduli were corrected to represent the moduli at 77^{o} F. The laboratory testing was performed at 77^{o}F and 1 Hz test frequency. From the table, it is evident that although the ratios of individual laboratory test results to the backcalculated layer moduli are different, the average ratio is close to unity.

TABLE 18- COMPARISON OF LABORATORY AND BACKCALCULATED ASPHALT CONCRETE MODULI

Station	Location	Lab. Modulus (ksi)	Backcalc. Modulus (ksi)	Ratio
115+00	OWP	815	1053	0.77
121+00	OWP	1017	720	1.41
126+00	OWP	1125	1323	0.85
134+00	OWP	1111	864	1.29
118+00	BWP	486	883	0.55
126+00	BWP	818	1276	0.64
134+00	BWP	703	702	1.00
AVERAGE				0.91

Fatigue

Twelve specimens were tested for fatigue using the indirect tensile mode. The test was performed at 77°F. In all cases, a stress controlled test was performed in which a constant vertical load was applied along the vertical diameter of the specimen. The load was applied with a frequency of 1 Hz (0.1 sec loading and 0.9 sec rest period) until a crack developed. The magnitude of the load was controlled to have a wide range of stress levels in different specimens. The selection of the load magnitude was based upon a trial and error procedure in order to complete the test within a reasonable time period. Several load magnitudes were used ranging from 600-1500 lbs. In all cases, the horizontal deformation was recorded in the first 20-30 minutes or before the specimen failed. By knowing the load and the initial horizontal deformation, the tensile stress and initial tensile strain were computed as:

$$\sigma_t = 0.156\ P/h$$

$$\varepsilon_t = X_t \quad \frac{0.03896 + 0.1185\,v}{0.06730 + 0.2494\,v}$$

where:

σ_t = tensile stress, psi

P = applied repeated load, lb

h = specimen thickness, in

ε_t = tensile strain, in/in

X_t = horizontal deformation, in

v = Poisson's ratio (assumed to be 0.35 at 77oF)

A linear regression between was conducted between the logarithm of strain and the logarithm of strain repetitions determined in the fatigue test. The analysis yielded the following fatigue relationship for porous asphalt concrete:

$$N = 10^{-5.395} \times (1/e)^{2.437}$$

where:

N = number of strain repetitions

ε = tensile strain in asphalt concrete (micro-inch/inch)

Gradation of Asphalt Concrete

The aggregates extracted from the cores of asphalt concrete were tested for gradation to detect any change in gradation that might happen due to degradation of the open graded aggregates after four years of service. TABLE 19 shows the results of the gradation analysis for the 1990 sampling of porous pavement, the as-built, and specified gradation for porous asphalt concrete. From the table it is evident that no signs of degradation are discernible.

TABLE 19- GRADATION OF ASPHALT CONCRETE AGGREGATES

Sieve No	Percent Passing			
	Specs	As Built (1986)	In service (1990)	
			OWP	BWP
1/2"	100	100	100	100
3/8"	82-100	100	100	100
#4	19-46	31	39	39
#8	0-28	10	13	13
#40	0-16	8	5	6
#200	0-5	1.5	1.9	2.1

Properties of Extracted Asphalt Cement

The extraction was performed in accordance with ASTM method D2172. The extracted asphalt was then recovered by the Abson method (ASTM D1856). Penetration (ASTM D5) and absolute viscosity (ASTM D2171) of the extracted asphalt cement were determined. TABLE 20 shows the test results of these tests as well as these parameters determined immediately after construction. It is apparent that there has been an increase in viscosity of the asphalt cement.

TABLE 20 - ASPHALT CEMENT PROPERTIES

	1986 tests			1990 tests		
	AC Con.	Pen.	Viscosity	AC Con	Pen.	Viscosity
	(%)	(1/10 mm)	(poises)	(%)	(1/10 mm)	(poises)
OUTER WHEEL PATH:						
Mean	5.98	-	10,933	5.48	5.4	68,386
Std. Dev.	0.12	-	4,636	0.33	0.89	20,036
C.V. (%)	2.0	-	42.4	6.0	16.5	29
n	3	-	3	5	5	5
BETWEEN WHEEL PATH:						
Mean	-	-	-	5.34	5.6	69,374
Std. Dev.	-	-	-	0.23	2.44	27,032
C.V. (%)	-	-	-	4.3	43.8	39
n	-	-	-	7	7	7

ASPHALT TREATED BASE

The asphalt treated base (ATB) samples were tested for extraction, moisture content of AC, asphalt content, gradation, Abson recovery, penetration and viscosity following ASTM methods D2172, D1461, C136, D1856, D5 and D2171 respectively. The ATB samples were combined with each other. Usually the samples at consecutive station locations were combined. The large sample sizes were necessary to get enough recovered asphalt to perform the penetration and viscosity tests. Samples were not combined until the extraction, moisture content and gradation were measured. TABLE 21 shows the properties of extracted asphalt cement and TABLE 22 shows the gradation of ATB aggregates along with as-built and specified gradations. Values of TABLE 21 are for future comparison of ATB asphalt properties. TABLE 22 shows that the gradation of the ATB has not changed after four years in service.

TABLE 21- PROPERTIES OF ATB ASPHALT CEMENT (1990 TESTS)

	OWP			BWP		
Statistic	AC Content	Penetration	Viscosity	AC Content	Penetration	Viscosity
	(%)	(1/10 mm)	(poises)	(%)	(1/10 mm)	(poises)
Mean	1.38	6	128,149	1.78	3.4	87,762
Std. Dev.	0.42	2.2	72,416	0.44	1.67	42,055
C.V. (%)	30	37	56	25	49	48
n	4	5	5	5	5	5

TABLE 22- GRADATION OF ASPHALT TREATED BASE AGGREGATES

Sieve No	Percent Passing			
	Specs	As Built (1986)	In service (1990)	
			OWP	BWP
1"	100	100	100	100
3/4"	90-100	94	91	95
1/2"	-	68	65	67
3/8"	30-50	38	38	39
#4	0-5	7.4	8	8
#8	0-2	3.2	3.6	1.2

OPEN GRADED SUBBASE

The moisture content of the subbase samples were determined according to ASTM D2216. The samples were then tested for gradation as per ASTM C136. The gradation analysis results as well as built and specified gradation results are shown in TABLE 23. The subbase samples were also tested for relative density (ASTM D4253). TABLE 24 shows the test results. The relative density tests were intended to assess the volume change of open graded subbase materials over the years of service. From TABLE 23, it is evident that there is no change in gradation of subbase materials four years after construction.

TABLE 23- GRADATION OF OPEN GRADED SUBBASE AGGREGATES

Sieve No	Percent Passing			
	Specs	As Built (1986)	In service (1990)	
			OWP	BWP
1"	100	100	100	100
3/4"	95-100	97	97	93
3/8"	25-50	37	42	35
#4	0-5	3.8	3.5	4
#8	0-2	1.1	0.8	0.67

TABLE 24- RELATIVE DENSITY OF OPEN GRADED SUBBASE MATERIALS

Statistic	Min. Density (pcf)	Max. Density (pcf)
Mean	83.9	96.2
Std. Dev.	2.1	6.5
C.V. (%)	2.5	6.7
n	6	6

SUBGRADE

Moisture content measurements were conducted on subgrade soils in accordance with ASTM D2216. The average moisture contents at the outer wheel path locations and between wheel path locations were 4.7% and 1.5% respectively. These moisture contents were well below the optimum moisture content of 13% used during the design phase.

DISTRIBUTION OF MOISTURE IN THE PAVEMENT

TABLE 25 shows the distribution of moisture contents in each layer of the porous pavement. No unusual moisture presence was detected in any layer.

TABLE 25- DISTRIBUTION OF MOISTURE IN THE PAVEMENT (1990 DATA)

	Moisture Content (%)	
Layer	OWP	BWP
AC	0.12	0.10
ATB	0.13	0.20
Sub base	0.36	0.42
Subgrade	4.7	1.5

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The porous pavement test section has performed satisfactorily for five years. Although a slight decrease in the infiltration rate has occurred, both the infiltration rate and the storage capacity are above the design values. The storage capacity of the pavement subbase and trench drain system has been under utilized. This might suggest an overly conservative design. If a design intensity storm occurs during the remaining service life this should be verified. Visual observation during rain storm has shown that the surface of the porous pavement section does not include sheet flow. This provides a marked difference in stripe delineation and pavement glare during night time inclement weather driving when compared to conventional pavement.. Mu-meter skid test results for the porous pavement section are comparable to those of conventional pavements (control). It was expected that the porous pavement would have higher skid resistance due to its improved drainage characteristics. This expected condition may likely exist with heavier concentrations of water than what is applied during Mu-meter skid testing.

Several problems developed during the construction of the pavement structural section. Stability problems within the open graded subbase and asphalt treated base layer resulted in serious rutting and a loss of section at the roadway median. A thin overlay was required during construction to restore the roadway surface to proper grade and riding qualities. Even with the additional overlay, the Mays roughness values are higher for the porous pavement than the conventional pavement. No significant increase in roughness has occurred with time and usage since the project was completed. Future design should consider using only stabilized materials with additional examination of the stability of the asphalt treated base layer.

Although a detailed analysis of the cost-effectiveness of the porous pavement section was not performed for this report, the authors do not believe that this section provided significant, if any, cost savings over conventional design. True construction costs are seldom achievable with experimental sections.

Material tests conducted on the pavement components indicate that the Marshall stability, resilient modulus, and asphalt cement viscosity of the open graded asphalt concrete have increased with time. No cracking or significant surface deformation have occurred during the five years of service.

Annual FWD testing was conducted to establish the changes in layer properties. To date, little change has occurred in the layer moduli except for the open graded subbase whose modulus has decreased with time. This phenomenon is unexplained at present. Since these moduli were obtained through backcalculation analysis of FWD data, it is not certain whether the results are an artifact of the backcalculation procedure or "true" properties of the material.

No unusual presence of moisture was detected in any layer of the pavement system. The subgrade moisture content has achieved equilibrium and less than optimum moisture content determined during the design process.

Recommendations

It is recommended that the porous pavement be monitored for another five years to establish its performance characteristics. The performance monitoring scheme should include biennial Mays roughness, Mu-meter, rut depth and FWD deflection data collection. Visual distress surveys are recommended every other year. Laboratory tests of the cores and samples taken from this section should be conducted at the seventh and the tenth years. The test results are recommended to be correlated with observed performance.

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APPENDIX A

RUT DEPTH MEASUREMENTS

TABLE A1 – RUT DEPTH MEASUREMENT (IN INCHES) BY STATION

STATION	1986		1987		1988		1989		1990	
	OWP	IWP	OWP	IWP	OWP	IWP	OWP	IWP	OWP	IWP
POROUS										
138+00	1/8	1/8	0	0	0	1/8	1/8	1/8	3/16	1/8
133+00	1/4	1/8	1/8	0	1/8	1/8	0	1/8	1/4	3/16
128+00	1/8	1/8	1/8	1/8	1/8	1/8	1/8	1/8	1/8	3/16
123+00	1/4	0	1/8	1/8	1/8	1/8	1/8	1/8	1/4	3/16
118+00	3/8	1/8	1/4	1/8	1/4	1/8	3/8	1/8	3/8	3/16
113+00	1/4	1/8	1/8	1/8	1/4	1/8	1/8	1/8	3/16	3/16
108+00	1/4	1/8	1/8	1/8	1/8	1/8	---	---	5/16	3/16
AVERAGE	0.17		0.11		0.13		0.12		0.21	
CONVENTIONAL										
143+00	1/8	0	0	0	0	0	1/8	1/8	1/8	1/16
141+00	1/8	0	0	1/8	1/8	0	1/8	1/8	3/16	3/16
104+00	1/8	1/8	0	0	0	0	---	---	0	0
102+00	1/8	1/8	0	0	0	0	---	---	1/16	1/16
AVERAGE	0.13		0.02		0.02		0.13		0.07	

APPENDIX B

FWD TEST LOCATIONS

TABLE B1 – FWD TEST LOCATIONS

Type	Lane	Location of Testing			
		Location Mile Post	Outer W. P.	In Between W. P.	Inner W.P.
Experimental	3	169.0877N	X	-	-
		169.1256N	X	-	-
		169.1824N	X	X	X
		169.2203N	X	-	-
		169.2771N	X	-	-
		169.3150N	X	X	X
		169.3718N	X	-	-
		169.4097N	X	-	-
		169.4665N	X	X	X
		169.5044N	X	-	-
		169.5612N	X	-	-
		169.5801N	X	-	-
Conventional	3	169.0877S	X	-	-
		169.1824S	X	X	X
		169.2771S	X	-	-
		169.3718S	X	X	X
		169.4665S	X	-	-
		169.5612S	X	X	X
		169.6190S	X	-	-
		169.6190N	X	-	-
		169.6559N	X	-	-

APPENDIX C

WORK PLAN FOR POROUS PAVEMENT PROJECT

SCOPE OF WORK AND ESTIMATED BUDGET
for
HPR-PL-1(25) 227
POROUS PAVEMENT FOR CONTROL OF HIGHWAY RUNOFF

Performing Organization

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Arizona Department of Transportation
206 South 17th Avenue Mail Drop 075R
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February 2, 1990

PROBLEM STATEMENT:

Paved surface increases surface run-off and overloads the existing sewer system if alternative drainage is not provided. Rainfall is the only source of surface run-off in Phoenix area. Typical summer storms have high intensity and short duration while typical winter storms have low intensity and longer. This creates a large volume of run-off requiring large highway drainage structures. Up to 35% of the total cost of highway pconstruction rojects in Arizona's urban area is expended on drainage structures.

In an attempt to reduce the need for extensive drainage structure, porous pavements have been suggested as an alternative to conventional pavement. The basic concept of porous pavement design is that in addition to carrying traffic, the porous pavement will also serve as a drainage system by absorbing, storing and dissipating storm waters into the ground.

To determine the constructibility and subsequent performance of porous pavement as a drainage system and pavement structure in an urban area and a desert environment, ADOT constructed a 3500 ft long porous pavement experimental test section as part of the construction project F045-1(4). The section is located in the three north bound lanes of SR 87 (Arizona Avenue) between Station 105+00 and 140+00 in the city of Chandler between Elliot and Warner Roads. Completed in summer of 1986, the pavement section consists of 6" Open Graded Hot Mix Asphalt Concrete, 6" Open Graded Asphalt Treated Base (ATB) and 8" Open Graded Sub base. A filter fabric was placed for separation of the subbase and subgrade. The open graded layers of the pavement drain in to a trench at the edge of the pavement which is filled with open graded aggregate. The water from the drainage trench was expected to dissipate into the natural ground. An alternative drainage system was also provided for the experimental section. This was intended for use as a bcak-up system in the event of failure of the designed experimental drainage system. The pavement was designed to handle the run-off expected from a 100-year storm or two 10-year storms on consecutive days.

RESEARCH OBJECTIVES:

The purpose of this research is to evaluate the material properties and correlate the results with the functional and structural performance of the porous pavement after five years in service. The performance attributes planned to be evaluated are porosity, stability, durability, rideability and drainage capacity. The performance of the porous pavement will be compared with the performance of adjacent conventional pavement used as a control section.

The specific objectives are as follows:

1) Determine the porosity of the pavement in service. Cores will be taken at predetermined locations on the pavement at 3 and 5 years. The permeability and the percent air voids of the cores will be used as a measure of porous pavement's porosity.

2) Determine the moisture content of each layer to establish the moisture distribution in the pavement cross section.

3) Determine the structural capacity, stability and fatigue resistance of the open graded asphalt concrete mix by testing each core for its resilient modulus, Marshall stability and fatigue strength.

4) Determine the water susceptibility or stripping potential of the open graded asphalt concrete mix by testing each core for its Tensile Strength Ratio (TSR).

5) Determine the durability of the open graded asphalt concrete mix and aging characteristics of the asphalt cement used in the porous pavement mix by testing asphalt extracted from the cores for penetration and absolute viscosity.

6) Determine the correlation between laboratory density and Nuclear Gauge density of open graded asphalt concrete mix by determining Nuclear gauge density at each core location.

7) Determine the change in rideability of the porous pavement by analyzing Mays meter roughness data over the life of the project.

8) Determine the change in frictional characteristics of the porous pavement by analyzing the Mu-meter data over the life of the project.

9) Detect the plastic deformation characteristics of the porous pavement system by analyzing the rutting data over the life of the project.

10) Determine the change in pavement layer moduli and critical responses (tensile strain at the bottom of asphalt concrete layer and vertical compressive strain at the top of the subgrade) by analyzing Falling Weight Deflectometer (FWD) data taken every year over the life of the project.

11) Determine the hydraulic performance of the porous pavement by analyzing rainfall data and well point (at STA 130+00 NB) readings. Determine the moisture equillibrium of the porous pavement system using subgrade moisture monitor data (at STA 97+40, 138+00, 143+25 SB and 108+00 and 138+00 NB)

<u>WORK PLAN:</u>

The work plan is primarily devoted to an evaluation study with specific objectives outlined earlier. The accomplishment of the tasks outlined in this work plan will establish the long term performance of the porous pavement.

The following tasks shall be accomplished to fulfill the research objectives:

Task 1. Survey Rut Depths

This task shall be accomplished to establish the vertical deformation characteristics of the porous pavement system.

Rut measurements will be taken by two methods:

a) Biannually during the summer and winter months using a 10-ft straight edge and a stepped wedge with smallest step equal to 1/8 th of an inch at 100 ft intervals in the north bound direction starting at STA 105+00 and ending at STA 140+00 on both wheel paths of the outermost lane. The measurements for the control sections shall be at STA 102+00, 104+00, 141+00 and 143+00 in the north bound direction.

b) Annually Vertical control survey at P.K. shiners at STA 106+00, every 500 ft from STA 110+00 to STA 135+00 and STA 139+00 with reference points at 1', 3.5', 6', 8.5', 11', 13.75', 16.5', 19.25',22', 25', 28', 31' and 34' from the face of the curb and gutter.

Additional rut depth measurement may be made by automated method like by PASCO system.

Table 1 shows the locations where rut depth measurements shall be taken.

The end product of this task will be the rut depths on the outer most lane of the project.

Task 2. Core Retrieval

This task shall be accomplished to get the cores necessary for characterization of porous pavement materials in the laboratory. The outermost lane, or the travel lane, shall be selected to represent the entire experimental section.

Lineal Area Definition: The outermost lane of the 3-lane NB roadway shall be subdivided into two distinct lineal areas as shown in Figure 1. It is assumed that structural behavior of one lineal area is different from the another, therefore, cores are needed from each lineal area. Each lineal area is of the size 3500' X 2'.

Coring Plan: The cores shall be retrieved from the exact locations defined in the coring plan composed of Figures 2, and 3. A total of 18 cores shall be retrieved from each lineal area. 15 cores are to be used in the laboratory testing scheme and 3 are to be set aside as reserve. The number of cores and core locations were determined according to the methodology described in Appendix A.

Nuclear Gauge Density test (ARIZ 412) shall be run at each core location prior to coring.

12 cores shall have diameter of 4 inches and 6 shall have diameters of 6 inches. Cores shall include Aspahlt Concrete layer and the Asphalt Treated Base layer (total depth of coring is approximately 12 inches). Intact cores may not be obtainable for the asphalt treated base layer(ATB). The open graded subbase and subgrade are to be sampled at the 6" diameter core locations. Aggregate subbase layer materials and any core that are not intact are to be stored in air tight plastic containers. The subgrade shall also be sampled at each core location and the material be stored in air tight containers.

Each core should be marked with a water-proof crayon according to the following nomenclature:

LCC

where,

L:	Linear Area Number (1, or 2)
CC:	Core Number (01 - 18)

Coring will be done in the third and fifth year of the project. The fifth year coring plan shall be prepared based on the test results from the third year evaluation following the same methodology described in Appendix A.

Task 3. Laboratory Testing of the Cores

This task essentially describes different tests to be done on the cores, subbase and subgrade materials to be retrieved from the porous pavement.

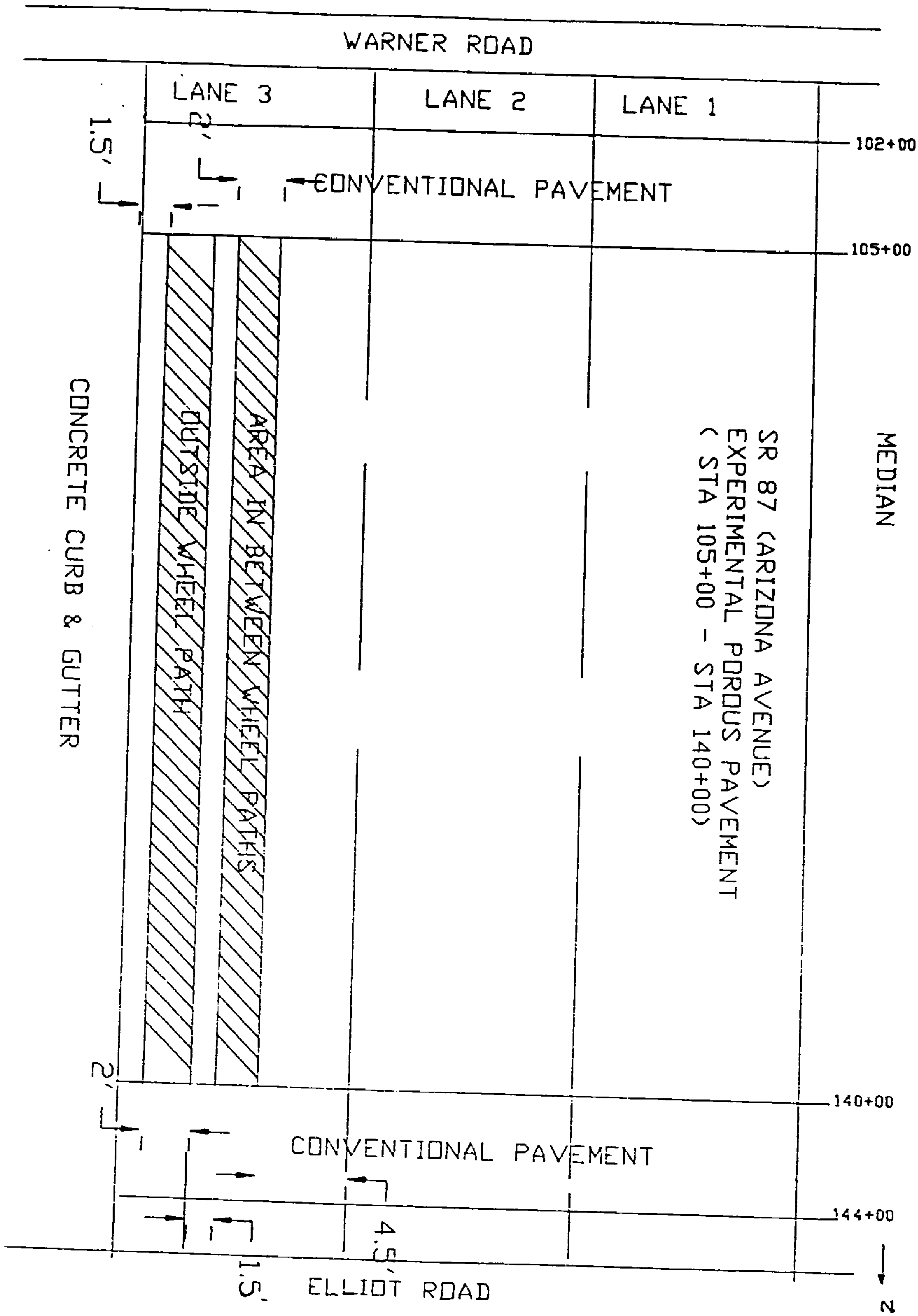

Figure 1. Linear Area Definition

Each of the areas of Outer Wheel Path and In-Between Wheel Path will be a Lineal Area of size 3500' X 2'.

Lineal Area - 1: Outside Wheel Path
Lineal Area - 2: In Between Wheel Path

Lineal Area - 1: Outside Wheel Path

Station Location	Distance From Curb & Gutter(ft)	Core Number	Core Diameter (in)
105 + 00	2.5	2	6
106 + 00	1.5	15	4
111 + 00	2.5	8	6
113 + 00	2.0	18*	4
115 + 00	1.5	1	6
116 + 00	3.0	10	4
118 + 00	1.5	16*	4
119 + 00	3.5	6	4
121 + 00	2.5	4	4
122 + 00	3.5	5	6
123 + 00	2.5	13	4
125 + 00	3.5	9	6
126 + 00	2.5	11	4
129 + 00	2.5	14	4
132 + 00	2.5	12	4
134 + 00	2.5	7	6
135 + 00	2.5	3	4
138 + 00	2.5	17*	4

* Additional cores to offset any loss in coring and subsequent handling.

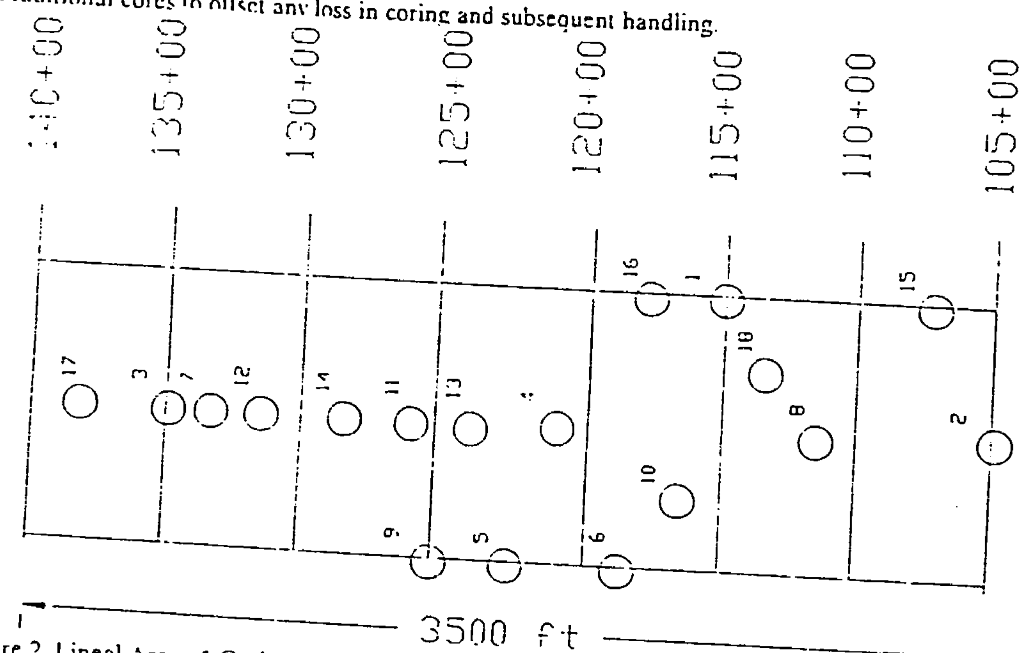

Figure 2. Lineal Area - 1 Coring Plan

Lineal Area - 2: In Between Wheel Path

Station Location	Distance From Curb & Gutter(ft)	Core Number	Core Diameter (in)
107 +00	5.0	16*	4
110 +00	7.0	7	6
111 +00	6.5	10	4
113 +00	5.0	15	4
115 +00	5.5	1	4
117 +00	5.5	2	6
118 +00	5.0	17*	4
122 +00	6.0	18*	4
123 +00	5.5	14	4
126 +00	7.0	3	4
128 +00	7.0	13	4
129 +00	6.0	11	4
131 +00	7.0	9	6
132 +00	5.0	4	6
133 +00	5.0	5	6
136 +00	5.0	12	4
137 +00	6.0	6	6
140 +00	7.0	8	4

* Additional cores to offset any loss in coring and subsequent handling.

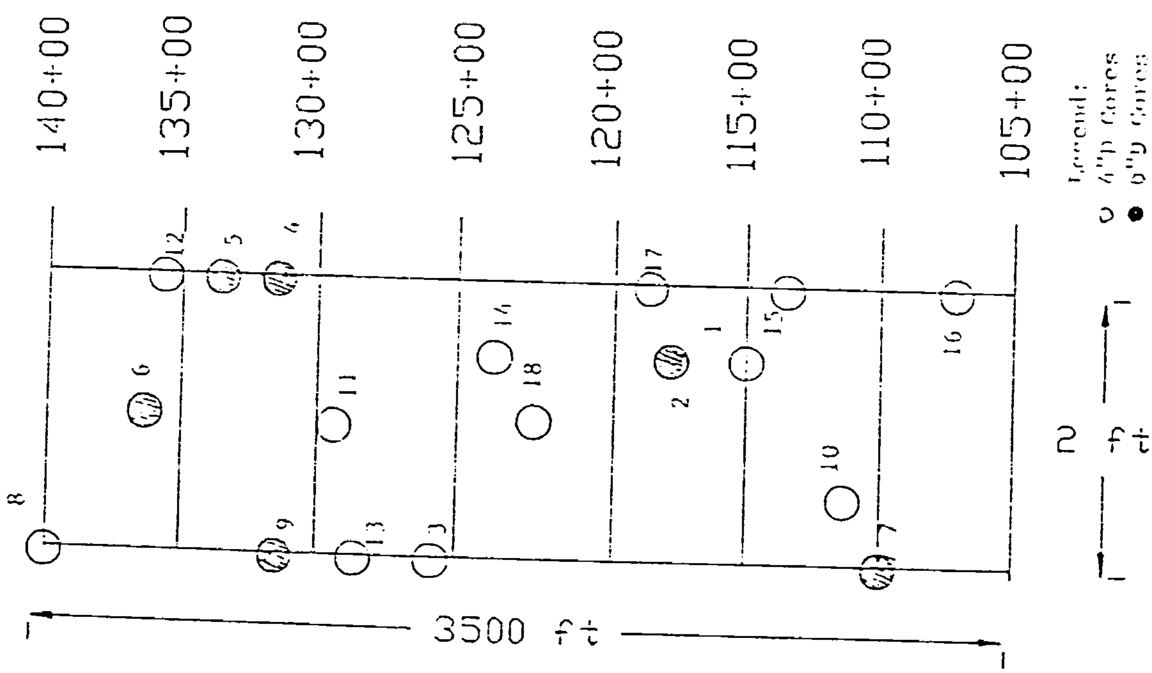

Figure 3. Lineal Area - 2 Coring Plan

TABLE 1. RUT DEPTH MEASUREMENT LOCATIONS

STATION	MEASUREMENT LOCATION	MEASUREMENT TYPE
102+00	I, O	A
104+00	I, O	A
105+00 - 140+00 @ 100 ft	I, O	A
106+00	X	B
110+00 - 135+00 @ 500 ft	X	B
139+00	X	B
141+00	I, O	A
143+00	I, O	A

Note:

I: Inside Wheel Path
O: Outside Wheel Path

X: 1', 3.5', 6', 8.5', 11', 13.75', 16.5', 19.25', 22', 25', 28, 31' and 34' from the face of the curb and gutter

A: Using a 10-ft straight edge and a stepped wedge with smallest step equal to 1/8th of an inch
B: Vertical control survey at P.K. Shiners

Each core of the bound layers shall be measured for thickness by ASTM method D3549.

The 6 inch diameter cores shall be trimmed to have 4 inch diameters following bulk density and permeability testing. Permeability tests may be run on trimmed 4 inch diameter cores.

Laboratory testing shall include as a minimum, the following tests: bulk density, permeability, resilient modulus, fatigue, tensile strength ratio (TSR), Marshall stability and flow, extraction, Abson recovery, moisture content, gradation, penetration at 77°F and absolute viscosity. A complete matrix of tests to be run on the cores of bound material and subbase and subgrade material appears in Table 2, Figure 4 and 5 show the hierarchial arrangement of the tests on the cores. Note that all 15 AC and intact ATB cores are to be sliced and trimmed into two halves of dimension 2.5" height and 4" diameter following bulk density and permeability tests.

Additionally, the following shall be calculated: Maximum density, air voids and VMA.

The laboratory testing shall be completed within 4 months of delivery of the samples to the laboratory. Testing shall be accomplished in the third and fifth year of the project.

Accomplishment of this task will lead to the laboratory characterization of the porous pavement materials.

Task 4 Data Collection

Annually collect the Falling Weight Deflectometer (FWD) deflection, the Mays meter roughness, Mu-meter skid and Maintenance cost data on the experimental test section. Supplement these data by annual pavement condition survey as per PAVER method on the section.

Task 5. Analysis

This task shall include analysis of all the laboratory test results, performance data and deflection test results.

The followings shall be accomplished as a minimum:

1. Compare the test results obtained from the cores to their respective specification requirements for construction and draw rational conclusions.

2. Analyze the viscosity and penetration data and establish the penetration viscosity number (PVN') to determine the aging characteristics of the porous pavement asphalt cement. Compare viscosity test results with those immediately after construction. Establish trends if they are evident.

3. Analyze the flow results in regard to in-service rut depths.

4. Develop the correlation between Marshall stability, resilient modulus and fatigue testing parameters of open graded asphalt concrete mix and relate to pavement performance.

The design of the porous pavement was based on the anticipated pavement loading and assumed strength parameters of the section selected. This study will provide an indication of the changes in the laboratory test results of the various strength tests in regard to actual pavement performance over a five year period. Correlations can then be made to ascertain which tests or combinations of the tests can be used to predict performance of open graded asphalt concrete mix.

TABLE-2. TEST MATRIX FOR EACH LINEAL AREA:

AC Core:

Test	Method ASTM	No.of Tests	Sample	Objective
Bulk density	D1188	15	Core	Percent air voids in service. Relative densification in wheel path and in between wheel paths. Sample selection for Fatigue and TSR test
Permeability	D3637	15	Core	Check against design permeability. Change of permeabilty with time.
M_R	D4123	30	Half Core	Structural capacity assesment. Input in layered elastic analysis and comparison with back calculated value. Change over time.
Fatigue	Kennedy*	6	Half core**	Estimation of remaining life. Comparison with remaining life found from elastic layer analysis using the backcaluated layer moduli.
T.S.R	Tunnicliff	12	Half core**	Water susceptibilty of the mix.
Marshall	D1559	12	Half core	Empirical measure of stability. Flow will be correlated with rutting
Extraction	D2172	6	Combined half cores	For quantitive extraction of Asphalt from the cores
Moisture	D1461	6	Combined half cores	For moisture content determination.
Recovery	D1856	6	Combined half cores	Asphalt content determination. To establish trend (if any) between M^R and AC content.
Gradation	C136	6	2 lb	To establish the uniformity of the mix. For construction control assessment.
Penetration	D5	6	.2 lb	Empirical measure of the hardening of the asphalt in service by calculating penetration viscosity number (PVN).
Abs. Viscosity	D2171	6	.08 lb	Consistency of in-service asphalt. To calculate penetration viscosity number (PVN) for temp. susceptibility assessment.

*Indirect Tension

**Of comparable bulk density

Table -2 (continued)

ATB Core: All tests on the Asphalt Treated Base (ATB) cores are subject to the condition that intact cores will be retrieved.

Test	Method ASTM	No.	Sample	Objective
Bulk density	D1188	15	Core	Percent air voids in service. Relative densification in wheel path and in between wheel paths. Sample selection for Fatigue and TSR test
Permeability	D3637	15	Core	Check against design permeability. Change of permeabilty with time.
MR	D4123	30	Half Core	Structural capacity assessment. Input in layered elastic analysis and comparison with back calculated value. Change over time.
Extraction	D2172	6	Combined half cores	For quantitive extraction of Asphalt from the cores
Moisture	D1461	6	Combined half cores	For moisture content determination.
Recovery	D1856	6	Combined half cores	Asphalt content determination To establish trend (if any) between M^R and AC content.
Gradation	C136	6	10 lb	To establish the uniformity of the mix. For construction control assessment.
Penetration	D5	6	.2 lb	Empirical measure of the hardening of the asphalt in service by calculating penetration viscosity number (PVN').
Abs. Viscosity	D2172	6	.08 lb	Consistency of in-service asphalt. To calculate penetration viscosity number (PVN') for temp. susceptibility assessment.

Tests on Open Graded Aggregate Subbase:

Test	Method ASTM	No.	Sample	Objective
Moisture	D2216	6	8.8lbs	Moisture distribution in the subbase layer
Rel. Density	D4254A	6	-	Relative idea of compaction.Correlation with rutting
Gradation	C136	6	2 lb	For construction control assessment. Change of gradation over time.

Tests on Subgrade:

Moisture	D2216	6	100g	Moisture distribution in the subgrade layer

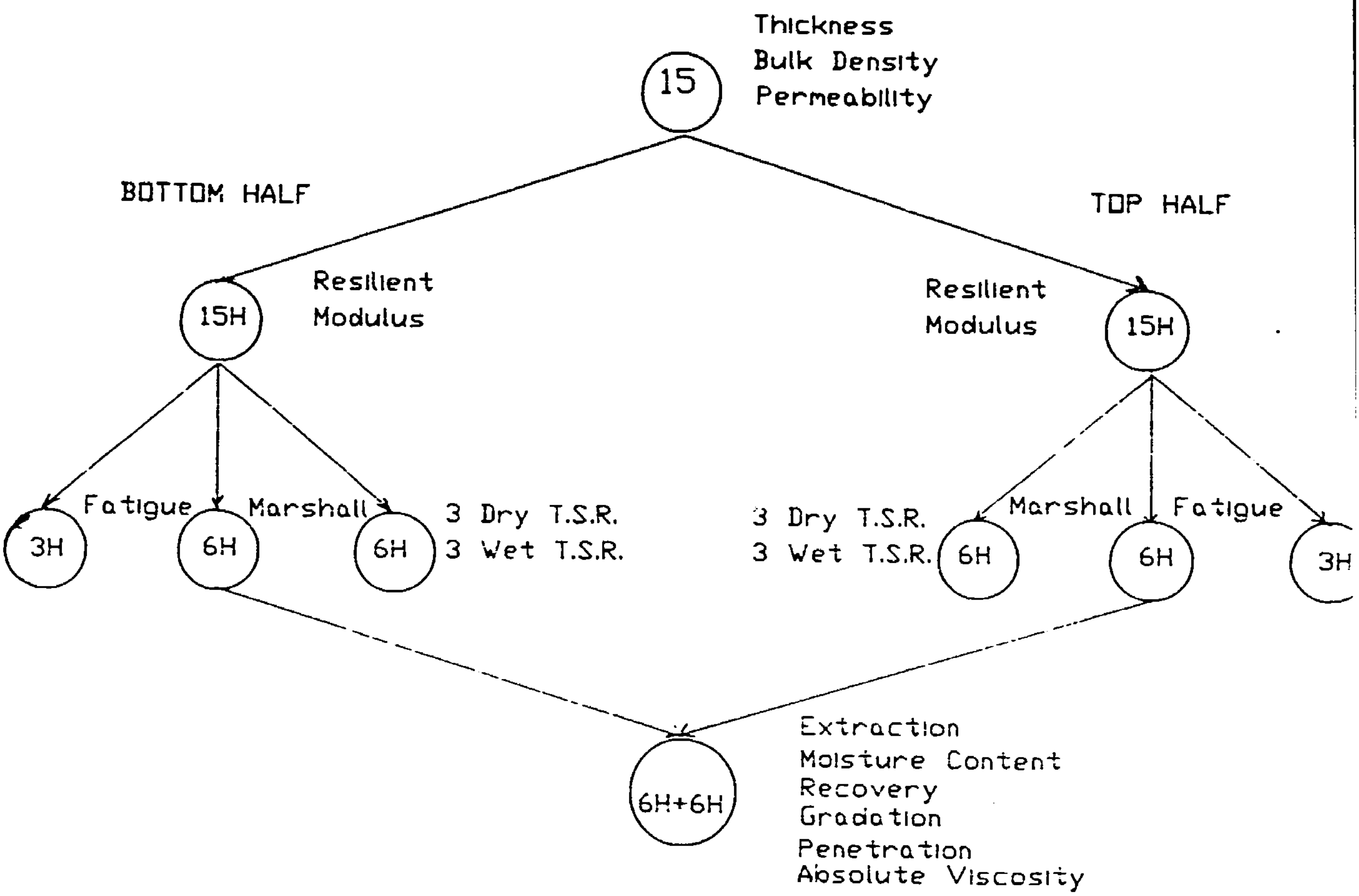

Figure 4 Hierarchial Arrangements of the Tests on AC Cores

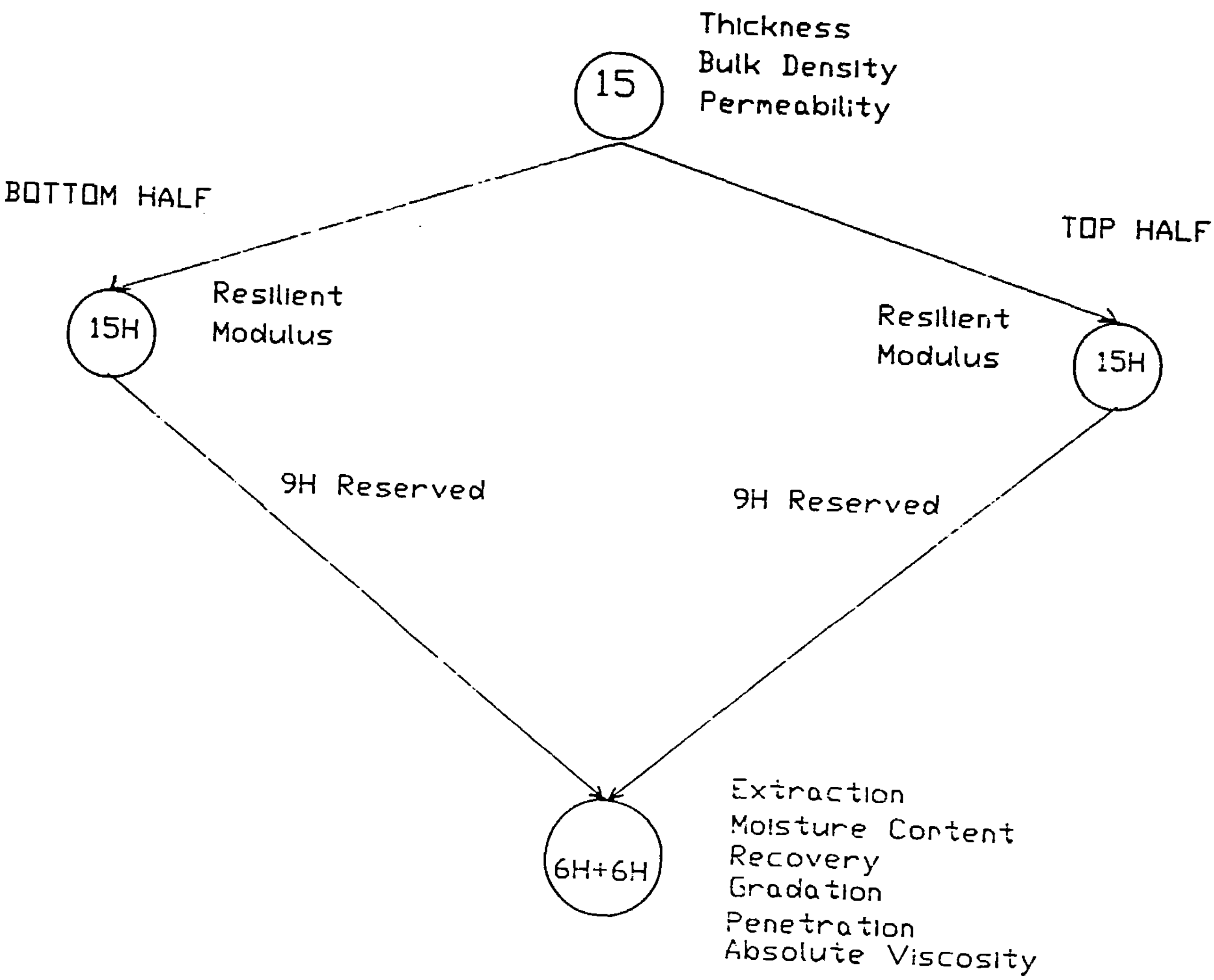

Figure 5 Hierarchial Arrangements of the Tests on the ATB Cores

5. Evaluate all data in terms of performance vs. laboratory determined parameters. Ascertain if trends are evident or appear to be developing. Consider the possibility of multiple correlation of parameters to predict performance i.e. fatigue and resilient modulus test results in regard to deflection results of FWD testing.

6. Determine the layer moduli by back calculation from FWD test results and compare the asphalt concrete and Asphalt treated base (ATB) moduli to laboratory determined values. Compute the critical responses (tensile strength at the bottom of asphalt concrete layer and vertical compressive strain at the top of the subgrade) for each year of deflection testing data and determine if any trends are evident. Comment on back calculation validity.

7. Determine the hydraulic performance of the section by analyzing rainfall data and well point data. Analyze the subgrade moisture meter data to conclude about the moisture equilibrium of the system. Comment on the efficiency of the design.

8. Determine the trend in the performance of the section in terms of serviceability by analyzing May's roughness data.

9. Determine the trend in the frictional characteristics of the section by analyzing Mu-meter data.

10. Develop performance curve and remaining life estimates (from both laboratory fatigue data and back calculated layer moduli in conjunction with the fatigue criteria developed in CODA).

11. Determine a cost/benefit ratio for the section based on the results obtained from this study. The ratio shall be calculated from all costs associated with this section including construction and maintenance costs. The costs shall be related in time to cumulative 18K ESALs.

Accomplishment of this task will establish the characteristics, performance and cost effectiveness of the porous pavement.

Task 6. Documentation

Prepare an interim report in the third and fifth year documenting in detail the followings:

1. The correlation of the in-situ porous pavement mixture properties to the specific requirements. Included shall be a discussion relating the results of the testing to the design parameters for the original construction project and changes observed over time.

2. Document the hydraulic and functional performance of the pavement section.

3. Document the structural response of the pavement section.

4. The results of the laboratory testing to date.

Prepare a final report documenting in details the followings:

1. The correlation of the in-situ porous pavement mixture properties to the specific requirements. Included shall be a discussion relating the results of the testing to the design parameters for the original construction project and changes observed over time.

2. Long term hydraulic and functional performance of the pavement section.

3. Long term structural response of the pavement section.

4. Include an executive summary, findings, conclusions and list of recommendation based on this study.

The estimated time schedule per task is shown in Figure 6. 66 calendar months are required to complete this research project.

EQUIPMENT AND MANPOWER

The laboratory testing of the cores will be contracted out to a qualified lowest bidder consultant. Thus, no special equipment is necessary for this project. Analysis of all test results, performance, rutting and deflection data will be done in-house by the Principal and Co-principal investigators. The Principal and Co-principal Investigators' salary will be paid by the Arizona Department of Transportation.

IMPLEMENTATION

The study will establish the feasibility of construction and performance of the porous pavement as a pavement system and a drainage structure. The findings of this study will be valuable input in the future design process of this type of pavement. The affected user group will be the Materials Section of the Highways Division of Arizona Department of Transportation.

BUDGET ESTIMATE

The estimated budget for the project is $30,000. The estimated budget excludes the cost of coring, Nuclear gauge density testing and traffic control which are assumed to be provided by the Central Materials Laboratory and District-I of ADOT. The cost of running any automated rut depth survey is also excluded from the cost estimate. The laboratory testing is estimated to cost $28,200 and miscellaneous expenses are at $1,800. Table 3 summarizes the estimated expenses for the project.

REPORTS

An Interim Report will be submitted in the third and fifth years of the project.

A Final report will be submitted which documents the findings, conclusions and recommendations of this study. The format will be per DOT-TSF-75-97 Standard for the Preparation of DOT Scientific and Technical Reports.

A brief technical summary no longer than four pages in length will be submitted and shall include the study's purpose, research approach, findings and recommendations.

TIME MONTHS

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Task 1						O						O						O						O
Task 2																								
Task 3																								
Task 4												O												O
Task 5																								
Task 6																								

	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
Task 1						O						O						O						O
Task 2												O												
Task 3												O	O	O	O									
Task 4												O												O
Task 5												O	O	O	O	O	O							
Task 6																	O	O	O					

	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66
Task 1						O						O						
Task 2												O						
Task 3												O	O	O	O			
Task 4												O						
Task 5												O	O	O	O	O	O	
Task 6																O	O	O

Figure 6. Time Schedule of the Project

TABLE 3. ESTIMATED COST

TYPE	ESTIMATED COST
Salary: P.I.	-
Co P.I.	-
Co P.I.	-
Automated Rut Depth Survey	-
Vertical Control Survey	-
Laboratory Testing	$28,200
Coring and Drilling	-
Nuclear Gauge Density Testing	-
Traffic Control	-
Miscellaneous	$1,800
Total	$30,000

APPENDIX D

STUDENTS t-TEST RESULTS

TABLE D1 -- STUDENTS t - TEST RESULTS

STATISTIC	t - value	p - value	RESULTS*
m1 - m2	3.41	0.016	significant
m1 - m5	-7.09	0.00	"
m1 - m3	3.59	0.023	"
m3 - m6	-8.4	0.00	"
m2 - m8	-4.88	0.001	"
m2 - m6	4.55	0.011	"
m1 - m7	12.31	0.00	"
m6 - m8	3.31	0.003	"
m6 - m4	17.64	0.00	"
m3 - m7	-5.26	0.00	"

* AT 5% LEVEL OF SIGNIFICANCE

NOTE:
m1: 1986 Nuclear Density in W.P.
m2: 1986 Nuclear Density in between W.P.
m3: 1986 Core Density in W.P.
m4: 1986 Core Density in between W.P.
m5: 1990 Nuclear Density in W.P.
m6: 1990 Nuclear Density in between W.P.
m7: 1990 Core Density in W.P
m8: 1990 Core Density in between W.P.