DRAINAGE OF CONCRETE PAVEMENT STRUCTURES

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The usual design criteria for PCC highway pavement slabs are mainly functions of concrete thickness, concrete properties, subgrade support, and the position and magnitude of an applied wheel load. Most design methods for concrete pavements assume a uniform support will be provided for the concrete. When this uniform support is provided, conventional criteria appear more than adequate for both static and dynamic loads. However, it is important to note that the action of dynamic loads on inadequately drained pavements can (a) reduce subgrade support in some areas to zero, (pumping) resulting in critical stresses in edge and corner stress regions, and (b) redistribute subgrade and subbase materials so that serious dislocations (faulting) occur in jointed pavements. Water which is trapped under the concrete slabs can have other deleterious effects, such as contributing to blowups, corrosion of load transfer devices, uneven swelling of subgrade soils, differential frost heave, and concrete deterioration or spalling. According to a recent research report (1) from one State:

> "The results of field study on Interstates 70 and 77 have indicated that (concrete) pavement performance is directly related to drainage conditions. In projects where the shoulder, base, and subbase were designed with adequate drainage, it was noted that these pavements have performed superbly, even after 15 years in service. On the other hand, the lack of positive drainage, poor subbase with high fines content, plugged base course, and drainage connectors have resulted in joint deterioration and pavement failures."

Road life studies by Corri and Houghton (2) show that concrete pavements have an average life of 27 years. However, the life of individual pavements range from 1 year to over 50 years even though they were designed to meet the same criteria. Housel (3) reports similar wide variations in performance versus age in a study of concrete pavements in Michigan. Why is there so much variation? This wide disparity in performance is a strong indication that the present design criteria does not include consideration of some engineering characteristic having a profound influence on the service performance of the pavement. This paper will show that subsurface drainage is this important factor in the performance of concrete pavements. In addition, it will describe means to achieve adequate drainage and describe ongoing research related to subsurface drainage of pavements.

Drainage consists of handling the flow of water over (surface), through (internal), and under (subsurface) the highway pavement. Beginning with McAdam and Telford, drainage has been an important item in the design and construction of pavements. Initially, the primary purposes of drainage were to minimize both softening of the subgrade (strength) and inundation of the pavement surface (safety). Since then, highway engineers have developed some standards for draining springs and wet weather seepage encountered during construction. Hydraulic engineers have long been concerned with surface drainage, including that of pavements, and have developed rational methods for predicting storm runoff. Standard designs are available for gutters, gutter inlets, median and embankment inlets, and bridge deck drainage. Some of these are given in "Drainage of Highway Pavements" (4). Design for off-the-road surface drainage are given in "Design of Roadside Drainage Channels" (5) and "Design Charts for Open Channel Flow." Further research needs for highway surface drainage are outlined in Highway Research Circular No. 138 (6).

Although much progress has been made in solving the problems of draining both groundwater seepage and surface water, water entrapped in the structural section is still a major

contributor to the poor performance of some concrete pavements. The three types of pavement drainage are illustrated in Figure 1. For good performance, all three must be considered by the designer. He must estimate where every drop of water will go. However, only internal drainage will be discussed here. The other two are important and have been mentioned to remind the designer that all water intercepted at the surface, or from subsurface seepage, is that much less to handle in the internal drainage system of the pavement.

Until recently, a scientific approach to internal pavement drainage has received little attention, even though the effects of poor internal drainage have been prevalent. For instance, concrete pavement test sections at the AASHO Road Test (7) were poorly drained. A granular subbase, containing about 6.5 percent passing the No. 200 sieve, extended through the shoulder. Because of the fines content, calculations based on estimated permeability (k) in the equation $Q = kiA$, indicate that from 2 months to 1 year would be required to drain 50 percent of the water from the saturated subbase. Even this long period of time is wishful thinking, since capillary forces in the fine material, not usually considered in drainage calculations, would probably result in less than 5 percent of the water being actually drained. A rapid decrease in the serviceability of the AASHO rigid test sections occurred after they started to "pump" (Figure 2). Sixty-seven out of two-hundred-sixty-four sections had a terminal PSI of less than 1.5 after 2 years of traffic, and these sections failed chiefly during the second year when it can be assumed that the pavement was saturated. If pumping had been prevented through the use of a drained subbase, there is a strong possibility that the PSI of the failed sections would have remained high.

Emphasis on internal drainage is needed to qualify the design of concrete pavements as "good engineering." The pavement industry has traditionally taken the position that pavements can be designed strong enough to resist the effects of water. This concept of strong pavements is certainly a viable alternate solution, but in many instances, present thicknesses are not great enough because the design assumption of uniform support is not always in agreement with the actual field conditions. For example, calculations show that a 9-inch pavement over a uniform subgrade support of 100 psi will deflect 0.024 inches, while considering a corner of the pavement as a cantilever with a fixed end, a thickness of 17.4 inches is required to limit the deflection to the same amount (0.024 inches) when 24 inches of the subbase has been removed by pumping (Figure 3). Whether to use strong pavements, or thinner pavements with drainage becomes an economics problem not presently being adequately treated in the design of concrete pavements.

The classical structural analysis of concrete pavements by Westergaard in 1929 (8) is a theoretical static structural approach which does not consider the possible effects of water either in causing faulting or loss of subgrade support through erosion (pumping). Later, Bradbury (9), Pickett (10), and others extended the Westergaard analysis but none considers the problems associated with poor internal drainage of the pavement structure.

Qualitatively, some attention has been given to pavement support and drainage. In 1951, Concrete Pavement Design (11) had a short discussion on subbase materials; it attributes slab faulting to poor subgrade compaction, and recognizes the pumping problem in a section on improving poor quality subgrade soils with cement. By 1955, a Concrete Pavement Manual (12) had a section devoted to both surface and subsurface drainage. However, the problems of "bathtub" sections and "leaky roofs" were not covered. In 1964, Ray (13) pointed out that the development of severe pumping, leading to the rapid deterioration of some sections at the AASHO Road Test, was restricted to short periods associated with heavy rainfall, a phenomenon very similar to that which occurred on some of the test sections at the Road Test 1 in Maryland (14). This important observation seems to have received little attention until recently, even though drainage in concrete subbases has been a subject of controversy for a number of years.

Some pioneers in pavement design recognized many of their pavement problems as being related to poor drainage and attempted to solve them by trial and error. In 1947, a survey of subgrade soil practices on rigid pavements by Shelburne (15) indicated that highway engineers were not in accord as to whether the subbase should be dense or a porous free-draining material. Thirteen States preferred dense-graded subbase courses while 32 States preferred porous subbase courses. Preference for open- or dense-graded courses was not related to whether a State was in a region of deep frost penetration.

Even though 32 States advocated porous subbases, there is serious doubt as to whether

their specified gradings permitted sufficient drainage capacity to abrogate the effect of water on performance. It may be that drainage considerations were compromised in order to obtain compaction with available equipment. Some of these 32 States permitted subbases with up to 20 percent passing the No. 200 sieve with a PI of 6. Subbase materials with much fewer fines than this are still practically impervious. Since no drainage calculations or permeability measurements were made, it also may be that early designers overestimated drainage capabilities on the basis of reasonable quantities of flow in a vertical direction. When this is examined by using principles of hydraulics, as shown in Figure 4, quantities of flow in a horizontal plane through thin layers can easily be only 1/100 of the vertical flow because of the lower hydraulic gradient and smaller area of drainage material. These lower quantities of flow in horizontal drainage layers could explain why 33 of the reporting States in the survey also indicated pumping problems in concrete pavements.

In 1951, a survey of the State's subsurface drainage systems for highways by Keene (16) indicated "clogging" of backfill drainage material, and sometimes the pipe, as the chief cause of failure of subsurface drainage systems.

These two surveys (Shelburne and Keene) illustrate the two major criteria in the design of subsurface drainage systems which need to be considered, i.e., quantity of flow and prevention of clogging.

As early as 1959, Yoder (17) recognized that surface infiltration was a major source of water in concrete pavements and advocated good sealing practices. This has since been partially quantified in Connecticut by Ridgeway (18) who suggests that the water infiltrating a concrete pavement through cracks and joints is (0.1) (no lanes + 1 + $\frac{\text{Pavement Width}}{\text{Slab Length}}$). This can easily amount to three gallons of water per foot of length of pavement per hour. Yoder also found that soils having more than 55 percent sand and gravel do pump, refuting the prevailing idea that subbases high in granular materials would not pump. This observation was especially apparent at the AASHO Road Test. He also notes that pumping is related to the magnitude of deflection and subsequent reactive pressures. However, deflection is still not included as a direct design criteria for concrete pavements, although it is related to performance by its influence on pumping, as shown in Figure 4. When subbases become saturated, the reactive pressures are partially exerted by the water. This high water pressure causes pumping and subbase erosion, and it is this pressure which the designer should try to minimize through good subdrainage practices. Yoder also advocates using filter principles around the pipes in a subdrainage system.

Just a few years later, a study reported by Cashell (19) in 1963 summarized the States subbase criteria by stating "Nearly all States limit the amount of subbase material passing the No. 200 sieve to 20 percent or less, with one-third of the States requiring 10 percent or less on heavy duty routes." This means that two-thirds of the States had upper limits ranging from 10 to 20 percent passing the No. 200 sieve. Calculations by Barber and Sawyer (20), for drainage of 50 percent of the water in a 20 foot wide saturated subbase, with fines of 10 to 20 percent, show that this drainage could take from 6 months to 2 years. Cashell also noted that "Most highway engineers consider that requirements for subbases are still in the development stage." Unfortunately, now almost 15 years later, the statement is still true.

RATIONAL DESIGN

Izzard (21) was one of the first to advocate a rational design for the drainage of pavement subbases. In 1944, he recognized that the major sources of water in pavements is through joints and cracks and at the pavement edge, and proceeded to analyze the time required for drainage on the basis of permeability of the subbase slope and amount of drainable water. For longitudinal grades of less than 1.8 percent, he calculated that more than 24 hours would be required to drain a subbase with outlets spaced at 80 foot intervals and a subbase permeability of 864 feet per day. Izzard also mentioned the need for the use of graded filters to eliminate the possibility of the subbase material washing out as water drains away. From this beginning, other engineers have further developed the concept of free draining subbases with the graded filter concept.

In 1960 (22), Cedergren proposed the use of a layered drain system consisting of an inner core of a highly permeable one-sized filter material, with an adjacent filter layer to prevent intrusion, as the most economical solution to most subsurface drainage problems.

Although the drain system was directed toward drainage of groundwater rather than infiltrated surface water, the principles of hydraulic capacity and filtering to prevent piping and/or intrusion are applicable.

The California Department of Transportation field tested a number of these two-layer drainage blankets (with permeabilities of from 7,000 to 10,000 ft/day) for groundwater seepage problems (23). Some of their conclusions were:

(1) The two-layer system can be placed successfully using normal construction procedures.

(2) If properly designed, two-layer installations can provide highly efficient drainage with no significant infiltration (of fines) over an extended period.

As a result of this study, California recommended that the two-layer drainage system be considered for use as a standard for groundwater seepage problem areas.

A study by Cedergren, O'Brien, and Arman for the FHWA, completed in 1972 (24) established rational design criteria for subsurface drainage systems for internal drainage of highway structures in locations where:

(1) the average annual rainfall is greater than 10 inches.

(2) lateral drainage through the base combined with the vertical drainage of all underlying materials is less than the design infiltration rate.

(3) when 250 or more 18,000-lb. axle loads per day are predicted during the design life of rigid pavement systems.

The Cedergren study recommends that cross-sections of new pavements incorporate a two-layer (drainage layer plus filter layer) drainage system to take care of surface infiltration, with design provisions for groundwater and/or frost penetration (Figure 6).

The design method considers both the permeability of the drainage layer and the trench backfill in analyzing the drainage capability of the system. Typical drainage layer permeabilities are 5000 ft/day and higher to provide a drainage time of 1 hour or less. To date, few pavements having the recommended drainage characteristics have been built, although some pavements in the Northeastern States having highly permeable layers are performing well where positive outlets are provided. Other States are beginning to construct pavements with open-graded layers on an experimental basis.

MEANS TO ACHIEVE ADEQUATE DRAINAGE

A suggested procedure for the analysis and design of drainage for pavement structural sections involves the following steps (25):

(1) Assemble data on highway and subsurface geometry, index properties (including permeability) and performance characteristics of soils and materials, precipitation, and frost penetration. Potential pavement subdrainage problems can often be averted by a simple inspection of the proposed structural geometrics and relative permeabilities of the various pavement components. High permeability materials bounded below and laterally by low permeability materials are a major source of subdrainage problems. Examine the geometrics for possible treatments to intercept rainfall at the surface. This might include changes in cross-slopes, guttering, or inlets at the pavement edge, and shoulder paving to minimize growth of vegetation which would otherwise slow the flow of water.

(2) Determine the net inflow that must be removed by the drainage system. This should include water from all possible sources, especially edge joints and cracks. Cedergren recommends using a surface infiltration rate of from 0.33 to 0.67x(1 hour/1 year rainfall intensity-frequency). Groundwater and other sources of water should be added to the surface infiltration. An allowance should be made for any natural outflow that can take place by vertical seepage into the soil beneath the pavement. Potential drainage rates into subgrades having low water tables are given in Table 1 (26).

(3) Analyze and/or design pavement drainage layers to provide for the rapid removal of the net inflow determined in Step 2. This should include the evaluation of the need for filter layers. Materials having a capillary rise of 4 to 6 inches and over are probably

not suitable as drainage layers since the capillary force will tend to reduce the effective head. This restricts materials for the drainage layers to those having particles larger than the No. 10 sieve.

(4) Analyze and/or design collection systems to provide for the disposal of water removed by the drainage layers. This includes the location and sizing of longitudinal and transverse collector drains, selection of filter material and determination of outlet spacing. Daylighted layers should be considered as a possible economic alternative to pipe collectors.

(5) Conduct a critical evaluation of the results of Steps 3 and 4 with respect to long-term performance, construction, maintenance, and economics of the proposed pavement drainage system.

Typical calculations for an inflow and outflow analysis can be found in reference 19 "Guidelines for the Design of Subsurface Drainage Systems for Highway Structural Sections," Summary Report.

CURRENT RESEARCH ON PAVEMENT SUBDRAINAGE

Current research is directed toward improving the drainage of structural sections of both new and existing pavements. The scope of the studies range from the theory and measurement of moisture movements to applied research aimed at developing guidelines for improving the subdrainage of existing pavements. Some effort is directed toward the design of more effective, permanent, economical collector systems for removing entrapped water, including research on filter fabrics and conduits. Some experimental projects of open-graded drainage layer systems are just getting underway. A more detailed description of current research projects on pavement subdrainage is given in Appendix A.

FUTURE NEEDS

Advances in three areas of pavement drainage have provided a great potential for building highway surfacings having more consistent performance and a vastly improved average life expectancy. These advances are in the areas of theory, economical pipe systems, and filtration systems.

Two major areas of work remain. One of these is in implementation. Designers need to be encouraged to consider the drainage of structural sections as an important criteria, in addition to static structural analysis, in order to achieve improved engineering practice and more economical pavements. A second area of needed work is in the development of construction techniques and equipment for building well-drained pavements. A large element of success of the designs for the drainage of the pavement structural sections will depend on the contractor. Once the contractor understands the reasons for the design, he will find better ways to install subdrainage systems.

SUMMARY AND CONCLUSIONS

Concrete pavements constructed during the past 20 years have a record of inconsistent performance, with some indicating that they will last far beyond their design life, while others already show premature distress.

Water infiltrating through cracks and joints and becoming trapped within the structural section appears to be a major factor in the performance of many concrete pavements, often resulting in loss of subgrade support and in pavement faulting due to redistribution of subbase material.

Present design criteria should be reevaluated using more realistic assumptions in order to adequately treat the economics problem of when to either build stronger concrete pavements or to provide improved subdrainage.

Where the economics indicate improved drainage as the preferred solution, the design of concrete pavements should utilize the latest subdrainage technology currently available.

TABLE 1. Possible Drainage Rates into Subgrade for Pavement on an Embankment

Subgrade permeability, k		Drainage rate (ft^3/day/lin. ft)	Typical Material
cm/sec	ft/day		
1×10^{-6}	0.003	0.02	Clayey silt
1×10^{-5}	0.03	0.18	Silts and rock dusts
1×10^{-4}	0.3	1.8	
1×10^{-3}	3.0	18.0	Fine sand (clean)
1×10^{-2}	30.0	180.0	Coarse sand (clean)

After Cedergren (20)

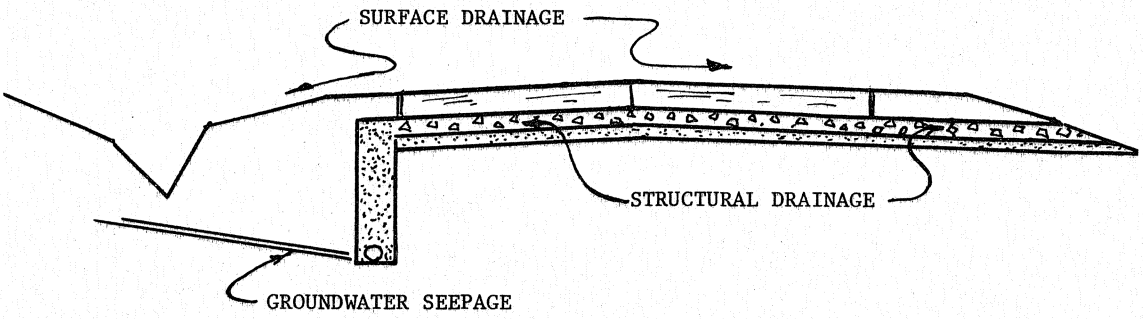


FIGURE 1. THREE TYPES OF PAVEMENT DRAINAGE

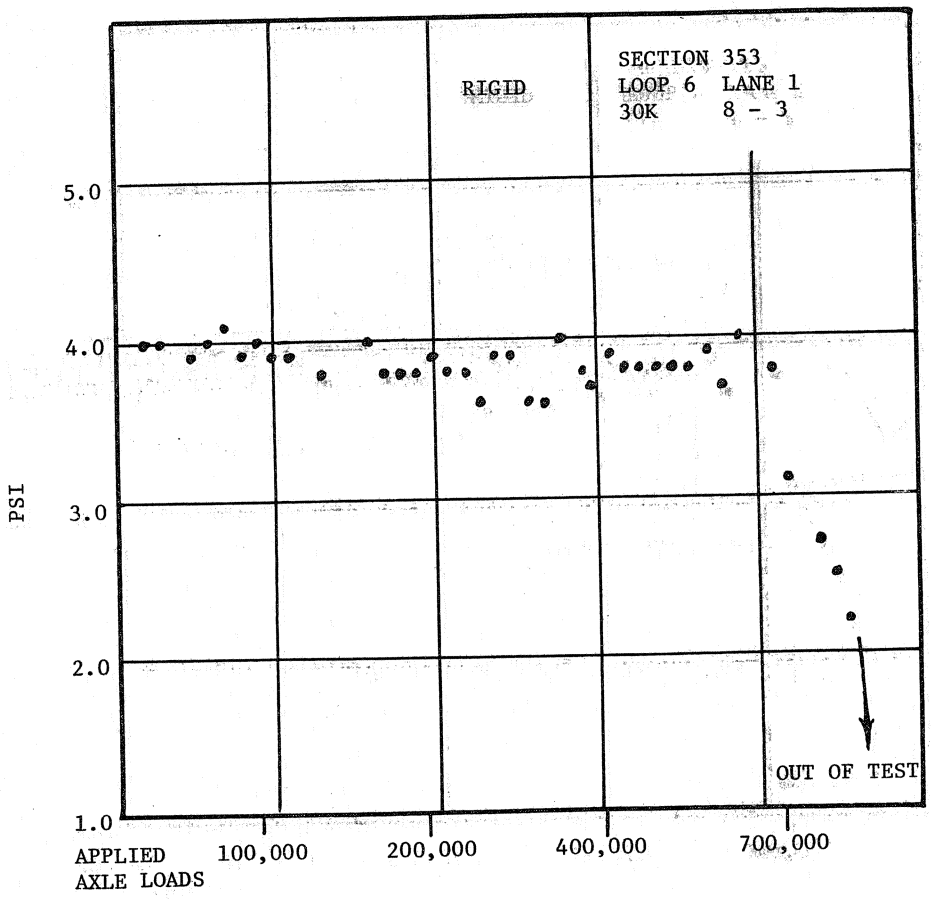
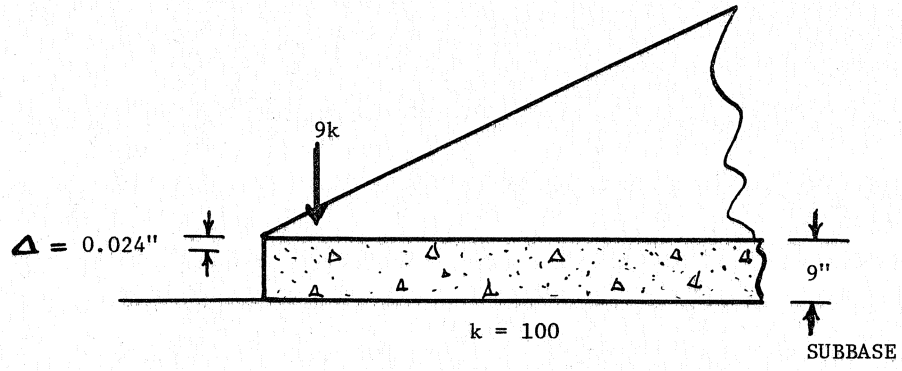
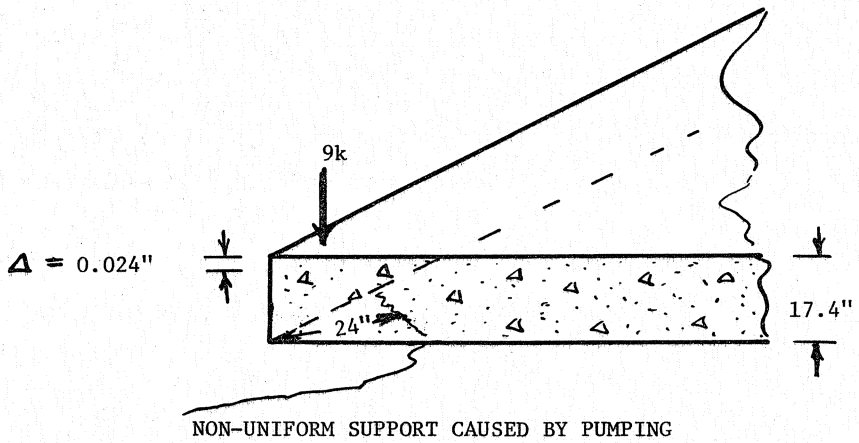


FIGURE 2. SERVICEABILITY OF A "FAILING" RIGID PAVEMENT SECTION AT THE AASHO ROAD TEST.



UNIFORM SUPPORT

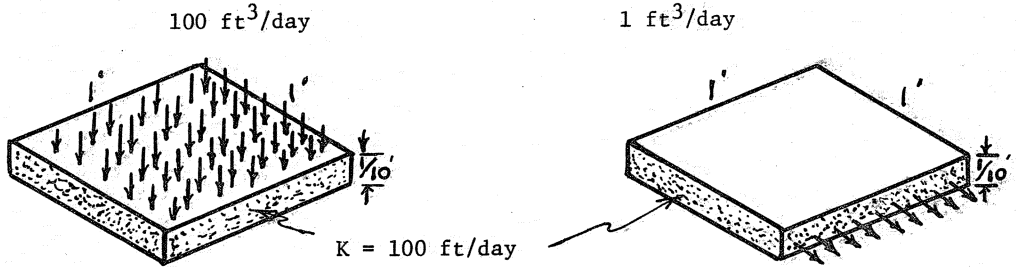


NON-UNIFORM SUPPORT CAUSED BY PUMPING

FIGURE 3. EFFECT OF NON-UNIFORM SUPPORT ON REQUIRED THICKNESS TO CONTROL DEFLECTIONS

VERTICAL FLOW

HORIZONTAL FLOW



$Q_v = K_v i_v A_v$

$= (100) \frac{1/10}{1/10} (1x1)$

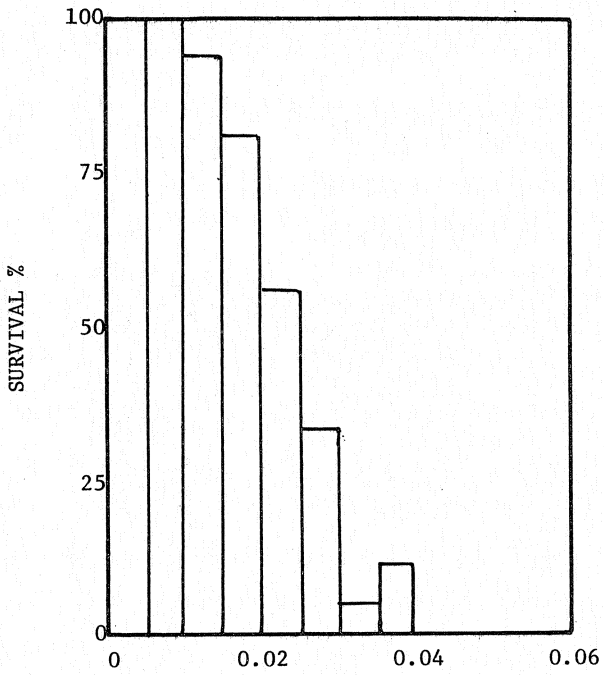
$= 100 \text{ ft}^3/\text{day}$

$Q_h = K_h i_h A_h$

$= 100 \frac{1/10}{1} (1x1/10)$

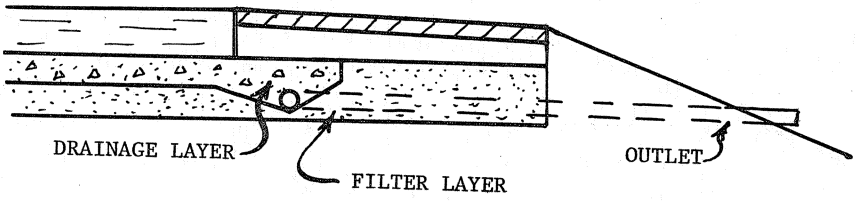
$= 1 \text{ ft}^3/\text{day}$

FIGURE 4. EFFECT OF HYDRAULIC GRADIENT AND AREA ON QUANTITIES OF FLOW

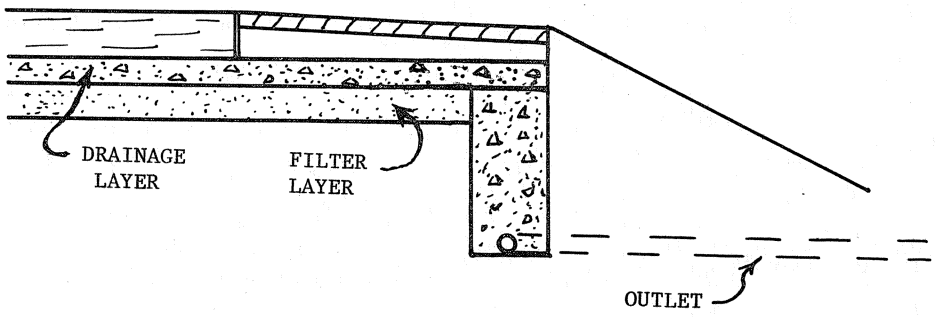


from HRB Special Report 61

FIGURE 5. RELATIONSHIP OF DEFLECTION TO PERFORMANCE OF CONCRETE PAVEMENTS



(a) NO GROUNDWATER



(b) WITH GROUNDWATER AND/OR FROST PENETRATION

FIGURE 6. TYPICAL CROSS SECTIONS OF TWO LAYER SUBDRAINAGE SYSTEMS

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APPENDIX A

CURRENT RESEARCH ON PAVEMENT SUBDRAINAGE

FHWA Administrative Contracts

1. "In Situ Determination of Permeability of Base and Subbase Courses"

   Principal Investigator: Dr. Lyle Moulton, West Virginia University

   Objectives: Develop a test method and apparatus to determine the in-situ permeability of base, subbase, and subgrade materials. The method should be valid for layers 3 to 18 inches thick under a variety of conditions and operate in the range of permeability 10^{-4} cm/sec to 10 cm/sec.

   Estimated completion date: December 1978

2. "Improving Subdrainage and Shoulders of Existing Pavements"

   Principal Investigator: In negotiation

   Objectives: Establish criteria for the early identification of existing pavements in need of improved subdrainage and shoulders. Develop a method for determining optimum time to effect remedial measures. Establish guidelines for making improvements in subdrainage and shoulders.

   Estimated completion date: June 1979

3. "Test Methods and Use Criteria for Filter Fabrics"

   To be funded in FY 1977.

   Objectives: Identify criteria for the engineering use of filter fabrics, particularly in subdrainage, erosion control, and soil reinforcement applications. Modify existing test methods and develop new test methods where needed to evaluate the engineering properties of filter fabrics.

   Estimated completion date: 1979

NCHRP Contracts

1. Project 4-11 "Buried Plastic Pipe Drainage of Transportation Facilities"

   Contractor: Simpson, Gumpertz, and Heger, Cambridge, Massachusetts

   Principal Investigators: Richard Chambers, Frank J. Heger

   Objective: Develop and evaluate the design, installation, and performance criteria for the use of buried plastic pipe in transportation facilities.

   Output to date: Interim Report, September 1975

   Available plastic pipe products were evaluated (preliminary) on the basis of pipe strength, soil-structure interaction, chemical and abrasion resistance and biological attack, and tentative guidelines established for their use in drainage applications. Field testing underway in actual highway applications.

   Estimated completion date: September 1978

2. Project 21-2(3) "Instrumentation for Moisture Measurement - Bases, Subgrades, and Earth Materials (Sensor Evaluation)"

Contractor: Southwest Research Institute

Principal Investigators: Ernest Selig, G. A. Matzkanin

Objectives: Refine and field test Nuclear Magnetic Resonance and Dielectric Capacitance moisture measurement devices.

Approximate completion date: September 1977

FHWA - Staff Research

1. "Load Tests on Plastic Pipe"

   Direct Federal Projects - Denver, Colorado

   Principal Investigator: Tom Courtney

   Laboratory tests to determine whether plastic pipe behaves as predicted by existing theoretical concepts. Final report in preparation.

   Estimated completion date: September 1977

HPR Studies

1. New Jersey, "Improved Drainage and Frost Action Criteria for New Jersey Pavement Design"

   Principal Investigator: George Koslov

   Objectives: To develop new pavement subdrainage criteria consistent with required strength and frost resistance.

   Estimated completion date: 1980

2. New Jersey, "Permeability of New Jersey Soil-Aggregate Bases"

   Principal Investigator: Bruce Cosaboom

   Objectives: Determine permeability and load bearing of soil-aggregate bases and subbases.

   Estimated complete date: July 1977

3. Louisiana "Evaluation of an Asphalt-Treated Drainage Blanket in a Rigid Pavement Section"

   Principal Investigator: W. H. Temple

   Objectives: Develop a stable, asphalt treated drainage layer system for use with rigid pavement sections.

   Shoulder drainage section constructed and evaluated. A second, revised section to be constructed.

   Estimated completion date: July 1978

4. Illinois, "Moisture Movement and Moisture Equilibria in Pavement Systems," IHR-604

   Principal Investigator: Barry Dempsey

   Objectives: Develop and verify a working soil moisture model.

Approximate completion date: December 1978

5. Arizona, "Environmental Factor Determination from In-Place Temperature and Moisture Measurements Under Arizona Pavements"

   Principal Investigators: George Way and Rowan Peters

   Objectives: Quantify environmental inputs and relate them to pavement structural characteristics. 34 sites. Nuclear moisture (21 sites), temperature, moisture sensors, Dunaflect Mays Meter (13 sites). Instruments in place - monitoring underway.

   Approximate completion date: 1978

6. Kentucky, "Subsurface Drainage Systems for Highway Pavements"

   Objectives: Design, construct, and observe the efficiency of a subsurface drainage layer to remove excess water from the pavement structural section.

   Estimated completion date: 1981

7. New York, "Pavement Deflection and Foundation Conditions"

   Principal Investigators: F. McCullagh and L. Hartvigas

   Objectives: Relate temporary and permanent moisture changes to performance of flexible pavements.

   Estimated completion date: 1980

8. California, "Determination of Load Carrying Capability of 18-inch Diameter Corrugated Slotted Pipe," D-4-146

   Estimated completion date: 1977

9. Oklahoma, "Polyethylene Plastic Corrugated Underdrain Pipe," Exp. project

   Estimated completion date: 1977

10. Illinois, "PVC Plastic Semi-Circular Underdrains," Exp. project

    Estimated completion date: 1977

11. Illinois, "Corrugated Polyethylene Tubing Underdrains," Exp. project, Evaluate in Project F237(33)

    Estimated completion date: 1977

12. Nebraska, "Seasonal Loss in Serviceability of Pavements"

    Measurement of deflection and PSI on selected projects.

    Estimated completion date: 1980