# Porous Pavement for Control of Highway Runoff in Arizona: Performance to Date

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In 1986 the Arizona Department of Transportation constructed a 3,500-ft-long porous pavement experimental test section on State Route 87 in the Phoenix metropolitan area. 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. The porous pavement test section has performed satisfactorily for 5 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 underutilized. If a design intensity storm occurs during the remaining service life, this should be verified. Visual observation during rain storms has shown that the surface of the porous pavement section does not include sheet flow, which provides a marked difference in stripe delineation and pavement glare during nighttime inclement weather driving as compared with conventional pavement. Mu-meter skid test results for the porous pavement section are comparable with 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 5 years of service. Annual falling weight deflectometer 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. 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.

Paved surfaces increase runoff and overload the existing sewer systems if alternative drainage is not provided. Rainfall is the only source of surface runoff in the Phoenix area. Typical summer storms have high intensity and short duration, whereas typical winter storms have low intensity but longer duration (*1*,*2*). This creates a large volume of runoff requiring costly highway drainage systems. Up to 35 percent 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 and storing storm waters and dissipating them into the ground. In 1986 the Arizona Department of Transportation (ADOT) constructed a 3500-ft-long porous pavement experimental test section on an urban highway. 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.

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## PROJECT LOCATION AND LAYOUT

The test section is located in the three northbound 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 mi southeast of Phoenix. SR 87 is heavily traveled by commuter traffic going to and from the Superstition Freeway, which is approximately 2.5 mi north of the project. Currently, the average daily traffic is approximately 30,000. Figure 1 shows the layout of the porous pavement section and the control section.

## DESIGN CONSIDERATIONS

### Porous Pavement Section

The porous pavement section consists of 6 in. of open-graded hot-mix asphalt concrete, 6 in. of open-graded asphalt-treated base (ATB), and 8 in. of 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 (*6*) design equation to carry the design traffic loading of 2,270,653 single-axle, equivalent 18-kip loads for a 20-year design period (*7*).

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 ground. An alternative drainage system was also provided for the experimental section as a backup in the event of failure of the designed experimental drainage system. The pavement structure designed was found to have adequate water-holding capacity to

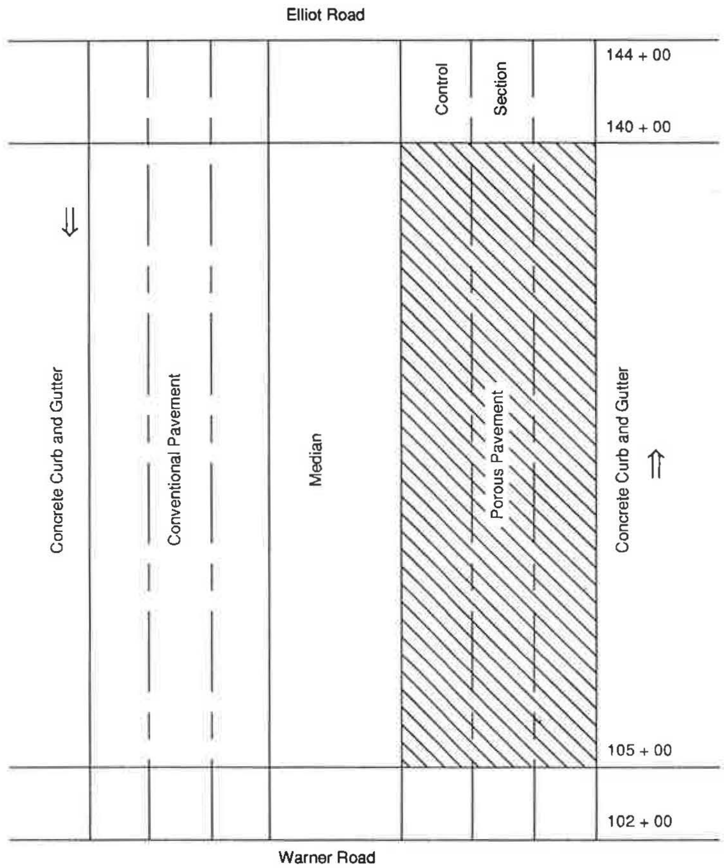


**FIGURE 1 Layout of porous pavement test section.**

temporarily store runoff from the 10-year 24-hr design storm. The intensity of this rain storm was found to be 0.11 in./hr. The design rainfall intensity for percolation of water through the surface course was based upon the 10-year frequency, 10-min duration storm. This intensity was estimated at 5.20 in./hr during the 10-min storm (*8*).

### Control Pavement Section

The control section of the project is located at the north end of the porous pavement section and consists of 8 in. of asphalt concrete over 7 in. of aggregate base. The same design was used for the three southbound lanes, which were used as a control section for Mays roughness and mu-meter testing. Figure 2 shows the structural section of the porous pavement and the control section.

The specific design data are summarized in Table 1. A design structural number (SN) of 4.5 was selected for both sections. The thicknesses of different layers were calculated on the basis of this structural number. A structural layer coefficient of 0.40 was assumed for the open-graded asphalt concrete.

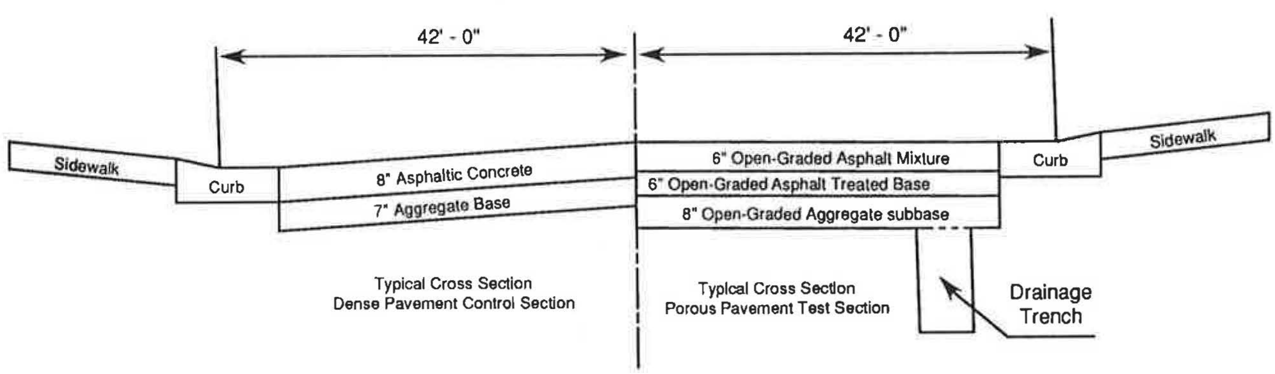


**FIGURE 2 Typical cross section of ADOT's experimental porous pavement.**

TABLE 1 Summary of Structural Design Data

| Material Type | 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 | 0.98 |
| | | | 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 | 0.88 |
| | | | 4.48 |

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

### Open-Graded Asphalt Concrete Mix Design

The mix design for the 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 for the porous asphalt concrete was 5.5 percent by weight of the total mix. The bitumen content of the ATB layer was 1.8 percent.

### 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 coefficient of permeability of the asphalt concrete, ATB, and open-graded subbase were 200, 16,000, and 23,000 ft/day, respectively. 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 (*10*).

### Drainage Trench Design

A parallel drainage trench was designed along the edge of the roadway and connected to the open-graded subbase such that runoff entering the pavement could readily flow into the trench. The trench was designed to drain the 10-year, 24-hr design storm from the subbase within 26 hr. A trench 2 ft wide by 4 ft deep was found to be adequate to drain one-half of the road plus the sidewalk and shoulder. 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 subbase were designed to be isolated from the subgrade soil by a permeable geotextile at the soil-aggregate interface (*10*).

## CONSTRUCTION PROBLEMS

There were minor difficulties in the construction of the open-graded subbase and base. The major problem occurred when traffic was being carried on the east half of the open-graded asphalt concrete while the west half was being constructed. Within 3 weeks, severe vertical deformation of the pavement was noted. Surface deformations were measured with a straightedge placed on the pavement. Vertical displacements from the straightedge varied from ⅛ in. to 1 in. The average depth was ⅜ in., with 139 of the 144 readings taken being ⅝ in. or less. After investigation, it was concluded that as the hauling units deposited ATB material, decompaction of the untreated subbase occurred, resulting in an increased 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 the vertical deformation. The entire section was subsequently rolled with a steel vibratory roller for three or four coverages, which produced some leveling of the surface. An additional thin lift of open-graded asphalt was placed to produce a surface at the proper elevation and cross-slope. The project was finally opened to traffic in July 1986 (*10*).

## INSTRUMENTATION

### Rain Gauge

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

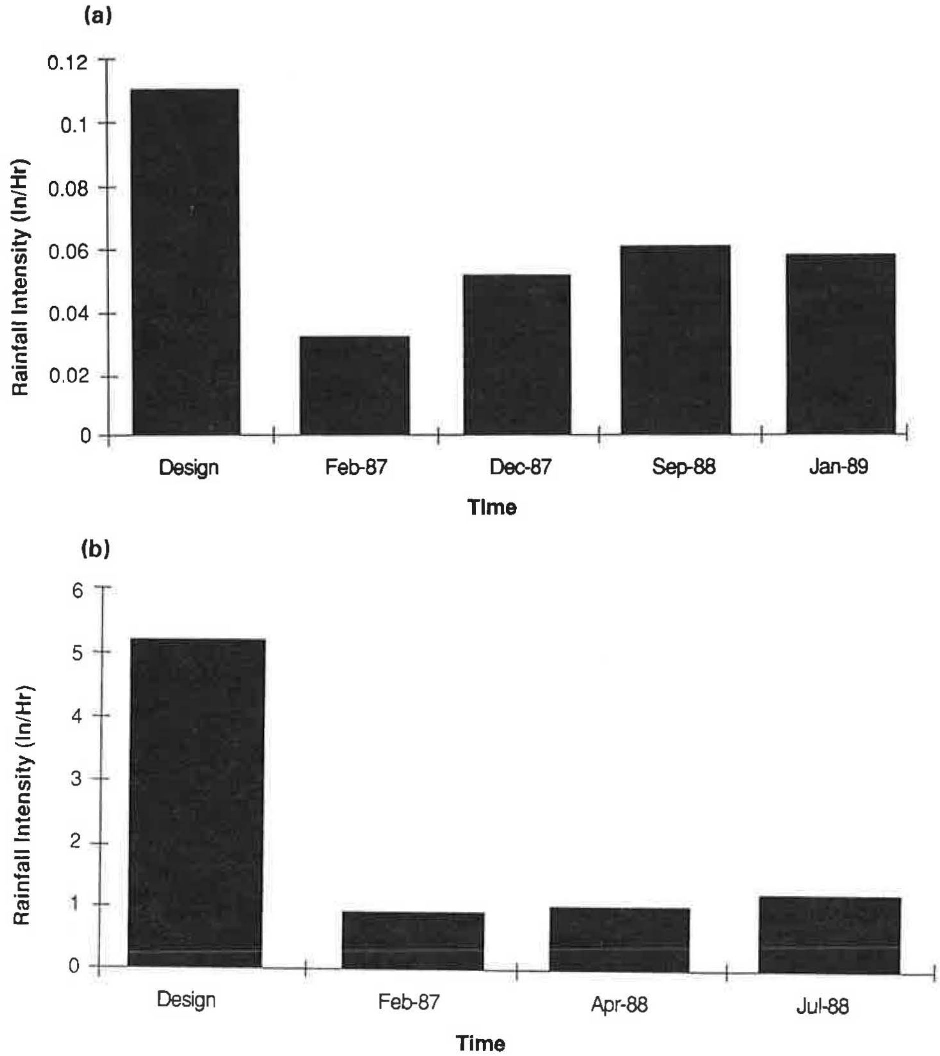


**FIGURE 3 Comparison of design and actual rainfall: (*a*) 10-year, 24-hr storm; (*b*) 10-year, 10-min storm.**

### Moisture Monitors

Soil moisture-monitoring devices (Soiltest soil moisture-temperature meter set, MC-312) 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. Cells were placed at depths of 1 and 3 ft below the top of the subgrade at distances of approximately 5, 10, and 20 ft 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 the 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 inadvertently flushed in summer 1989 by maintenance personnel flushing an adjoining project.

### Rut Depth Measurements

Rut depth measurements were taken on all three lanes in 1986, 1987, and 1988 and on the outermost lane in 1989 and 1990. Currently, the average rut depth on the porous pavement section (0.20 in.) is higher than that on the conventional pavement (0.10 in.). However, the average rut depth on the porous pavement section is within an acceptable limit.

## NONDESTRUCTIVE TESTING

### Purpose and Background

To detect the structural deterioration of porous pavements as well as dense-graded pavements through the change in backcalculated moduli of the layers, nondestructive testing (NDT) has been conducted every year since 1988 using a falling weight deflectometer (FWD), Dynatest Model 8002, with sensor locations of 0, 12, 24, 36, 48, 60, and 72 in. from the center load at load levels of 6,000, 9,000, and 12,000 lb. The testing was performed in early fall at 15 locations in 1988, 27 locations in 1989, and 90 and 21 locations in 1991. These tests were performed on the outer wheelpath of the outside lane, generally 2 to 3 ft from the edge of the pavement. The FWD deflection data were analyzed using the BKCHEVM elastic layer computer program to backcalculate the layer moduli (*11*). Details of the analysis methodology may be found elsewhere (*12*).

### Backcalculation Results

The results of the backcalculation analysis are summarized in Table 2 for porous and conventional dense-graded pavements. 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

**TABLE 2 Backcalculated Layer Moduli Summary Statistics**

(A) POROUS PAVEMENT

| Layer | Year | Backcalculated Layer Moduli (ksi) 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 |

(B) CONVENTIONAL PAVEMENT

| Layer | Year | Backcalculated Layer Moduli (ksi) Mean | Std. Dev. | Coeff. of Var. (%) |
|---|---|---|---|---|
| Asphalt* Concrete | 1988 | 1245 | 15 | 1 |
| | 1989 | 2163 | 328 | 15 |
| | 1990 | 2556 | 30 | 1 |
| | 1991 | 780 | 145 | 19 |
| Asphalt Treated Base | 1988 | 71 | 26 | 37 |
| | 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.

concrete modulus for the dense-graded pavement is almost two times that for open-graded asphalt concrete. The subbase modulus for porous pavement and aggregate base modulus for dense-graded pavement tend to decrease with time. No suitable explanation for 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 modulus values for both types of pavement are relatively constant over the period of time studied.

## PAVEMENT PERFORMANCE SINCE CONSTRUCTION

### Function Performance

#### *Roughness Testing*

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 southbound 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 3 shows the Mays roughness in inches per mile. 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 those for the conventional pavement. Neither type of pavement has shown significant increase in roughness with time and use.

#### *Skid Testing*

Skid measurements are 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 southbound direction. A mu-meter was used for the skid testing. Table 4 shows the mu-meter values resulting from each test. The 1990 measurements show a slight decrease of skid resistance as expressed by mu-meter values compared with the 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.

**TABLE 3 Mays Roughness for Porous and Conventional Pavements**

| Month/Year | Mays Roughness (ins/mile) | | | |
|---|---|---|---|---|
| | 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 |

**TABLE 4 Mu-Meter Values for Porous and Conventional Pavements**

| Month/Year | Mu-meter Values | | | |
|---|---|---|---|---|
| | 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 |

## Hydraulic Performance

### *Analysis of Rainfall Data*

The rain gauge data collected by the continuous recording rain gauge were analyzed over a 3-year period from 1987 to 1989. During 1986–1987, the highest amount of rainfall recorded over a 24-hr period was 0.82 in. on February 24, 1987. The total rainfall for this period was 7.07 in. The greatest estimated rainfall intensity occurred on February 26, 1987, when 0.42 in. of rain fell in an estimated 0.5 hr, giving an estimated rainfall intensity of 0.84 in./hr. In 1987–1988, the highest amount of rainfall (1.15 in.) over a 24-hr period occurred on December 17, 1987. The greatest measured rainfall intensity (1.0 in./hr) occurred on April 15, 1988. The design rainfall intensities for a 10-year, 10-min storm and a 10-year, 24-hr storm are 5.20 and 0.11 in./hr, respectively. The rainfall intensity in April 1988 is one-fifth the amount of a 10-year, 10-min storm. The rainfall intensity in December was slightly less than half that for a 10-year, 24-hr storm.

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

Design rainfall intensities are compared in Figure 3 for a 10-year, 24-hr storm and a 10-year, 10-min storm with actual rainfall on the project in years 1987–1989.

The surface of both pavements was 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 with respect to the bottom of the trench during the first and the second years was 3½ and 9 in., respectively. The readings indicated that the capacity of drainage trench had not been exceeded. No recording is available for the third year.

### *Subgrade Moisture Content*

All moisture monitors were read on June 7, 1986. The majority of the monitors then underwent a significant decrease in resistance before 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 gauges. 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 2 years, Station 108 Rt had an estimated increase in moisture content of 1.5 percent. The moisture content in the subgrade increased more for Gauges 5 and 6, which are located nearest the trench excavation.

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

Moisture monitor gauges located at Station 143 + 25 Lt indicated a fairly insignificant change in subgrade moisture except for Gauge 5. During the first monitoring period, Gauge 5 indicated a subgrade moisture increase of 9.2 percent. After 2 years of monitoring, the increase was 8.7 percent. This small change in moisture content indicates that the moisture content in this area of the subgrade has stabilized.

At all stations except 138 + 00 Rt, some gauges read 2000 or infinity. This indicates that the soil has dried out or that the monitoring gauge has malfunctioned (7).

## Structural Performance

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

# SAMPLING AND TESTING OF 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 determine 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 were also to serve as a datum for future comparison of material properties.

## Sampling

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 gauge readings were obtained at each coring location to measure the in situ density of porous asphalt concrete. The ATB material samples were collected at each location. Subbase samples were collected at 12 locations. The subgrade was sampled at six locations.

## TESTING AND RESULTS

### Bulk Density

Thirty cores were prepared for bulk density testing by saw cutting at the lift line between the asphalt concrete and the 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 D3203. As mentioned earlier, nuclear density gauge measurements were taken at the core locations. Table 5 shows the summary statistics of the density measurements of the cores as well as the nuclear density gauge measurements in 1986 (as built) and also in 1990 (4 years after construction). The small coefficient of variation of the measurements indicates somewhat the homogeneity of the porous pavement materials. Student's *t*-tests were performed to find the difference of the means of each measurement. At the 5 percent level of significance, significant differences were observed between all sets of data. From Table 5 it is apparent that, on 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 wheelpath and between-wheelpath locations, the range in values suggests that some densification has occurred in the wheelpaths.

### Permeability

Permeability tests were conducted on the cores using a constant head water permeability test procedure. Table 6 summarizes the test results along with the core unit weights. The coefficient of permeability during the mix design formulation was 200 ft/day. The permeability and porosity of the in-service porous pavement have decreased, but the values are well above the 26 ft/day required by design. It is to be noted that the average coefficient of permeability in the wheelpaths is less than that of the between-wheel locations.

### Marshall Stability and Flow

Marshall stability and flow values were determined on four cores from an outer wheelpath (OWP) in 1986 immediately after construction. In 1990 five cores from an OWP and seven cores from between wheelpaths (BWP) were tested. Results

**TABLE 5 Nuclear and Laboratory Densities of Porous Asphalt Concrete**

| Statistic | DENSITY (pcf) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | AS BUILT (1986) | | | | IN-SERVICE (1990) | | | |
| | Nuclear | | Laboratory | | Nuclear | | Laboratory | |
| | OWP | BWP | OWP | BWP | OWP | BWP | OWP | BWP |
| Mean | 118.5 | 116.3 | 116.9 | 113.6 | 112.4 | 121.9 | 120.1 | 119.8 |
| St. Dev. | 0.8 | 1.1 | 0.35 | 0.35 | 2.0 | 1.7 | 2.0 | 1.9 |
| C.V. (%) | 0.68 | 0.95 | 0.30 | 0.30 | 1.63 | 1.40 | 1.67 | 1.6 |
| number | 4 | 4 | 4 | 4 | 18 | 18 | 13 | 15 |

Note: C.V.: Coefficient of Variation (%).

**TABLE 6 Permeability Test Results**

| | 1986 (After Construction) | | 1990 (In service) | |
|---|---|---|---|---|
| | 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 |

show that, on average, there is a fourfold increase in the Marshall stability value since construction. There has also been an increase in flow value, which may be attributed to the flushing done in summer 1989.

### Resilient Modulus

The resilient modulus test was performed on cores from 14 locations in the outer wheelpath and from 16 locations between the wheelpath. Each specimen was sliced into two samples approximately 4-in. in diameter and 2.5 in. high to represent the two different lifts used in placing porous asphalt concrete. The resilient modulus test was performed on these samples at 77°F according to ASTM D4123. Each specimen was tested in two positions (90 degrees apart) and at three different loading frequencies (1, 0.5, and 0.3 Hz) with a load duration of 0.1 sec in all cases. The applied load was between 85 and 130 lb with the majority around 100 lb. The horizontal deformation was measured and the modulus was computed by assuming a Poisson's ratio of 0.35. The instantaneous resilient modulus was the same as the total resilient modulus in about 95 percent of the cases. Therefore, only total resilient modulus was used in the analysis. Table 7 shows the summary of the test results. The resilient modulus of the porous asphalt concrete mix has increased significantly. The average resilient responses of the porous asphalt mix at the outer-wheelpath and between-wheelpath locations are the same, as indicated by the similar average resilient modulus values at these locations.

### Gradation of Asphalt Concrete

The aggregates extracted from the cores of asphalt concrete were tested for gradation to detect any change that might have occurred because of degradation of the open-graded aggregates after 4 years of service. Comparison of the results of the gradation analysis for the 1990 sampling of porous pavement, the as-built, and specified gradation for porous asphalt concrete showed no signs of degradation.

### Properties of Extracted Asphalt Cement

The extraction was performed in accordance with ASTM 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. Comparison of the results with those parameters determined immediately after construction showed that there has been an increase in the viscosity of the asphalt cement.

### ATB

ATB samples were tested for extraction, moisture content of asphalt concrete, asphalt content, gradation, Abson recovery, penetration, and viscosity following ASTM D2172, D1461, D4125, C136, D1856, D5, and D2171, respectively. Usually the samples at consecutive station locations were combined to get enough recovered asphalt to perform the penetration and viscosity tests. Samples were not combined until the extraction, moisture content, and gradation had been measured. Results showed that the gradation of ATB aggregates was well within the as-built specified gradation.

### Open-Graded Subbase

The moisture content of the subbase samples was determined according to ASTM D2216. The samples were then tested for gradation as per ASTM C136. The gradation analysis results showed that there was no change in gradation of subbase materials 4 years after construction.

### Subgrade

Moisture content measurements were conducted on subgrade soils in accordance with ASTM D2216. The average moisture content at the outer-wheelpath locations and between-wheelpath locations was 4.7 and 1.5 percent, respectively. This was well below the optimum moisture content of 13 percent used during the design phase.

### Distribution of Moisture in Pavement

The moisture content of each layer of porous pavement was analyzed. No unusual moisture was detected in any layer.

**TABLE 7 Summary of Resilient Modulus Test Results: 77°F, 1 Hz**

| Statistic | RESILIENT MODULUS (ksi) | | | | |
|---|---|---|---|---|---|
| | 1986 Test | 1990 Test | | | |
| | 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 |
| number | 6 | 14 | 14 | 16 | 16 |

## CONCLUSIONS

The porous pavement test section has performed satisfactorily for 5 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 underutilized. 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 storms has shown that the surface of the porous pavement section does not include sheet flow, which provides a marked difference in stripe delineation and pavement glare during nighttime inclement weather driving as compared with conventional pavement. Mu-meter skid test results for the porous pavement section are comparable with those of conventional pavements (control). It was expected that the porous pavement would have higher skid resistance because of its improved drainage characteristics. This expected higher skid resistance may likely exist with heavier concentrations of water than that 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 ATB 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 for the conventional pavement. No significant increase in roughness has occurred with time and use since the project was completed. Future design should consider using only stabilized materials with additional examination of the stability of the ATB layer.

Although a detailed analysis of the cost-effectiveness of the porous pavement section was not performed for this paper, 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.

Materials 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 5 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. Because 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 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 5 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. Correlation of the test results with observed performance is recommended.

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