NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE 96

PAVEMENT SUBSURFACE DRAINAGE SYSTEMS

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE **96**

PAVEMENT SUBSURFACE DRAINAGE SYSTEMS

HALLAS H. RIDGEWAY
Chaplin, Connecticut

Topic Panel

RICHARD G. AHLVIN, *Vicksburg, Mississippi*
ROBERT BAUMGARDNER, *Federal Highway Administration*
DONALD K. EMERY, JR., *Georgia Department of Transportation*
LYNDON H. MOORE, *New York State Department of Transportation*
LEON M. NOEL, *Federal Highway Administration*
GEORGE W. RING, III, *Federal Highway Administration*
LAWRENCE F. SPAINE, *Transportation Research Board*
THOMAS F. ZIMMIE, *Rensselaer Polytechnic Institute*

RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. NOVEMBER 1982

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the Academy and its Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NOTE: The Transportation Research Board, the National Academy of Sciences, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

NCHRP SYNTHESIS 96

Project 20-5 FY 1979 (Topic 11-07)
ISSN 0547-5570
ISBN 0-309-03457-4
Library of Congress Catalog Card No. 82-74290

Price: $6.80

Subject Areas
Pavement Design and Performance
Soil Foundation
Soil and Rock Mechanics

Mode
Highway Transportation

NOTICE

The project that is the subject of this report was a part of the National Cooperative Highway Research Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council, acting in behalf of the National Academy of Sciences. Such approval reflects the Governing Board's judgment that the program concerned is of national importance and appropriate with respect to both the purposes and resources of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the National Academy of Sciences, or the program sponsors.

Each report is reviewed and processed according to procedures established and monitored by the Report Review Committee of the National Academy of Sciences. Distribution of the report is approved by the President of the Academy upon satisfactory completion of the review process.

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the Federal Government. The Council operates in accordance with general policies determined by the Academy under the authority of its congressional charter of 1863, which establishes the Academy as a private, nonprofit, self-governing membership corporation. The Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in the conduct of their services to the government, the public, and the scientific and engineering communities. It is administered jointly by both Academies and the Institute of Medicine. The National Academy of Engineering and the Institute of Medicine were established in 1964 and 1970, respectively, under the charter of the National Academy of Sciences.

The Transportation Research Board evolved from the 54-year-old Highway Research Board. The TRB incorporates all former HRB activities and also performs additional functions under a broader scope involving all modes of transportation and the interactions of transportation with society.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Printed in the United States of America.

PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire highway community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of interest to designers and others concerned with drainage of water from highway pavements. Detailed information is presented for consideration of drainage in designing new pavements and improving existing systems.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated, and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

Internal drainage of water entering the pavement section is an important step in ensuring good performance. This report of the Transportation Research Board reviews the basic principles and concepts of hydraulic flow that need to be considered in design construction and maintenance of pavements.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researcher in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

CONTENTS

ACKNOWLEDGMENTS

This synthesis was completed by the Transportation Research Board under the supervision of Damian J. Kulash, Assistant Director for Special Projects. The Principal Investigators responsible for conduct of the synthesis were Thomas L. Copas and Herbert A. Pennock, Special Projects Engineers. This synthesis was edited by Nancy A. Ackerman.

Special appreciation is expressed to Hallas H. Ridgeway, Chaplin, Connecticut, who was responsible for the collection of the data and the preparation of the report.

Valuable assistance in the preparation of this synthesis was provided by the Topic Panel, consisting of Richard G. Ahlvin, Vicksburg, Mississippi; Robert Baumgardner, Hydraulic Engineer, Office of Engineering, Federal Highway Administration; Donald K. Emery, Jr., Road Designer, Georgia Department of Transportation; Lyndon H. Moore, Director, Soil Mechanics Bureau, New York State Department of Transportation; Leon M. Noel, Chief, Pavement Design Branch, Office of Engineering, Federal Highway Administration; George W. Ring, III, Highway Research Engineer, Office of Research, Federal Highway Administration; and Thomas F. Zimmie, Associate Professor, Civil Engineering Department, Rensselaer Polytechnic Institute.

Lawrence F. Spaine, Engineer of Design, Transportation Research Board, assisted the NCHRP Project 20-5 Staff and the Topic Panel.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance were most helpful.

PAVEMENT SUBSURFACE DRAINAGE SYSTEMS

SUMMARY

Drainage of water from pavements has been an important consideration in road construction for more than 2000 years. However, modern processing, handling, and placement of materials frequently result in base courses that do not transmit water or drain; combined with increased traffic volumes and loads, this often leads to pavement distress caused by moisture in the structures.

Water is always present in pavement materials in the form of free water, capillary water, bound moisture, or water vapor. Free water is the form of most concern to the designer because it can decrease the strength of the pavement and is the only form of water that can be significantly removed by gravity drainage.

The primary source of water in pavements is atmospheric precipitation. This water can enter the pavement in several ways (e.g., cracks, infiltration, through shoulders and ditches, high groundwater) and is moved by an energy gradient, such as gravity, capillary forces, osmotic forces, and temperature or pressure differences. The drainage designer is primarily concerned with saturated gravity flow, which can be determined by application of Darcy's law.

To understand and analyze the conditions under which the pavement must function, the designer needs information on highway geometrics, surface drainage, nonpavement subsurface drainage, climate, and soil properties. These data enable the designer to predict the amount of free water that will enter the pavement structure, to predict the free water surface, and to establish the design subgrade moisture content. Two general types of subsurface drainage criteria are used: (a) a time for a certain percentage of drainage or (b) an inflow-outflow criterion.

The free water can be removed by draining vertically through the subgrade or laterally through a drainage layer. Several combinations of criteria and equations can be selected to calculate the required permeability of the drainage layer. The criterion selected has much more influence than the equation used; therefore, the drainage criterion should be selected carefully. Then the drainage layer and/or base can be designed to meet the selected criterion. The materials specifications should be checked to assure that permeability, strength, load-distribution, and construction stability requirements are met.

Among the conclusions of this synthesis are that Darcy's law is adequate for the design of subsurface drainage systems; subsurface drainage systems will only

drain free water, for which the primary source is infiltration; water held in the pavement structure by capillary forces cannot be removed by subsurface drainage systems; and permeability requirements for lateral flow are high because of low hydraulic gradient and small area of flow. The infiltration of free water into the pavement structure, its effect on material strength, and its removal by vertical flow or by a lateral subsurface drainage system should be an integral part of the pavement structural design process.

CHAPTER ONE

INTRODUCTION

The purpose of this synthesis is to examine subsurface drainage in relation to the design, construction, and maintenance of pavements. Discussion is confined to the pavement structure and the immediate surrounding area. This is not intended to be a report of all drainage problems related to transportation structures, slope stability, or techniques for lowering the water table, which are primarily of interest to engineers in the drainage and geotechnical sections of transportation agencies rather than those directly involved with pavement design. The pavement designer needs to understand the effects of water on the pavement structure, how the water gets there, and how it can be removed so that damage to the pavement is minimized.

The pavement subsurface drainage system is an integral part of the pavement structure, but the pavement itself, not the drainage system, is the desired end product. The pavement's function is to provide a surface to serve traffic safely, comfortably, and efficiently at a minimum or "reasonable" cost (*1*). To consistently achieve sound, economic pavements, it is necessary to understand and incorporate subsurface drainage principles into the pavement structure design process. There is no single solution that will solve every engineering design problem. The solution to a problem will depend on the design criteria, the existing conditions, and the materials available.

BACKGROUND

Pavement subsurface drainage has been a subject of interest for many years. Modern concern with water in or adjacent to the pavement structure began with P.M.J. Tresaquet, the originator of the "French drain," in France and Thomas Telford and John L. McAdam in England during the late 18th and early 19th centuries (*2*). These engineers were concerned with the removal of both surface water and subsurface water. McAdam's fundamental principle—"that it is the native soil which really supports the weight of traffic; that while it is preserved in a dry state it will carry any weight without sinking" (*2*)—is as applicable today as it was then. There are many indications that the drainage of water was an important consideration in road construction by the Romans, Greeks, and Egyptians 2000 years before McAdam, Tresaquet, and Telford.

Pavements constructed using the principles and techniques advocated by Tresaquet, McAdam, and Telford drained relatively well, but there were two major changes in pavement construction that affected the capability of the base and subbase to drain water. The first was paving of the surface with bituminous materials or portland cement concrete; the second was mechanization of materials processing, handling, and placing.

Before bituminous materials were used, the soil aggregate surface was designed as an impervious mat to drain away the surface water. When bituminous or portland cement materials came into use for the surface, the soil aggregate mixture became a base material. As a base material the impervious characteristic may not be a desirable characteristic.

Pavements designed according to the principles of Telford, McAdam, and others were constructed primarily by means of manual labor for both the transportation and placing of materials. As long as this was the case, pavements incorporating these design principles could be economically constructed. Early in the 20th century, mechanization of the processing, handling, and placing of materials resulted in the use of finer materials, such as the dense-graded base and subbase courses. These materials are easy to handle and place, are strong and durable, and transfer load well when they are not in a moisture condition that causes the effective stress to differ from the total stress under live load; however, they are not designed to transmit water or drain.

Pavements designed with bituminous or portland cement concrete surfaces usually performed better than the pavements with aggregate surfacing, even though design of the subsurface drainage of the pavement structure was ignored. Generally, the performance was satisfactory under the traffic and load conditions that existed before the Interstate era. However, with increased traffic and increased vehicle loads, and, in the case of airports, much heavier aircraft loading, pavement distress due to moisture in the pavement structure has become an increasingly apparent problem.

Reports concerning drainage of water from the base and subbase materials were published in 1944 by Izzard (*3*) and in 1952 by Casagrande and Shannon (*4*) and by Barber and Sawyer (*5*). Design of the pavement structure both during this period and more recently gave cursory recognition to subsurface drainage by such statements as "Generally, a free draining base course with provision for adequate subdrainage is to be recommended" (*6, 7*). This, however, was about the extent to which pavement subsurface drainage was considered. The principles discussed by Izzard and by Barber and Sawyer were not used to develop design criteria for the pavement structure.

Since about 1970 there has been considerable interest in pavement subsurface drainage. Publications by Cedergren (*8*), Cedergren et al. (*9, 10*), Moulton (*11*), and Dempsey et al. (*12*) are of particular interest. In addition to the renewed interest, there is also the influence of new materials that can be used for subsurface drainage. New types of pipes and filter materials are available and very useful for some applications. Results of research on filter fabric specifications (*13*) and the use of prefabricated underdrains (*14–16*) have been published.

The current interest in drainage includes both the design of new pavements with adequate provisions for drainage and the repair of existing pavements, both flexible and rigid, that have problems associated with moisture. Although there is concern, the current pavement design process does not generally include criteria related to the subsurface drainage requirements. However, to (consistently) obtain adequately designed pavement structures, the principles of subsurface drainage must be understood and applied to each and every pavement design with the same rigor that is currently used in designing the pavement for strength and load distribution.

NEED FOR DRAINAGE

Water is always present in soil and granular pavement materials in some form, but the forms that concern the pavement design are free water, capillary water, bound moisture, and water vapor.

Free water in the base, subbase, and subgrade is of particular concern because it can decrease the strength in the following ways: (a) reducing the apparent cohesion by lowering the capillary forces; (b) reducing the friction by reducing the effective mass of the materials below the water table; and (c) for quickly applied loads, possibly reducing the strength by the development of increased and/or oscillating pore pressures (*17*). The development of these pore pressures will be affected by the type of soil, compaction, magnitude of the load, rate of application of the load, and stiffness of the section. Measurement of the change in pore pressures caused by dynamic wheel loads is difficult, but a new type of sensor developed and reported on by Dempsey et al. (*18*) shows promising results.

Dempsey et al. (*12*), reporting on a study by Thompson, confirmed that granular materials at high levels of saturation became unstable under repeated loading.

Studies by Cedergren et al. (*9*) indicate that high pore pressures can be developed by the dynamic action of the wheel load on the pavement surface. Movement of the wheel along a pavement with a saturated subgrade can produce a moving pressure wave, which in turn can create large hydrostatic forces within the structural section. These pulsating pore pressures significantly influence the load-carrying capacity of all parts of the pavement structure.

One of the most dramatic demonstrations of the effect of pulsating hydrostatic forces is the pumping of material under rigid portland cement concrete pavements (Fig. 1). Pumping will also occur under flexible asphalt concrete pavements, but it is not as dramatic because the asphalt concrete normally fails by cracking before it develops the high elastic slab deflection that would allow it to act like a pump diaphragm.

When high pore pressures are developed in a base or subbase material, its load transfer properties are altered considerably so that the stresses applied to the subgrade are not reduced to their expected level (Fig. 2).

Free water within the pavement structure can also act as a source of water for frost activity.

Capillary water is water held in the pores of a soil above the level of saturation (water table, free-water surface, or phreatic line) under the action of surface tension forces (*11*). It is of interest to the pavement designer primarily because it

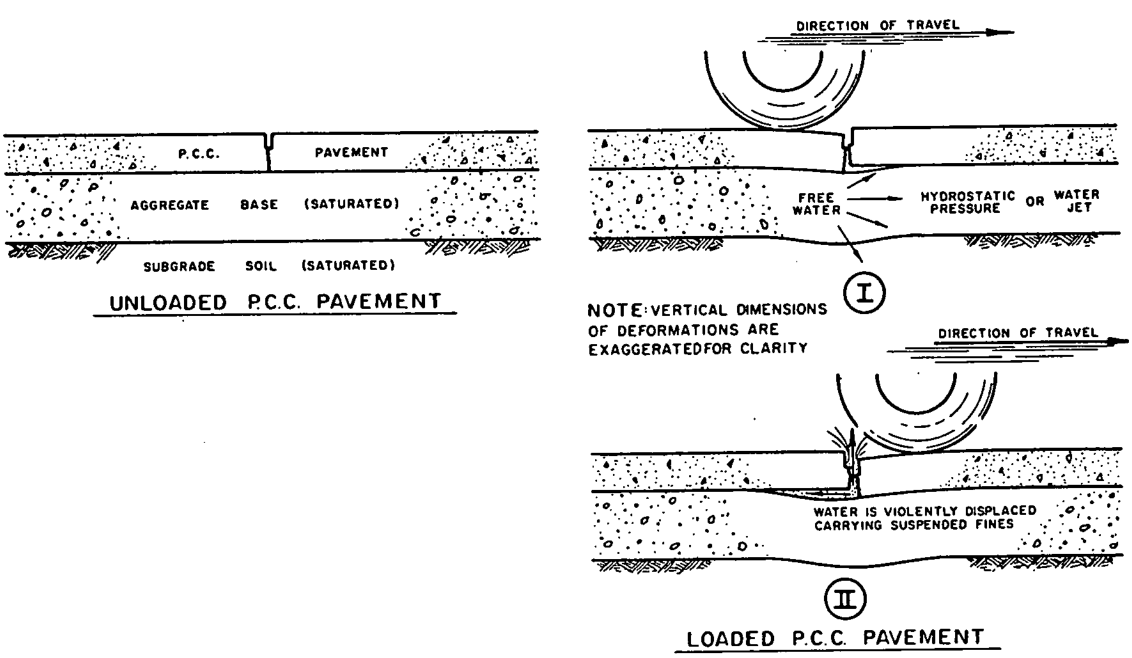


FIGURE 1 Pumping phenomena under portland cement concrete pavements (*10*).

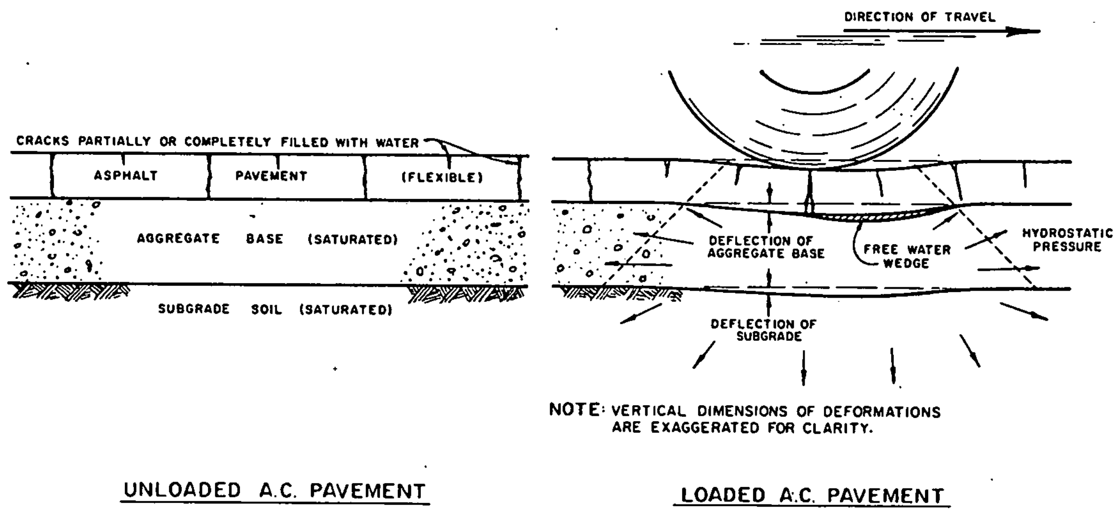


FIGURE 2 Action of free water in AC pavement structural sections under dynamic loading (*10*).

affects frost action and the long-term subgrade moisture condition.

Bound moisture and water vapor are present in all soils. Under some conditions, some of the bound water can be converted to water vapor. Water in its vapor state is not thought to be detrimental to the pavement structure, but under some conditions the water condenses and forms free water near the pavement surface. The pavement designer's main concern with bound moisture is the change in the volume and strength of some clay subgrades caused by changes in the amount of bound moisture and corresponding osmotic pressures.

Capillary water, bound moisture, and water vapor move through soils by various mechanisms, but they are not greatly affected by gravity. Only free-water conditions can be significantly altered by gravity drainage systems.

CHAPTER TWO

WATER IN PAVEMENTS

SOURCES OF WATER

There are many sources of the water that reaches the pavement structure and its immediate vicinity. To evaluate the various sources, the pavement designer should consider the entire profile and cross section of the highway and the surface and subsurface drainage systems that are to be used for the operation and structural integrity of the overall facility. The pavement structure designer, who may not be directly involved with the other aspects of the facility, cannot predict the possible sources of water and amounts without knowledge of the surface and subsurface drainage geometry.

Free water enters the structural section and the adjacent area from many sources (Fig. 3). Cedergren et al. (*10*) state that the most abundant and often overlooked source is undoubtedly atmospheric precipitation, by which surface water is supplied from rain (usually the largest amount), snow, hail, condensing mist, dew, and melting ice. This water reaches the structural section in several ways (Fig. 4):

1. Cracks in the pavement surface (*9–11, 19–21*). New pavements can be constructed so that they are virtually impermeable, but they cannot be constructed without joints or without cracks forming well before the desired life of the pavement structure is attained (*20, 21*). Various reported pavement permeabilities are given in Table 1. Runoff into surface cracks is given in Table 2.
2. Infiltration through the shoulders.
3. Infiltration from the side ditches.
4. Melting of an ice layer from a frost area during the thawing cycle (*11*).
5. Free water from pavement base. If the base is not prop-

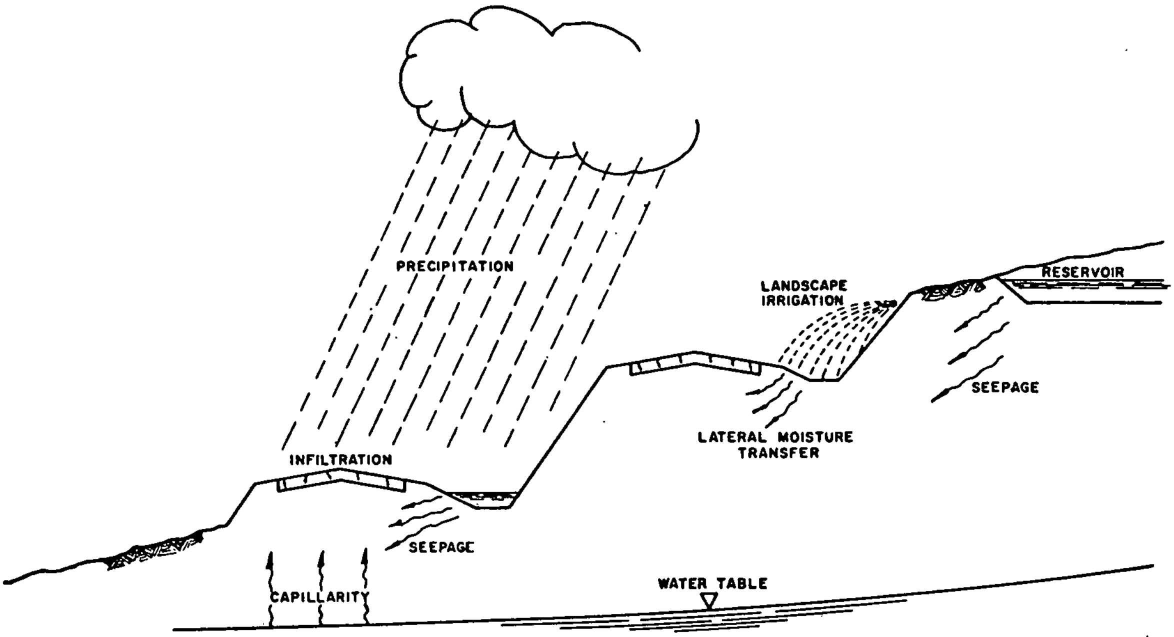


FIGURE 3 Sources of water entering highway pavement structural sections (*10*).

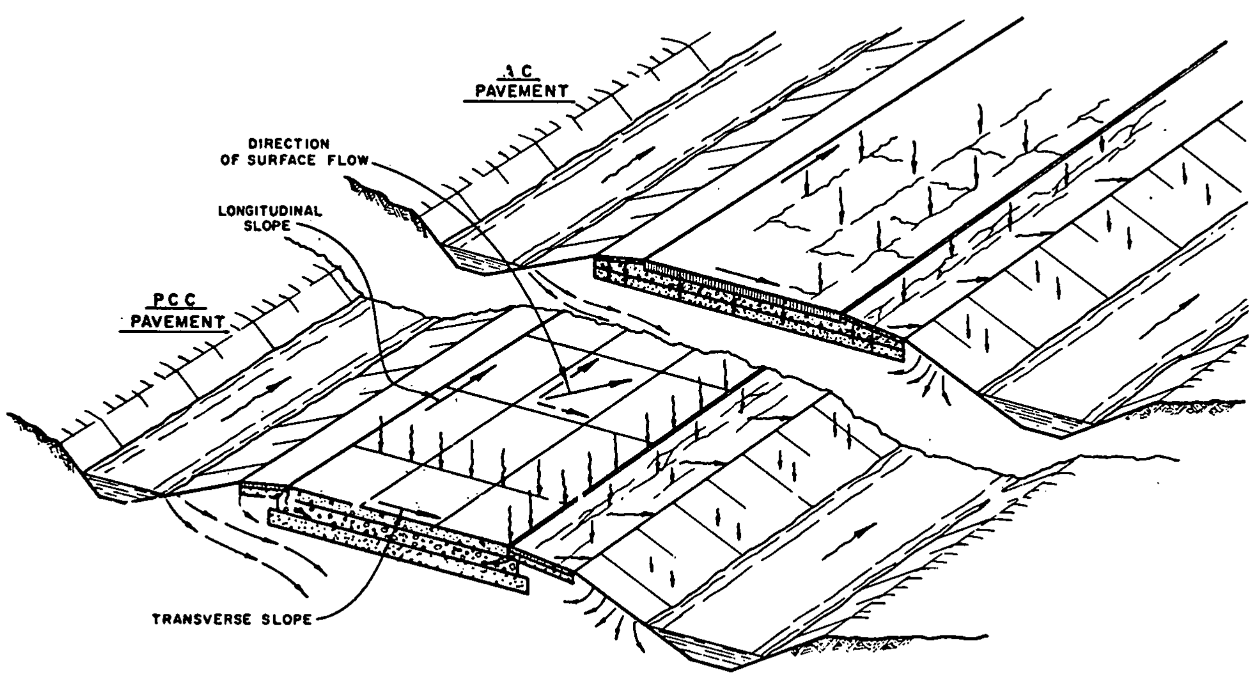


FIGURE 4 Points of entrance of water into highway pavement structural sections (*10*).

TABLE 1
PERMEABILITY OF ASPHALT CONCRETE PAVEMENTS (*10*)

Source of Information	k in./hr	cm/s	ft/day
New Pavements			
Kari & Santucci (US 101)[a]	75	0.053	150
Kari & Santucci (US 101, left wheel path)[a]	23	0.016	46
Kari & Santucci (US 101, btwn. wheel paths)[a]	45	0.032	90
Kari & Santucci (US 101, right wheel path)[a]	30	0.021	60
Cedergren	50	0.035	100
Reichert (Lessines, Belgium)	78	0.055	156
California Division of Highways Specification	20	0.014	40
Old Pavements			
Baxter & Sawyer (laboratory tests)	0.0001	0.0000	0.0002
Tomita (USNCEL, laboratory tests)	3.00	0.0021	6.00
Breen (Univ. of Conn. - traffic lane)	0.75	0.0005	1.50
Breen (Univ. of Conn. - shoulder)	2.25	0.0016	4.50
Reichert (Lessines, Belgium)	3.50	0.0025	7.00
South Africa (cracked surface)	1.00	0.0007	2.00

[a]Air permeability.

erly drained, it may act as a source of free water for the subbase and subgrade.

6. High groundwater table.
7. Condensation of water vapor (small amounts).

The first five sources can be particularly significant if the surface drainage is not properly designed or maintained.

Any free-water surface can act as a source of capillary water, which will move from the free-water surface when a capillary potential exists. The distance it moves depends primarily on the pore-size distribution in the soil. Capillary water can be changed to free water and vice versa (*22*). These changes may be affected by changes in temperature and changes in the pore-size distribution of the soil.

Free-water surfaces and capillary fringe water are both sources for water vapor. Under changing temperature and pressure conditions, water vapor can change back to either free water or capillary water (*23*).

MOVEMENT OF WATER

Water and moisture move through soils in response to an energy gradient. This gradient may be supplied by elevation (force of gravity), capillary forces, osmotic forces, and temperature or pressure differences.

In a specific situation, one of the forces usually so dominates the flow that the other energy gradient systems can be ignored; e.g., the flow of water in a coarse gravel is affected only by gravitational forces, whereas movement of water in frost-susceptible unsaturated soils is primarily caused by capillary and temperature gradients and thus gravitational forces can be ignored.

The movement of water in soil is sometimes discussed in terms of saturated and unsaturated flow. Subsurface drainage design generally involves saturated flow; however, considerable water can also move by unsaturated flow. Usually, subsurface drainage systems drain only free water from saturated soil using the energy gradient supplied by elevation (gravity). Some water will drain due to the capillary energy gradient, but the rate is much too slow to remove water laterally from the pavement structure.

Saturated Flow

Saturated flow in soils involves the movement of free water using a hydraulic gradient (head) supplied by elevation. The equation generally used for the computation of the flow of water through soils is based on experiments by Darcy in 1856 and is called Darcy's law:

$$Q = (ki)A = V_d A$$

where

Q = quantity of flow (cm^3/s),
k = coefficient of permeability (hydraulic conductivity) (cm/s),
i = hydraulic gradient (cm/cm), and
A = cross sectional area normal to the direction of flow (cm^2).

The velocity term (V_d or ki) is the superficial or discharge velocity. The average velocity of water through the pores (seepage velocity) is the discharge velocity divided by the effective porosity,

$$V_s = \frac{V_d}{N_e}.$$

Darcy's law is given in several different forms; extensive treatises on its limitation and uses can be found in texts by Cedergren (*24*), Taylor (*25*), Terzaghi and Peck (*26*), and others. Application of Darcy's law assumes laminar flow and constant viscosity of the water.

Taylor (*25*) states: "In soils there is a slow transition from

TABLE 2
RUNOFF INTO SURFACE CRACKS OF PORTLAND CEMENT CONCRETE PAVEMENTS (*10*)

Crack Width (in.)	Pavement Slope (%)	Runoff Entering Crack (%)
0.035	1.25	70
0.035	2.50	76
0.035	2.75	79
0.050	2.50	89
0.050	3.75	87
0.125	2.50	97
0.125	3.75	95

[a]Research by University of Maryland (laboratory test data).
[b]Precipitation intensity: 2 in./hr.

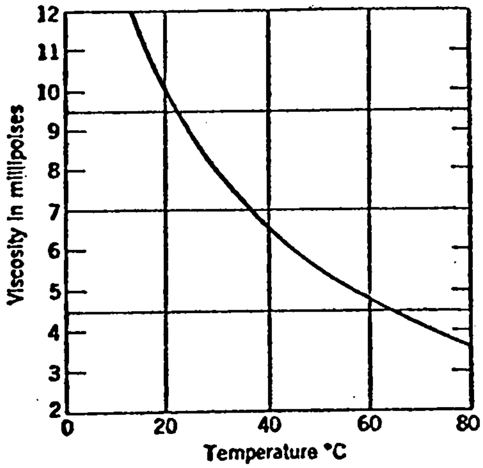


FIGURE 5 Viscosity of water (*24*).

purely laminar flow to a mildly turbulent condition, which precludes an accurate expression for the critical point, but which also makes a precise expression unnecessary." For the conditions that exist within the pavement structure the assumption of laminar flow is satisfactory.

Cedergren (*24*) states "Although the viscosity of water, like that of most fluids, becomes less at high temperature the range is much less than for other fluids. Over the widest range in temperature ordinarily encountered in seepage, viscosity varies about 100% [Fig. 5]. Although this variation is not highly important it causes variations in permeability of like amount; hence it is customary to standardize permeability values @ 20°C or 70°F and make a correction if field temperatures are substantially different." The correction can be made by the ratio (*25*):

$$k_1{:}k_2 = \mu_2{:}\mu_1$$

where

k_1 = permeability at temperature 1,
k_2 = permeability at temperature 2,
μ_1 = viscosity at temperature 1, and
μ_2 = viscosity at temperature 2.

The application of Darcy's law is sufficient for most pavement subsurface drainage problems. The errors caused by the use of Darcy's law are small compared to the variability and potential errors in other parts of the subsurface drainage design, construction, and maintenance.

The use of Darcy's law requires a determination of the permeability constant, k. Permeability has units of velocity and is a measure of the ease with which water can travel through a porous medium. It depends largely on (a) the viscosity of the flowing fluid (water); and (b) the size and continuity of the pore spaces or joints through which the fluid flows, which, in soils, depend on the size and shape of the soil particles, the density of the soil mass, the detailed arrangement (structure) of the individual soil grains, and the presence of discontinuities (*24*). When possible, permeability should be determined by testing.

One laboratory method of determining the permeability constant, k, is the constant-head permeameter test (ASTM D 2434-68). Other reliable laboratory methods of directly determining the permeability of a soil can be found in other publications (*24–27*). An excellent review of the state of the art in the measurement of permeability of fine-grained soils can be found in a study by Olsen and Daniel (*28*).

There have been a number of charts and nomographs developed for estimating permeability. Two of the most recent are a chart by Cedergren (Fig. 6) (*9*) and a nomograph by Moulton (Fig. 7) (*11*).

The pavement designer is usually interested in the permeability of processed materials and does not consider the permeabilities of large masses of undisturbed soils. However, if desired, the permeability of large masses can be determined by various field tests. These field tests are usually one of several types of well-pumping tests.

A technique for determining in situ permeability of bases and subbases was developed specifically for the use of highway engineers in the field by Moulton and Seals for the Federal Highway Administration (*29*). Reasonable estimates of permeability can also be determined by several methods developed by Healy and Laak (*30*). These are essentially simplified versions of a falling-head permeameter and a pumping or bailing test.

Although the permeability of a soil or rock mass may vary considerably from point to point, this should not deter the pavement designer from determining or estimating overall permeabilities as required for analysis and design of a drainage system. The best determination or estimation of permeability made from the available data and measurements is a tremendous improvement over no estimate at all. Satisfactory pavement designs with adequate subsurface drainage systems can generally be obtained if the in-place permeabilities are within the first significant digit of the permeability used for design.

Because of the variability of field permeability, both in undisturbed and reconstituted materials, it is generally better to make many quick tests on randomly selected samples, instead of a few carefully controlled tests. In-situ tests, such as that developed by Moulton and Seals (*29*), can be particularly valuable. A very precise determination of permeability on a single sample is not usually necessary, or for that matter, warranted.

Unsaturated Flow

The pavement designer is more interested in unsaturated flow as an analysis tool rather than a design tool. That is, the designer is concerned with the moisture conditions caused by unsaturated flow rather than with designing a subsurface drainage system based on the principles of unsaturated flow. Moisture held in soils by capillary forces cannot be drained with the standard subsurface drainage system.

Unsaturated flow includes flow caused by energy gradients supplied by capillary forces, temperature differences, and osmotic pressure. Vapor movement of moisture may also be included. Movement of water due to these energy gradients is more of interest in fine-grained materials than in coarse-grained materials. In coarse-grained materials, the capillary forces are almost equal to zero and movement caused by the other gradients is not normally of concern to the pavement designer.

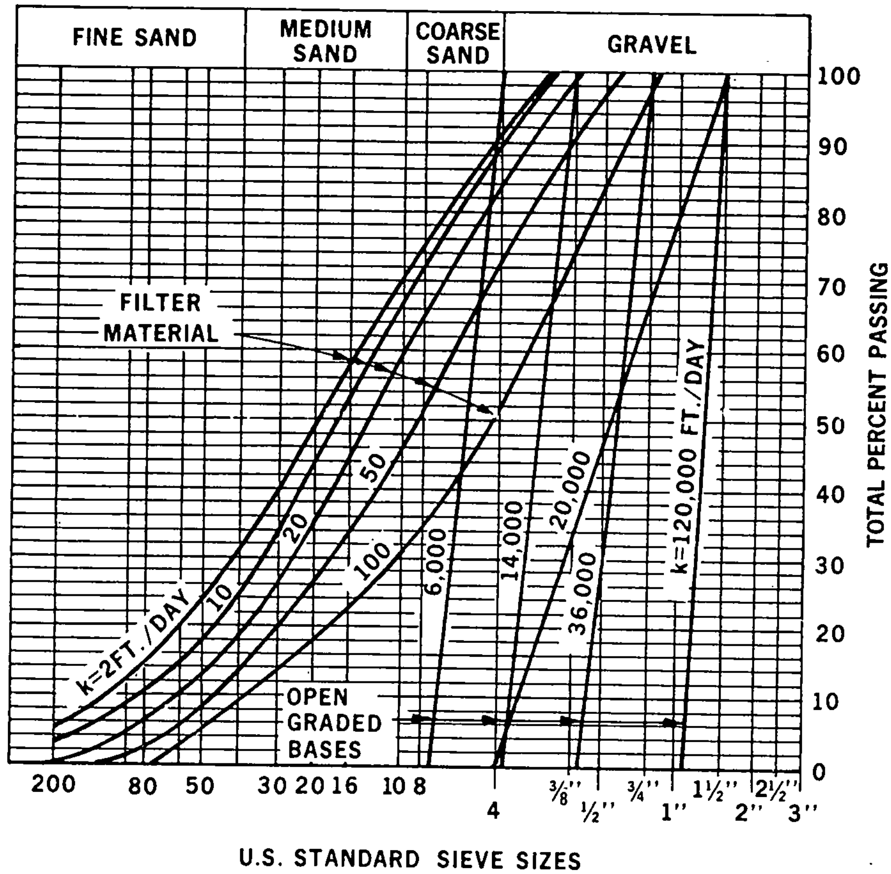


FIGURE 6 Typical gradations and permeabilities of open-graded bases and filter materials (*9*). (Note: 1 ft/day = 0.00035 cm/s.)

Capillary forces are tension forces in the water, indicated by negative pore pressures, that result from a combination of the surface tension of a liquid (water) and the tendency of some liquids to wet surfaces (soil particles) with which they come in contact (*25*). The potential magnitude of these forces is primarily a function of the pore-size distribution in the soil, which in turn is related to its grain-size distribution and density (*6, 11*). The magnitude of the forces (pore pressure) at a particular point is also a function of the position of the point relative to the free-water surface and of the point where the potential magnitude of the capillary force is developed. In a saturated soil below the phreatic surface, the capillary force is zero.

The flow of water is due to the total energy gradient; by including the energy gradient caused by capillary forces, Darcy's law, originally for saturated flow only, can be extended for use in unsaturated flow conditions as follows:

$$q = k_u\left(\frac{\Delta h}{\Delta l} + \frac{\Delta h_c}{\Delta l}\right)$$

where

q = unit rate of flow (cm/s),
k_u = unsaturated permeability (cm/s),
$\frac{\Delta h}{\Delta l}$ = energy gradient due to the change in elevation head (cm/cm), and
$\frac{\Delta h_c}{\Delta l}$ = energy gradient due to the change in capillary forces (cm/cm).

The equation is similar to that for saturated flow conditions. The use of the equation is more complicated, however, because both unsaturated permeability, k_u, and the hydraulic gradient due to the change in capillary forces are functions of the moisture content. In addition to being affected by moisture content, they are sometimes hysteretic (subject to the influence of past moisture conditions).

Simplified solutions to the above equation can be found in Taylor (*25*). Work by Elzeftawy and Dempsey (*31*) and Dempsey et al. (*12*) examine the problem in detail and contain an extensive list of references for further study. Work by Wallace and Leonardi (*32, 33*) is also of interest.

Summary

The movement of water, or moisture, through soils is usually considered to be either saturated or unsaturated flow.

$$k = \frac{6.214 \times 10^5 (D_{10})^{1.478} (n)^{6.654}}{(P_{200})^{0.597}} \quad \text{(ft./day)}$$

$$n = \text{Porosity} = \left(1 - \frac{\gamma_d}{62.4G}\right)$$

G = Specific Gravity

(Assumed = 2.70)

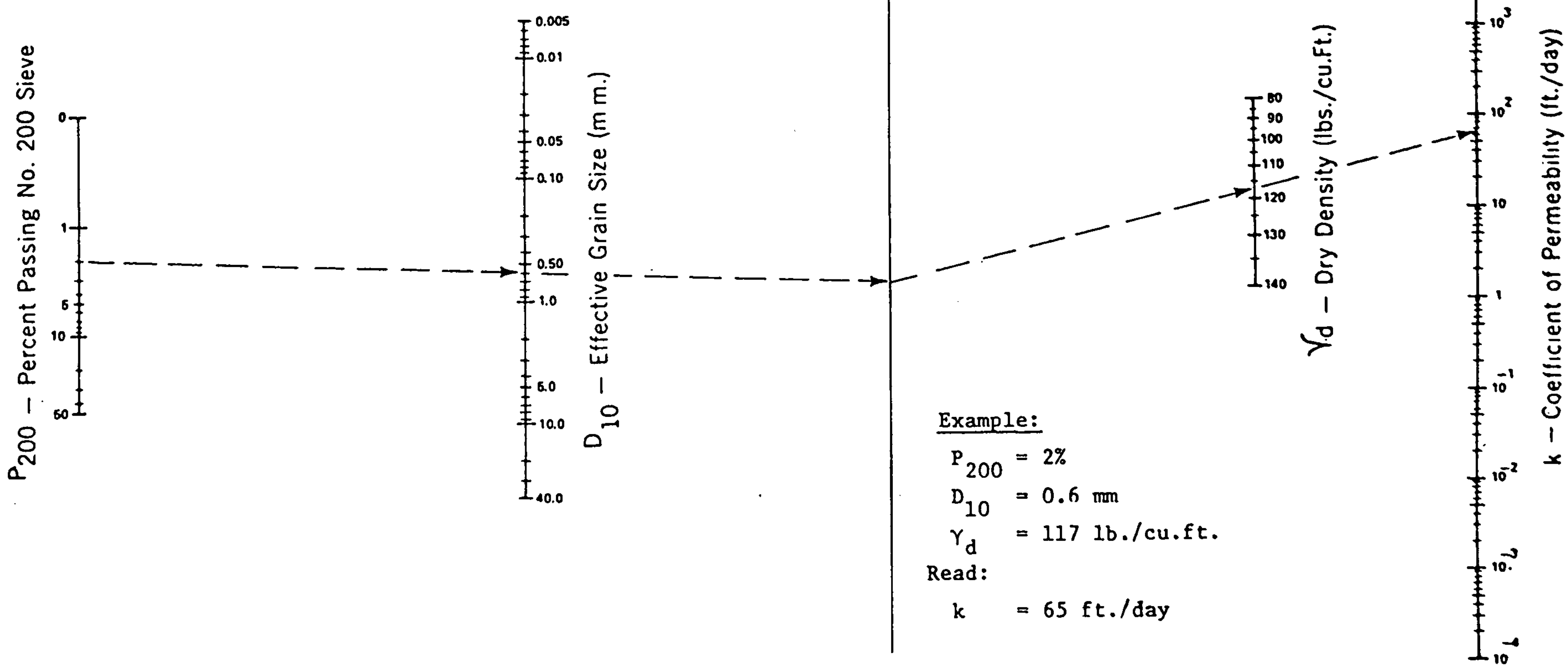


FIGURE 7 Nomograph for estimating coefficient of permeability of granular drainage and filter materials (*11*).

Saturated flow takes place due to the energy gradient supplied by elevation or gravity. Unsaturated flow is affected by the additional energy gradients of capillarity and temperature.

Subsurface drainage systems will only remove water from soils in which gravity is the primary energy gradient. Darcy's law is adequate for the design of subsurface drainage systems, but it should be emphasized that only free water (the amount is sometimes referred to as the specific yield) can be removed by the system. In fine-grained materials, moisture held primarily by capillary forces can significantly lower the load-carrying capacity of the material. Underdrains may not remove all of this moisture.

CHAPTER THREE

ANALYSIS OF PAVEMENT DRAINAGE

The pavement designer must consider many factors in addition to drainage, but the drainage of the pavement structure and the moisture conditions of the subgrade are of special concern; a design that does not address these problems is not complete. Basic information on highway geometrics, surface drainage systems, nonpavement subsurface drainage systems, climatology, and soil properties needs to be obtained to make the analysis of the conditions under which the pavement must function.

HIGHWAY GEOMETRICS

The pavement designer is usually expected to design the surface drainage system for runoff, or the subsurface drainage system to control groundwater flow, lower the water table, or stabilize slopes. The designer must be able to analyze the systems presented in the overall facility design to understand the environment in which the pavement must function. In many cases the pavement designer will recommend changes in geometrics, surface drainage, or subsurface drainage systems to create a better environment for the pavement structure.

Moulton (*11*) gives the following statement concerning highway geometry:

> Almost all of the geometric design features of a highway can exert some influence upon the analysis of the design of subsurface drainage. Therefore, before attempting to undertake this work, the designer should be armed with as much information as possible on these features. Included should be sufficiently detailed profiles and cross-sections to permit assembly of the following data for each section of roadway under consideration: (a) longitudinal grades; (b) transverse grades (including superelevation); (c) widths of pavement and shoulder surface, base and subbase; (d) required thickness of pavement elements based on normal structural design practice for the particular area under consideration; (e) depths of cuts and fills; (f) recommended cut and fill slopes; and (g) details of ditches and other surface drainage facilities. Much of this information might be obtained from a detailed set of "typical cross-sections." However, a set of roadway cross-sections showing original ground and at least the gross features (i.e. cut and fill slopes, ditches, etc.) of the proposed construction is considered to be a necessity.

SURFACE DRAINAGE

A good surface drainage system is a prerequisite to a good subsurface drainage system. The surface water should be removed quickly and completely from the vicinity of the pavement structure. The surface drainage system should ensure that ponding will not occur on the driving lanes or on the shoulders, and that water will not remain standing in the side ditches. Any water that is left standing will either evaporate or infiltrate the subsurface materials where it will affect load-carrying ability. For detailed information on surface drainage, see previously published reports (*6, 8, 34–36*).

All inlets and underground conduits should be located so that they can be used in the pavement subsurface drainage design if it is desirable.

SUBSURFACE DRAINAGE

Planned subsurface drainage facilities needed to control groundwater, stabilize slopes, or lower the water table in the vicinity of the highway should be carefully examined. Although these subsurface drainage systems are not part of the pavement design itself, the proper design and installation of these systems are crucial if the pavement is to perform satisfactorily. The examination of the proposed subsurface drainage system should include the horizontal and vertical location of all of the conduit systems to assure that they will in fact carry water away from the pavement structure (and not serve as a source of supply) and, if desired, to enable conduit used for drainage of the pavement structure to connect with existing piping for the ultimate removal of water from the roadway system.

CLIMATE

The climate of the project area should be determined. Precipitation is of particular significance; intensity, duration, type, and distribution are as significant as annual average amounts. It is also important that temperature distribution and freezing index be determined in frost-susceptible areas.

SOIL PROPERTIES

To accomplish the pavement drainage design, the subgrade soil permeability, capillary potential, and swell characteristics should be obtained in addition to the usual classification and strength characteristics. The basic soils information should also include the seasonal groundwater profile.

ESTABLISHING THE FREE-WATER SURFACE IN THE SUBGRADE

By using the basic data of the original groundwater profile and the proposed highway geometry, surface drainage facilities, and subsurface drainage facilities, the free-water surface in the vicinity of the pavement can be predicted. Techniques for making these predictions are available (*11, 24–27*). The location of the seasonal free-water surface is important because it affects the equilibrium moisture content, the bearing capacity, the frost susceptibility of the subgrade, and the rate at which the infiltrated water can be drained from the base and subbase materials.

Recommendations on the minimum depth to the free-water surface from the pavement surface vary. Typical criteria are: Massachusetts—7 ft (2.1 m); Michigan and Minnesota—5 ft (1.5 m); Saskatchewan—8 to 12 ft (2.4 to 3.7 m); and Nebraska—3 to 4 ft (0.9 to 1.2 m) in granular materials and 7 ft (2.1 m) in cohesive soils (*37*, p. 58).

Investigators in Germany concluded that a critical depth is 2 m (6.6 ft) below the pavement surface (*34*). Researchers in Sweden found significant reduction in bearing capacity when the water table is raised to within 70 cm (27 in.) of the surface, and further reduction when it is raised to within 30 cm (11 in.) of the surface (*38*). The research in Sweden is particularly significant because it shows the effect of the water table on subgrade strength independent of its relationship with frost-heave problems. This study was conducted using both a gravel base and a crushed-stone base on a frost-susceptible silt subgrade (no details on gradation or permeability were given).

Although no specific criteria considering these variables were found, the critical depth to the water table is probably a function of subgrade strength, subgrade permeability, subgrade capillarity, and the ratio of the design vertical live load stress to the live load plus dead load vertical stress. These items are important because the strength of the subgrade must be assessed at the effective stress level (i.e., the total stress less the pore pressure), whereas the driving force to cause failure is at the total stress level.

ESTABLISHING THE DESIGN SUBGRADE MOISTURE CONTENT

Yoder and Witczak (*39*) state: "The ultimate moisture and density condition that will exist in the subgrade largely determines the load-carrying capacity of the pavement under traffic." The strength and modulus of the subgrade material are related to the moisture content; therefore, it is important to estimate the maximum seasonal moisture content anticipated in the life of the subgrade. In measuring or estimating strength and modulus properties of the subgrade materials for design, the samples should be at expected maximum moisture content. If this is not the case, the estimated load-carrying ability will be too high. The primary factors that control the moisture content of a given subgrade are soil properties, precipitation, depth to the water table, and temperature.

Prediction of the moisture content of subgrades was the subject of a report prepared by the Organisation for Economic Co-operation and Development (OECD) in August, 1973 (*40*). The report contains two general methods for estimating the water content of highway subgrades: the rational method and empirical relationships.

The rational method for estimating the water content of highway subgrades, as developed by the British Road Research Laboratory, depends on two conditions (*40*): (a) The temperature of the subgrade is constant, uniform, and above 0°C (32°F). (b) The subgrade cannot receive moisture through the highway pavement or through migration from adjacent soil masses with a higher pore-water pressure, nor can it give up moisture by evaporation or migration to adjacent soil masses having a lower pore-water pressure.

The empirical relationships presented in the OECD report (*40*) are generally based on relationships with one or more of the following geotechnical characteristics of the soils concerned: (a) the plastic index (PI); (b) the plastic limit (PL); (c) the liquid limit (LL); (d) the optimal water content indicated by a normalized compaction test; and (e) the particle content passing a 74-μm (No. 200) sieve. Three of the empirical relationships are as follows (*40*):

1. Swanberg and Hansen (Minnesota State Highway Department). Tests were run mostly on clayey silt, with plastic indexes from 15 to 30, but some sandy soils and some clay soils were also included. Their equation is for an estimate of the equilibrium water content (W_n) (in percent) of the top 15 cm (6 in.) of a subgrade compacted to 95 to 105 percent of modified Proctor density:

$$W_n = 1.16\ \mathrm{PI} - 7.4\%.$$

2. U.S. Navy. An investigation of sandy and clay subgrades of 70 airports, excluding cases where the water table was less than 60 cm (24 in.) below the subgrade surface, concluded:

$$W_n \leq \mathrm{PL} + 2\%.$$

3. In a review study submitted at an international symposium of the Highway Research Board in 1958, Wooltorton concluded that the maximum water content that can be expected in a plastic subgrade with a $6 < \mathrm{PI} < 28$ is:

$$W_n = 1.17\ \mathrm{PL} - 4\%.$$

Yoder and Witczak (*39*) suggest four different categories as indicators of the ultimate moisture condition that might exist under the pavement. These can be used for estimating subgrade moisture condition for design purposes.

1. Frost Areas. For a given location, field measurements should be made during the frost-melt period to determine typical moisture conditions under pavements in frost areas. In lieu of making field moisture measurements, *soaked conditions* can be assumed to control the California Bearing Ratio test and near-saturation conditions control other types of tests.
2. Annual Rainfall More than 20 Inches, Water Table Greater than 20 Feet, Nonfrost. In areas where the water table is greater than about 20 feet and the annual rainfall is quite high, the primary influence of saturation is from precipitation and water infiltration through the pavement surface or at the pavement edges. There is no accurate method for estimating moisture content for these conditions other than from field tests. In lieu of actual data, a reliable guide would be to test samples in the soaked or saturated condition.
3. Arid to Semiarid Climates, Water Table Greater than 20 Feet. As discussed above, the primary consideration here is surface infiltration. In arid climates a conservative value for design purposes is that corresponding to tests made at optimum moisture content. Correlation studies should be made that relate the field moisture content under existing pavements to the plastic limit.
4. Depth to Water Table Less than 20 Feet. For relatively high water tables that are not covered in those enumerated above (frost action, high rainfall, etc.) the final moisture condition is determined by the height of capillary rise.

Yoder and Witczak (*39*) state that the estimated moisture content can then be found using the previously discussed rational method. Where equipment for making these measurements is not available, an estimate can be made of moisture content by field tests below the zone of seasonal fluctuation—generally below 3 ft (0.9 m) (*39*). The sampling of similar subgrade materials under existing pavements in the vicinity of a project is advisable where possible.

It should also be noted that efforts to predict moisture content assume either good pavement drainage and/or that well-sealed pavements are part of the design and maintenance strategies (*34*).

EFFECTS OF SUBGRADE MOISTURE

The importance of estimating the subgrade moisture content for the structural design of the pavement cannot be overemphasized. If in doubt, it is better to be wrong on the high side than on the low side.

Testing to evaluate the strength of the subgrade should always be done at moisture contents at or exceeding the predicted ultimate field moisture content. There is also some indication that subgrade materials, especially fine sands and silts, should be evaluated using cyclic testing procedures if the predicted degree of saturation exceeds about 80 percent. Figures 8 and 9 show the results of repeated load tests run on gravel and crushed-stone base course materials used in the AASHO Road Test (*41*). The tests were triaxial tests run at stress levels approximating the stresses that existed at the base course level, a confining stress of 15 psi (100 kPa) and a deviator stress of 70 psi (480 kPa). The tests were run on base course materials with a lower confining stress and a higher deviator stress than would be expected at the subgrade level, but a deterioration of the performance of subgrades at high degrees of saturation and subjected to repeated load can be anticipated.

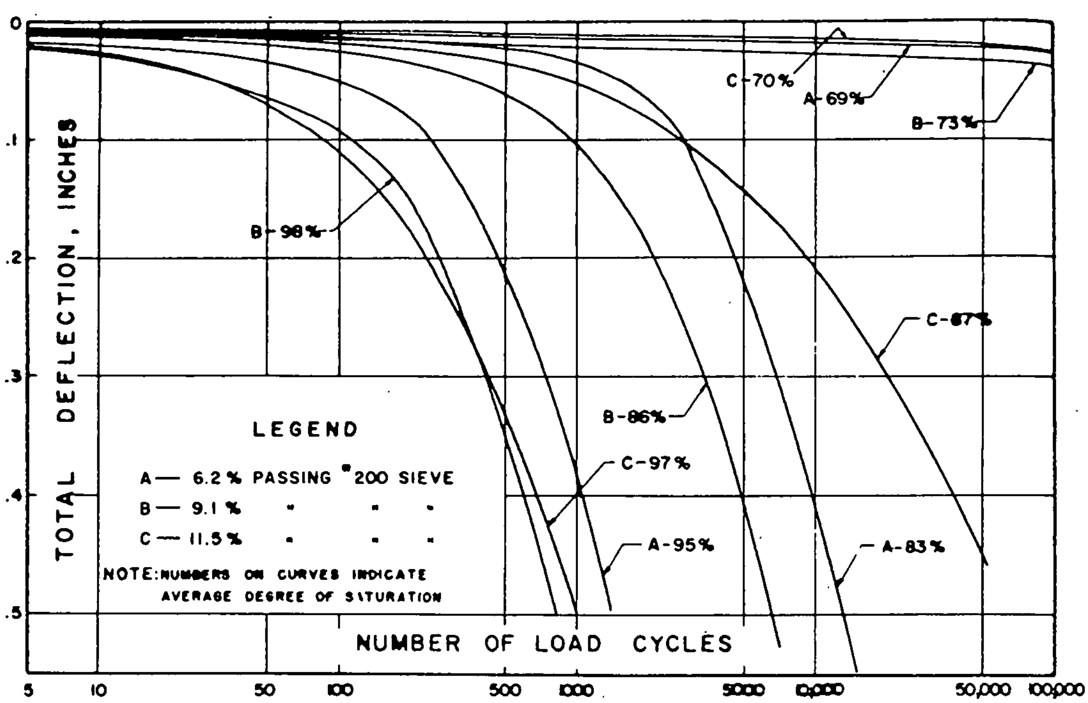


FIGURE 8 Deflection history of gravel specimens (*41*).

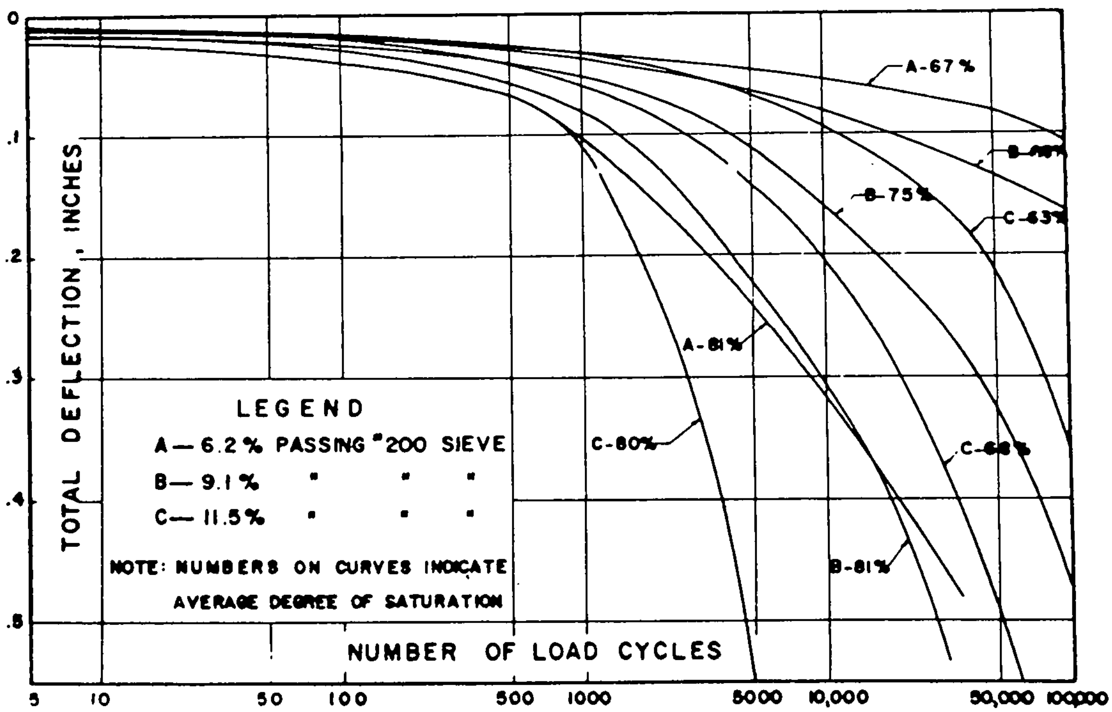


FIGURE 9 Deflection history of crushed-stone specimens (*41*).

The need to consider the degree of saturation when evaluating the strength of granular material has been further substantiated in recent work by Rada and Witczak (*42*). They indicated that the primary variables influencing the resilient modulus (M_r) of granular materials are the stress state, the degree of saturation, and the degree of compaction. The resilient modulus is a dynamic test response defined as the ratio of repeated axial deviator stress, σ_d, to the recoverable or resilient axial strain, ϵ_r, as indicated by the equation (*41*):

$$M_r = \frac{\sigma_d}{\epsilon_r}.$$

Accurate estimates of the strength of subgrades at high degrees of saturation must be based on effective stress and rapidly changing pore pressures. Static and semi-static tests may significantly overestimate the strength of most saturated subgrade soils. Estimating subgrade strengths using soaked samples and the careful correlations of a particular soil's field performance with static tests can yield satisfactory results.

CHAPTER FOUR

DESIGN OF PAVEMENT SUBSURFACE DRAINAGE

The analysis stage of pavement drainage establishes the conditions with which the pavement designer must deal: the strength of the subgrade, the permeability of the subgrade, the moisture condition of the subgrade, and the boundary conditions that will control the drainage. The pavement subsurface drainage system is primarily used to drain free water that enters by infiltration. If analysis shows groundwater or other moisture problems that will be detrimental to pavement performance, the designer should seek assistance from drainage and/or geotechnical specialists. Rarely is a pavement subsurface drainage system the most efficient way of handling water other than infiltrated or frost melt water.

In the following discussion, the drainage layer is considered to be the layer of material immediately under the pavement surface. (This material may be referred to as the base or subbase by different authors.) The base course is usually considered to be the best location for the drainage layer, but some designers may prefer to use a lower layer.

DESIGN CRITERIA

Two general types of pavement subsurface drainage criteria have been proposed:

1. The time for a certain percentage of drainage of the base or subbase beginning with the completely flooded condition should be less than a certain value.
2. An inflow-outflow criterion where the base or subbase should be capable of draining the water at a rate equal to or more than the inflow rate without becoming completely saturated or flooded.

The original criterion of the time for 50 percent drainage was proposed by Casagrande and Shannon (*4*) in 1952. It was recommended, for airport pavement drainage design, that the time required for 50 percent drainage of free water from the base course be not more than 10 days. This criterion has been used by several agencies but is too slow for two reasons. First, the permeability required for 50 percent drainage of free water is low enough to permit the inclusion of enough fines to permit a substantial capillary potential. This means that even after the free water is removed by the drains, the base can be close to saturation. Second, a substantial portion of the base is at or near complete saturation for 10 days and the material is fine enough to develop pore-pressure differentials under cyclic loading conditions. Figures 8 and 9 are indicative of how bases can be expected to react to these conditions. This criterion is not sufficient for highway pavements with frequent repetitions of loads. The general concept of time for 50 percent drainage is sound, however, and a criterion using a time of 1 hr or less may be useful. Darter et al. (*43*) propose a criterion of 85 percent drainage in 5 hr.

Two inflow-outflow criteria have been proposed:

1. Cedergren et al. (*10*) recommend that the design infiltration rate be found by multiplying the 1-hr duration, 1-yr frequency precipitation rate (Fig. 10) by a coefficient varying from 0.50 to 0.67 for portland cement concrete pavements and 0.33 to 0.50 for bituminous concrete pavements. The outflow capacity of the drainage system should equal the inflow rate or, in areas subject to frost, be sufficient to drain the completely flooded pavement base or subbase in 1 hr, whichever is greater (*10*).
2. Ridgeway (*20, 21*) recommends an inflow rate estimated by the water-carrying capacity of a pavement crack or joint, and by an estimated joint or crack length. The recommended inflow rate is 0.1 ft³/hr/ft of crack (0.01 m³/hr/m), and the equations for total inflow when lateral drainage (drainage to longitudinal drains) is to be used are as follows:

a. For rigid pavements—

$$Q = q\left(N + 1 + \frac{W}{S}\right)$$

b. For flexible pavements—

$$Q = q\left(N + 1 + \frac{W}{40}\right)$$

where

Q = ft³/hr/linear ft of pavement
q = 0.1 ft³/hr/ft of crack,
N = number of lanes,
W = lane width (ft),
S = transverse joint spacing (ft), and
40 = estimated mean spacing of transverse cracks in flexible pavements (ft).

The actual infiltration of water is a complex phenomenon that depends on the global or overall permeability of the pavement, the slope of the pavement surface, the intensity of rainfall, and the duration of rainfall. Cedergren's criterion is based on the estimated global permeability of the pavement surface and rainfall intensity.

Permeabilities of homogenous bituminous concrete after being subjected to traffic and of portland cement concrete are in the order of 10^{-5} ft/day (10^{-9} cm/s) (*5*). This indicates that most of the infiltrated water that enters the base and subgrade will enter through cracks, joints, or other discontinuities in the pavement surface. Calculations based on laminar flow theory, assuming that atmospheric pressure is maintained under the pavement, show that a 0.1-in. (2.5-mm) wide crack can carry about 0.15 ft³/sec/ft of crack (0.14 m³/s/m) under a hydraulic gradient of one (*20*). Research at the University of Maryland (Table 2) has shown that a clean, smooth 0.125-in. (3-mm) wide crack on a slope of 2.5 percent will intercept 97 percent of a 2 in./hr (50 mm/hr) rainfall. Research at the University of Connecticut (*20*), however, indicates that most cracks are filled with sand and other debris from the roadway surface, thus restricting the inflow of water. The mean measured flow obtained through cracks in pavements where the flow was not restricted by base and subbase conditions was 0.1 $ft^3/hr/ft$ of crack (0.01 $m^3/hr/m$).

If infiltration is considered to be primarily through the crack and if the carrying capacity of the crack is 0.1 $ft^3/hr/ft$ (0.01 $m^3/hr/m$), then rainfall in excess of that required to supply the crack capacity will run off. For the cracking pattern suggested by Ridgeway (*20*), this occurs at a rainfall intensity of approximately 0.1 in./hr (2.5 mm/hr). Thus it appears that the storm duration is more significant than storm intensity.

In areas of frost, Moulton (*11*) suggests that flow caused by frost melt (calculated using Figure 11) should also be included in the inflow rate.

No matter which criteria the pavement designer selects (those given above or others), and whether or not the designer decides that the probability of the frost melt occurring during a critical rainfall period is worth considering, the fact remains that there is a considerable amount of free water to be removed.

REMOVAL OF FREE WATER

The infiltrated free water must be removed from the base and subbase materials. This can be done by draining the free water vertically through the subgrade or laterally through a drainage layer to a system of drainage pipes that carry the water away from the pavement structure. In many cases the actual drainage will be a combination of the two methods.

The design using either method of removal uses the concepts of saturated flow with the energy gradient supplied by changes in elevation head, and Darcy's Law ($Q = kiA$) is assumed to hold. The base and subbase can be designed to carry the water vertically, provided that the condition of the subgrade is such that the free water can be removed at a rate equal to or more than the infiltration rate. If the surface drainage is properly designed, the global infiltration rate cannot exceed the rainfall rate. Therefore, under conditions where the depth of frost penetration is less than the pavement thickness (surface plus base and subbase) and the maximum height of the free-water surface (water table) is more than 3 ft (0.9 m) below the surface of the subgrade, a subgrade permeability equal to or more than the 1-hr duration, 1-yr frequency storm should be satisfactory for vertical drainage.

Cedergren et al. (*9*) state that in areas of frost, vertical drainage cannot be relied on. This is true for conditions where the permeability is near the minimum required for vertical drainage, but at some higher level of permeability, vertical drainage will continue to function. However, the determination of this level of permeability requires more research.

Where there is no frost, but the maximum free-water surface and/or the permeabilities are less than the 1-hr duration, 1-yr frequency storm, a careful analysis of the estimated inflow-outflow condition may indicate that vertical flow is indeed possible and a drainage system designed to provide lateral flow will not be required. Details of methods to estimate the amount of vertical outflow from the pavement

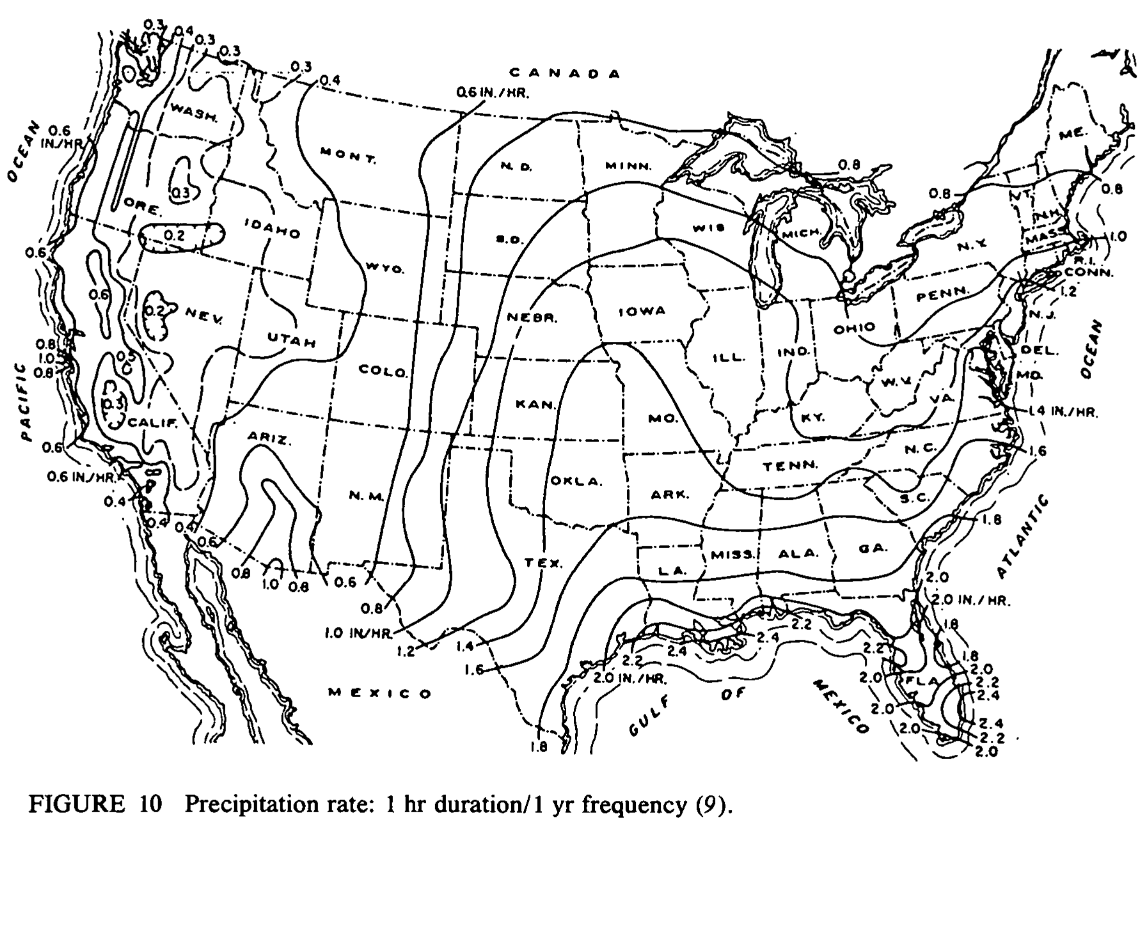


FIGURE 10 Precipitation rate: 1 hr duration/1 yr frequency (*9*).

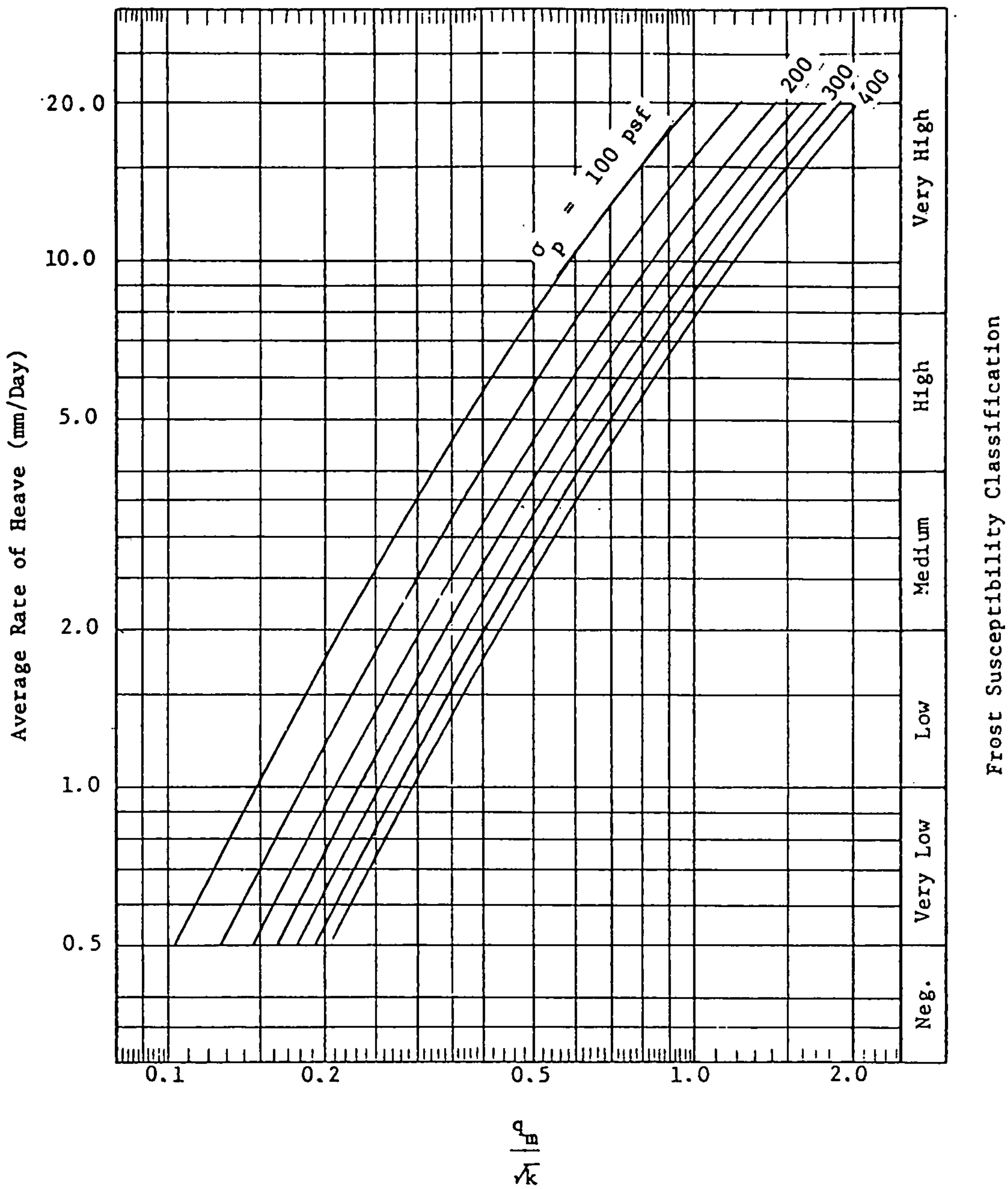


FIGURE 11 Chart for estimating design inflow rate of melt water from ice lenses (*11*).

structure can be found in Cedergren et al. (*10*) and Moulton (*11*).

Where the estimated vertical outflow is not sufficient to remove water from the base and subbase at a rate equal to or more than the estimated inflow rate, lateral drainage is needed. The quantity and rate of lateral drainage needed can be computed using the estimated inflow minus the estimated vertical outflow. Under frost conditions where vertical flow is insufficient, the lateral drainage layer must be designed to remove all of the estimated inflow. A design for lateral flow that is only equal to the estimated inflow less the vertical outflow should be considered very carefully, because the removal of free water laterally depends on the depth of flow; both the hydraulic gradient (I) and the area (A) are functions of the depth of flow. This means that the free water will saturate most of the drainage layer, and drainage layers designed for small lateral flows may be subject to partial liquefaction by repetitive loads.

The system of lateral drains uses a drainage layer, usually but not necessarily the base, to carry the infiltrated water to collector drains installed parallel to the center line and supplemented by transverse collectors at critical locations (Fig. 12). After the criterion for the amount of infiltrated water and the design drainage geometry are selected for the section, the required thickness and permeability can be determined.

The design section should be one in which the distance to collector is near a maximum and slope is near a minimum. The hydraulic gradient will be the elevation head available to the slope of the subgrade surface plus the gradient due to the thickness of the drainage layer. The most accurate determination of the required permeability can be obtained by the careful construction and use of flow nets, but approximate solutions are generally satisfactory.

Approximate solutions include the following equations:

1. $k = \dfrac{n_e L^2}{2 t_{50} (H + L \tan \alpha)}$ (*4*).

2. $k_d = \dfrac{(TF)\, n' L^2}{H_d t}$ (*11*, developed from *4* and *17*).

3. $k = \dfrac{qL}{H(sL + H/2)}$ (*5*).

4. $k = \dfrac{q}{Hs}$ (an approximation of equation 3 above).

For all of the above equations:

$k = k_d$ = permeability (ft/day),
$n_e = n'$ = effective porosity or yield,
L = length of drainage path (ft),
t_{50} = time for 50 percent drainage (days),
$H = H_d$ = thickness of drainage layer (ft),
α = angle of slope of drainage layer,
TF = time factor (see Fig. 13),
t = time (days),
q = quantity of inflow (ft^3/day/ft of pavement), and
s = slope of drainage path (%).

The approximation in equation 4 is conservative as it does not include the energy gradient provided by the thickness of the drainage layer. The approximation should probably not be used when $s/(s + H/2L) < 0.5$.

Table 3 gives solutions to a sample problem using the above equations, several of the criteria mentioned earlier, and a specific design section. The calculations are given in the appendix. The criteria are as follows:

Criterion 1 (*4*). The time for 50 percent drainage of a saturated base of 10 days.

Criterion 2 (*10*). The time for complete drainage (95 percent) of a saturated base of 1 hr.

Criterion 3 (*10*). Drainage at a rate equal to the inflow rate; computed by multiplying the 1-hr duration, 1-yr frequency precipitation rate from Figure 10 by a coefficient of global permeability of 0.50 to 0.67 for portland cement concrete and 0.33 to 0.50 for asphalt concrete.

Criterion 4 (*21*). Drainage at a rate equal to the inflow rate, computed using the following equations:

Flexible pavements:

$$q = 0.1\left(N + 1 + \frac{W}{40}\right)$$

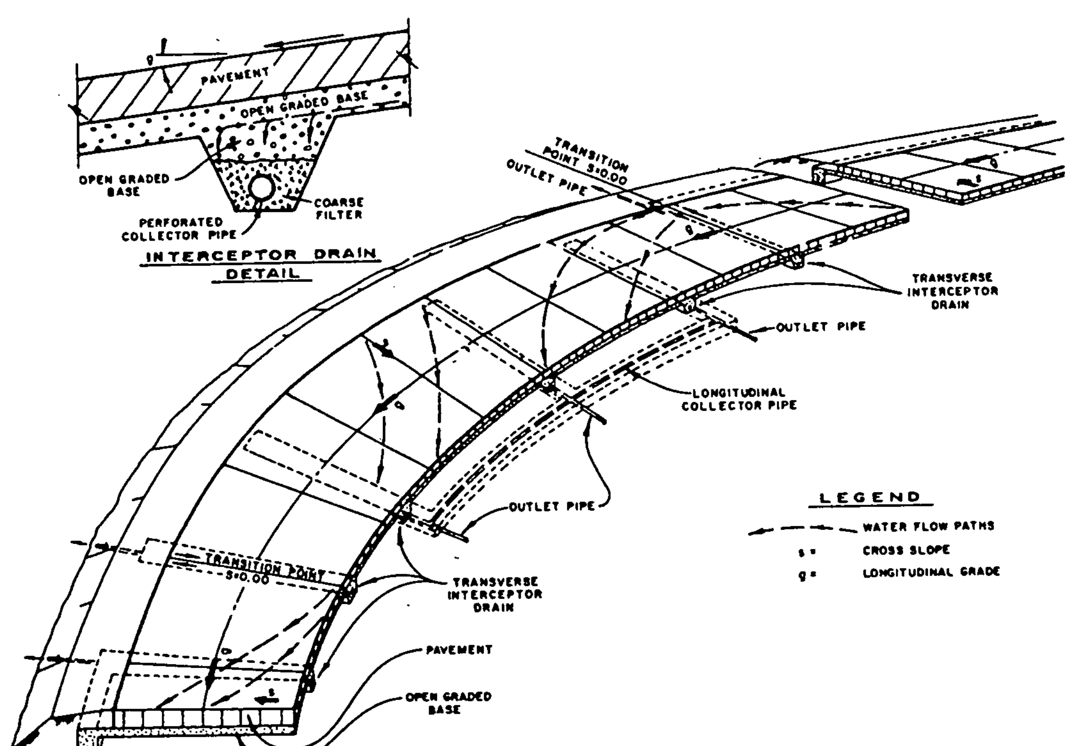


FIGURE 12 Transverse drains are needed on superelevated curves (*9*).

TABLE 3
SOLUTIONS TO A SAMPLE DRAINAGE PROBLEM FOR VARIOUS COMBINATIONS OF CRITERIA AND COMPUTATION METHODS

Criterion	Computation Method	k Required (ft/day)	t_{50} (Equation 1)
1	Equation 1	1.95	10 days
1	Eq. 2 & Fig. 13	1.90	10 days
2	Eq. 2 & Fig. 13	8000	7 min
3	Equation 3	3300	17 min
3	Equation 4	6700	8 min
4	Equation 3	850	66 min
4	Equation 4	1700	33 min
5	Eq. 2 & Fig. 13	750	75 min

Rigid pavements:

$$q = 0.1\left(N + 1 + \frac{W}{S}\right)$$

where

q = inflow rate (ft^3/hr per linear ft of pavement),
N = number of lanes,
W = pavement width (ft),
S = transverse joint spacing (ft), and
0.1 = average infiltration of water into cracks in the pavement surface (ft^3/hr/ft of crack).

Criterion 5 (*43*). The time for 85 percent drainage of a saturated base of 5 hr.

The design section selected for the sample problem has a superelevation of 1 percent, two 12-ft (3.7-m) lanes, and subdrains at the edge of a bituminous concrete pavement. The minimum base thickness needed to distribute the load is 6 in. (150 mm).

An examination of Table 3 reveals that the selection of a criterion for design is very important, but the method of computation, once the criterion is established, does not have a large effect on the decision on the permeability required. The selection of a criterion for design should be made very carefully. For highway pavements that are to drain laterally, the permeability required to meet Criterion No. 1 is much too low. In conditions that require lateral drainage, material having this permeability will remain saturated for a long period of time. It will have drained only 50 percent of the free water after 10 days. Materials that meet this criterion may be 85% or more saturated after the free water is removed. When saturated, this material does not perform well, and it acts as a source of free water to the subbase and subgrade materials.

The designer should assess the conditions under which the pavements must perform when selecting a criterion. It must be kept in mind, however, that to remove free water from the pavement structure laterally to the shoulder requires a very high permeability because the energy gradient, which can only be supplied by the slope of the subbase surface and the depth of free water in the drainage layer, is small, and the area per longitudinal foot of flow is always numerically equal to or smaller than the thickness of the drainage layer.

To obtain permeabilities required to meet Criteria 2, 3, 4, or 5, materials have to be quite coarse. Table 4 (*17*) gives the general relationship between gradation and permeability. (This relationship can also be seen in Figures 6 and 7.) The effect of materials passing the No. 200 sieve is shown in Figure 14 (*17*). Table 5 (*24*) gives permeabilities of untreated and asphalt-treated open-graded aggregates. An FHWA report (*44*) indicates that the grading of the asphalt-treated permeable material (ATPM) should be approximately as follows:

Sieve Size	Percent Passing
1"	100
3/4"	90–100
3/8"	30–50
No. 4	0–5
No. 8	0–2

Portland cement concrete materials having permeabilities that are approximately the same as those for the ATPM are also available. The state of California specifies the same aggregate gradations for the ATPM and porous portland cement concrete materials (*45*).

The lateral drainage layer design must include some method of removing the free water from the edge of the pavement. One method is to carry the drainage layer through the shoulder to the edge of the embankment or to the side ditches. However, this method, often referred to as "daylighting," has several drawbacks. First, the construction and maintenance of the side slope tends to clog the surface of the drainage blanket, thus reducing the effectiveness of the drain. Second, although this method is intended to carry water *to* the side ditches, there have been occasions when the drainage layer has carried water *from* the ditch to the pavement structure. Third, in some cases a substantial amount of material is required to reach the edge of the embankment or the ditch line.

In most cases a system of longitudinal collectors, with some transverse collectors at critical points, is required to remove the free water from the drainage layer. The collection system consists of a set of perforated or slotted pipes that are utilized to remove water from the pavement drainage layers and to convey it to suitable outlets outside the roadway limits. The design of such systems includes consideration of (a) the type of pipe used, (b) the location and depth of transverse and longitudinal collectors and their outlets, (c) the slope of the collector pipes, (d) the size of the pipes, and (e) provision for adequate filter protection to provide sufficient drainage capacity and to prevent flushing of drainage aggregates into the pipes through the slots or perforations (*11*). Figures 15 and 16 show some typical cross sections and layouts of collector systems. Details on the designs of the collector systems can be found in reports by Cedergren et al. (*10*) and Moulton (*11*).

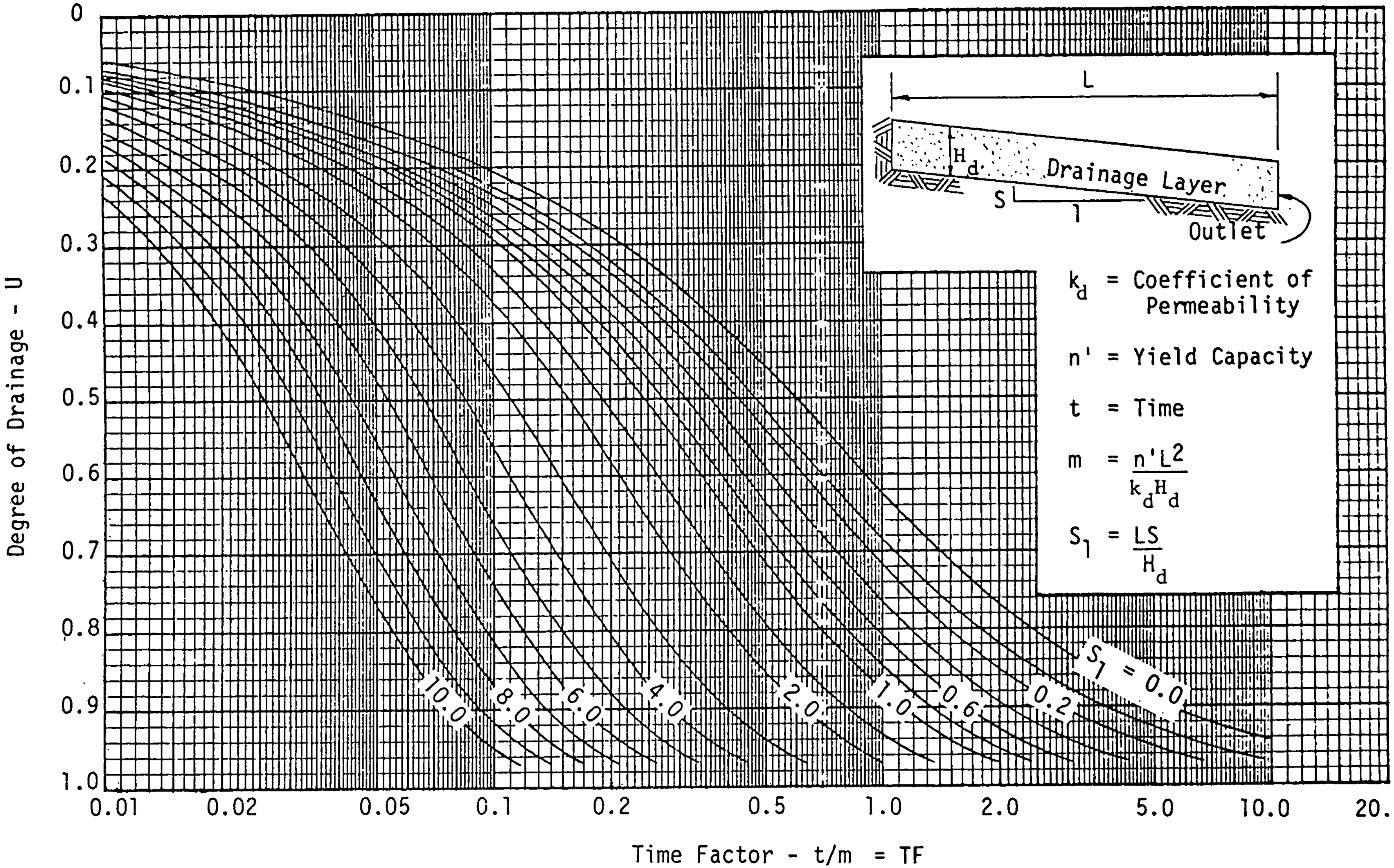


FIGURE 13 Time-dependent drainage of saturated layer (11).

TABLE 4
PERMEABILITY OF GRADED AGGREGATES (*17*)

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
Percentage passing—						
3/4-inch sieve	100	100	100	100	100	100
1/2-inch sieve	85	84	83	81.5	79.5	75
3/8-inch sieve	77.5	76	74	72.5	69.5	63
No. 4 sieve	58.5	56	52.5	49	43.5	32
No. 8 sieve	42.5	39	34	29.5	22	5.8
No. 10 sieve	39	35	30	25	17	0
No. 20 sieve	26.5	22	15.5	9.8	0	0
No. 40 sieve	18.5	13.3	6.3	0	0	0
No. 60 sieve	13.0	7.5	0	0	0	0
No. 140 sieve	6.0	0	0	0	0	0
No. 200 sieve	0	0	0	0	0	0
Dry density, lb. per cu. ft.	121	117	115	111	104	101
Coefficient of permeability, ft. per day	10	110	320	1,000	2,600	3,000

FILTERS

The drainage layer and the collector system must be prevented from clogging if the system is to remain functioning for a long period of time. This is accomplished by means of a filter between the drain and the adjacent material. The filter material, which is made from select aggregates or fabrics, must meet three general requirements: (a) it must prevent finer material, usually the subgrade soil, from piping or migrating into the drainage layer and clogging it; (b) it must be permeable enough to carry water without any significant resistance; and (c) it must be strong enough to carry the loads applied and, for aggregate filters, to distribute live loads to the subgrade.

Aggregate filters have been used for a long time and, if properly constructed, will perform very well. Numerous criteria for the design of these filters have been developed, but most of the criteria are quite similar.

To meet the first requirement, the filter must solve two problems at the same time; i.e., the filter material must be coarse enough so that it does not pipe or migrate into the drainage layer, and it must be fine enough so that the sub-

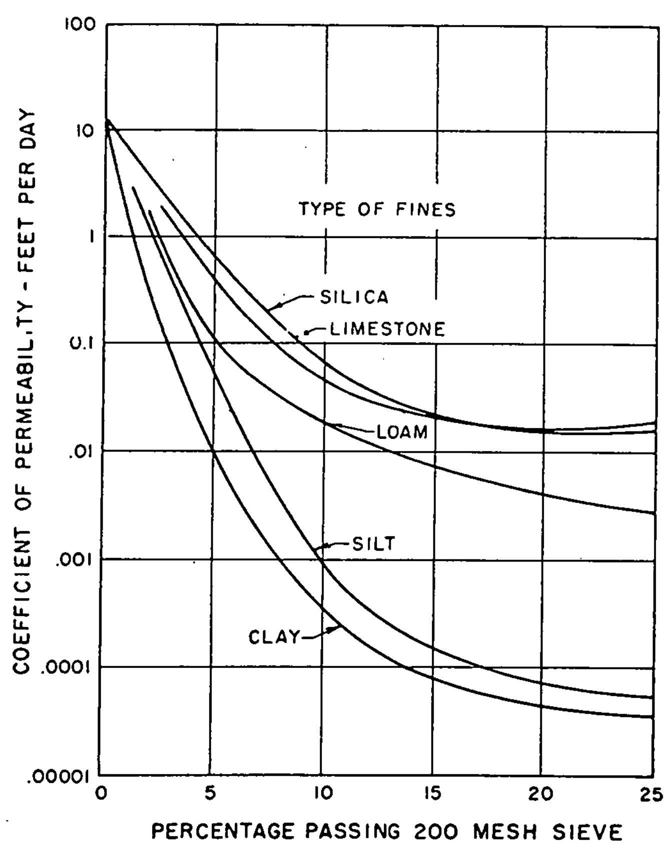


FIGURE 14 Effect of fines on permeability of graded aggregate (*17*)

TABLE 5
PERMEABILITIES OF UNTREATED AND ASPHALT-TREATED OPEN-GRADED AGGREGATES (*24*)

Aggregate size	Permeability, ft/day: Untreated	Permeability, ft/day: Bound with 2% Asphalt
$1\frac{1}{2}$ to 1 in.	140,000	120,000
$\frac{3}{4}$ to $\frac{3}{8}$ in.	38,000	35,000
No. 4 to No. 8	8,000	6,000

grade material will not migrate into the filter. The following criterion will accomplish this:

$$\frac{D_{15} \text{ size of the coarse layer}}{D_{85} \text{ size of the fine material}} \leq 5.$$

The D_{15} size means that 15 percent of the particles, by weight, are smaller than this size.

To meet the second requirement, the filter should be as coarse as possible. Moulton (*11*) states that the D_5 size of the filter should be $\geq 0.074\ \mu$m. If the drainage layer is to drain away the free water laterally, the filter layer (usually the subbase) will be completely saturated until the drainage layer is drained. The filter layer can then begin to drain itself. As long as the interface between the subgrade and the filter (subbase) is saturated, the filter will act as a supply of free water to the subgrade. The quantity of free water to be removed from the subbase after the drainage layer is drained is equal to the effective porosity of the filter. The total time for the drainage of the filter can be computed using both the amount of vertical and lateral flow.

The third requirement of the filter is to carry and distribute the loads applied to it. Because of the conditions mentioned above, the strength of the filter must be assessed at 100 percent saturation and the effects of cyclic loading taken into account. The condition of the subbase is not as critical as that of the base, however, because at the level of the subbase the dead-load stress is higher and the live-load stress is lower. This means the differential pore pressures due to live loading are less, and they will have less effect on the strength and load distribution qualities of the material. Figure 17 shows materials that must meet filter criteria when the base is used as the drainage layer.

Filter fabrics can also be used to protect the drainage layer from clogging. As with all filters, there are two general requirements for the filters: (a) to retain soil and (b) to allow water flow (*46*). Because filter fabrics are thin, they do not distribute loads to the subgrade, but they must be tough enough to remain intact during construction and chemically stable in the roadway environment.

There are three types of filter fabric (knitted, woven, and non-woven), any of which can be used satisfactorily if it meets design requirements. In each case the function of the filter should be examined carefully to determine whether or not it must transmit water as well as retain soil. In most cases, where lateral drainage is to be used, the retention of the soil is the prime consideration, and transmission of free water is a minor consideration. However, if the filter cloth is to be used as a filter for a subsurface drainage system and the free water to the system must be transmitted through the filter, then the permeability of the filter becomes important.

Criteria to prevent piping or material from passing through the filter and clogging the drainage layer are the same for both woven and non-woven fabrics. The following criteria, which were developed by the Corps of Engineers and have been accepted by many other agencies (*16, 46, 47*), are extracted from an FHWA report (*47*):

> a. Filter cloth adjacent to granular materials containing 50 percent or less by weight of minus No. 200 materials should have a ratio of
>
> $$\frac{\text{85 percent size of soil}}{\text{opening size of EOS sieve}} \geq 1$$
>
> and should have an open area not to exceed 36 percent.

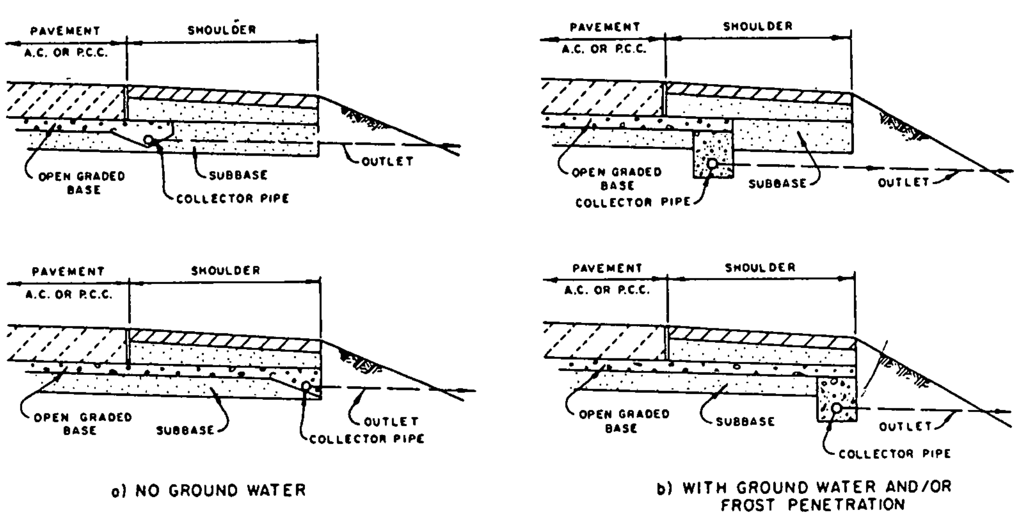


FIGURE 15 Typical cross sections of subdrainage systems (*9*).

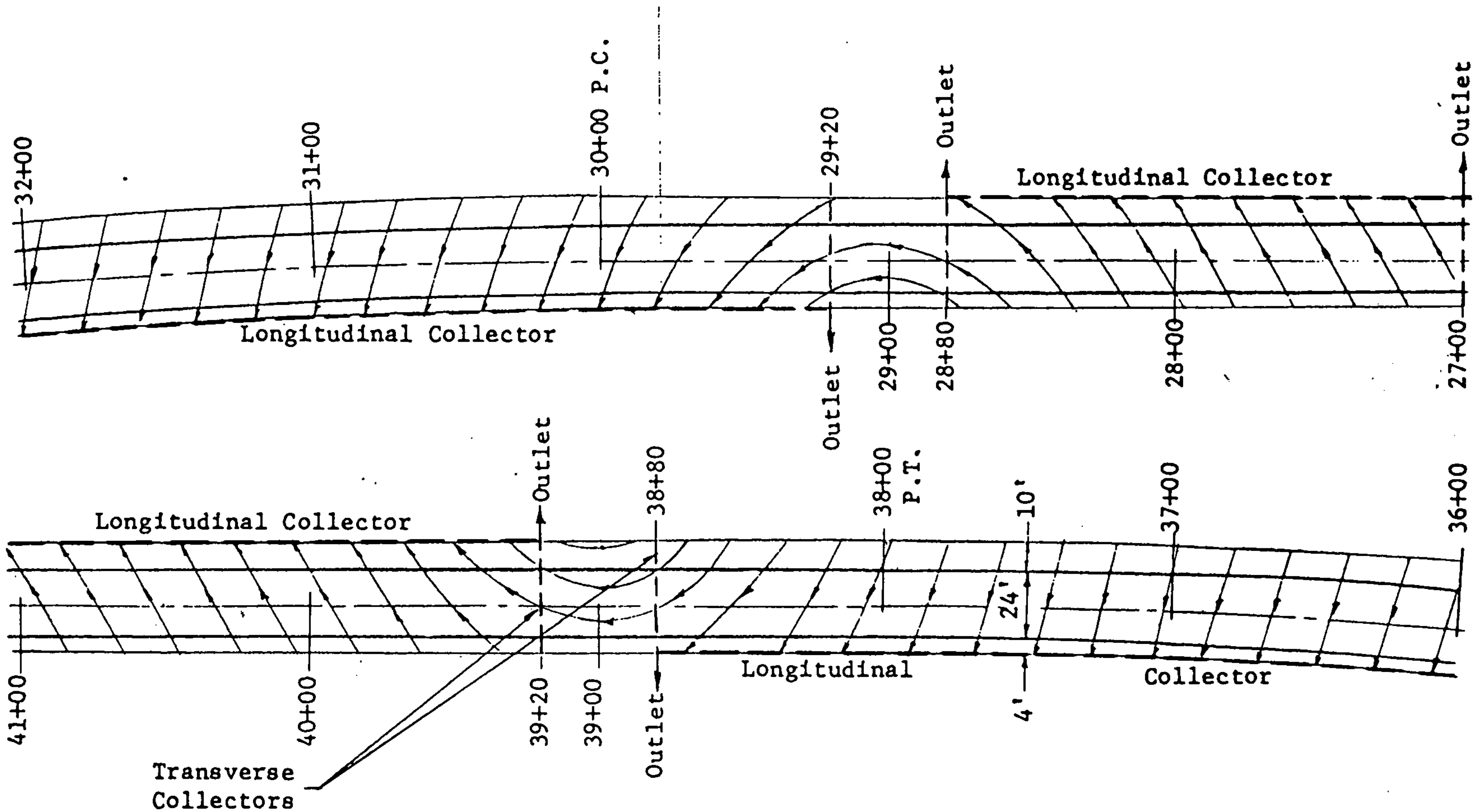


FIGURE 16 Layout of proposed drainage system showing direction of flow in drainage layer (*11*).

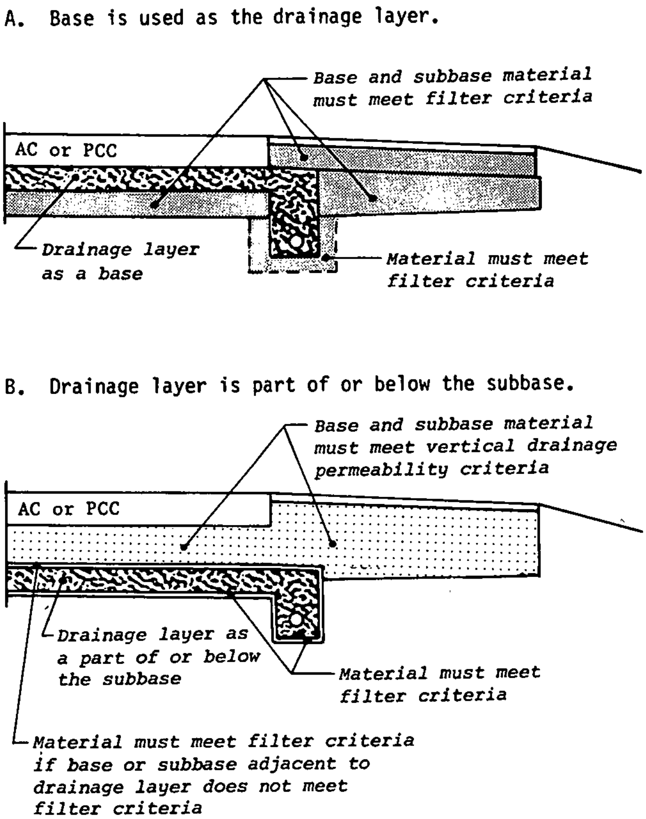


FIGURE 17 Location of material that must meet filter criteria.

> b. Filter cloths adjacent to all other types of soil should have an EOS no longer [larger] than the openings in the U.S. Standard Sieve No. 70 (0.0083 in.), and an open area not to exceed 10 percent.

The equivalent opening size shall be obtained in the following manner (*47*):

> Five unaged samples shall be tested. About 150 g of each of the following fractions of a sand composed of sound rounded particles shall be obtained:

Passing	Retained on
10	20
20	30
30	40
40	50
50	70
70	100
100	120

> The cloth shall be affixed to a standard sieve having openings larger than the coarsest sand used in such a manner that no sand can pass between the cloth and the sieve wall. The sand shall be oven-dried. Shaking shall be accomplished as described in ASTM D 422, and shall be continued for 20 minutes. Determine by sieving (using successively coarser fractions) that fraction of sand of which five percent or less by weight passes the cloth; the equivalent opening size of the cloth sample is the "retained on" U.S. Standard Sieve number of this fraction.

Criteria to allow the desired permeability through the filter cloth are not as well established as the criteria to retain particles. For woven fabrics, the Corps of Engineers uses criteria based on the percentage of open area (*16, 46, 47*). Part of the specification is for minimum permeability (*47*):

> c. To reduce the chance of clogging, no cloth should be specified with an open area less than four percent and/or an EOS of less than the No. 100 sieve (0.0059 in.). It is preferable to specify a cloth with openings as large as allowable to permit drainage and prevent clogging.

For non-woven fabrics, a gradient ratio (G.R.) test developed by B. D. Marks and used by the Corps of Engineers appears to be applicable to selection of non-woven fabrics for filtration (*46*). The gradient ratio is determined in the following manner (*46*):

> 1. The soil specimen shall be 5 inches in diameter and 4 inches in height. It shall consist of the soil that is to be protected in the field by the fabric.
> 2. A piece of hardware cloth with ¼-inch openings shall be placed beneath the filter fabric specimen to support it. The fabric and the hardware cloth shall be clamped between flanges so that no soil nor water can pass around edges of the cloth.
> 3. Piezometer taps shall be placed one inch below the fabric, and 1, 2 and 3 inches above the fabric.
> 4. Tap water shall be permeated through the specimen under a constant head loss for a continuous period of 24 hours. The tail water level shall be above the top of the soil specimen. The gradient ratio shall be determined from the readings taken at the end of the 24-hour period.
> 5. The gradient ratio is the ratio of the hydraulic gradient over the fabric and the one inch of soil immediately next to the fabric, (i_f), to the hydraulic gradient over the two inches of soil between one and three inches above the fabric (i_s).

$$G.R. = \frac{i_f}{i_s}$$

Other specifications for both woven and non-woven fabrics specify a required permeability; typical is that required by the Alabama Highway Department (*47*): 2×10^{-2} cm/sec minimum and 3×10^{-1} cm/sec maximum.

In a recent study, Haliburton et al. (*48*) suggested minimum engineering fabric selection criteria for filtration/drainage applications (see Table *6*).

For additional details on tests on filter fabrics, see previously published work (*16, 46–50*). Various uses of engineering fabric in the pavement structure design are shown in Figure 18.

Fabric filters have two distinct advantages for the pavement designer: (a) they do not store a significant amount of water within the fabric layer, and (b) because they are manufactured products, there is more flexibility in the selection the type and material properties desired. Because the fabric filter does not store water, the designer can put the drainage layer at the surface of the subgrade (Figure 17*B*). If this is done, the layers above the lateral drainage layer (the base and possibly the subbase) should be designed with a permeability that can provide vertical flow to the drainage layer. When this type of design is used, the material immediately above the drainage layer must meet standard filter requirements so that base or subbase materials will not migrate, or pipe, into and clog the drainage layer, possibly causing an unevenness in the pavement surface. It may be desirable to have filter fabric over as well as under the drainage layer.

TABLE 6
RECOMMENDED MINIMUM ENGINEERING FABRIC SELECTION CRITERIA IN FILTRATION/DRAINAGE APPLICATIONS (*48*)

I. PIPING RESISTANCE (all applications)

A. Soils with 50% or less particles by weight passing U.S. No. 200 sieve:

EOS $\leq D_{85}$ of adjacent soil

B. Soils with more than 50% particles by weight passing U.S. No. 200 sieve:

EOS $\leq$ U.S. No. 70 sieve size (0.211 mm)

NOTE:

1. Whenever possible, fabric with the largest possible EOS should be specified.
2. When protected soil contains particles from 1-in. size to those passing the U.S. No. 200 sieve, use only the gradation of soil passing the U.S. No. 4 sieve in selecting the fabric.

II. CLOGGING RESISTANCE

A. Severe/critical applications

1. Woven fabrics: percent open area $\geq$ 4.0% and EOS $\geq$ U.S. No. 100 sieve size (0.149 mm)
2. Woven fabrics not meeting item 1 and all other fabrics: gradient ratio $\leq$ 3.0

B. Less severe/less critical applications—all fabrics—equivalent Darcy permeability of fabric $\geq$ 10 times Darcy permeability of soil to be drained.

III. CHEMICAL COMPOSITION REQUIREMENTS/CONSIDERATIONS

A. Fibers used in the manufacture of engineering fabrics shall consist of a long-chain synthetic polymer, composed of at least 85% by weight of polypropylene, -ethylene, -esteramide, or -vinylidene-chloride, and shall contain stabilizers and/or inhibitors added to the base plastic (as necessary) to make the fabric resistant to deterioration from ultraviolet and heat exposure.

B. The engineering fabric shall be exposed to ultraviolet radiation (sunlight) for no more than 30 days total in the period of time following manufacture until the fabric is covered with soil, rock, concrete, etc.

IV. PHYSICAL PROPERTY REQUIREMENTS (all fabrics)

	Fabric Unprotected	Fabric Protected[a]
Grab Strength (ASTM D 1682)	200 lb	100 lb
Puncture Strength (ASTM D 751-68)[b]	80 lb	35 lb
Burst Strength (ASTM D 751-68)[c]	320 psi	160 psi

[a]Fabric is said to be protected when used in drainage trenches or beneath/behind concrete (portland or asphalt cement) slabs. All other conditions are said to be unprotected.

[b]Tension testing machine with ring clamp, steel ball replaced with a 5/16-in. diameter solid steel cylinder with hemispherical tip centered within the ring clamp.

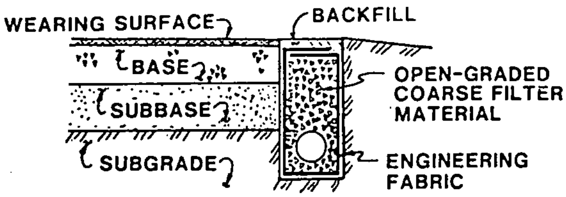
[c]Diaphram test method.

SUMMARY OF THE DESIGN PROCESS

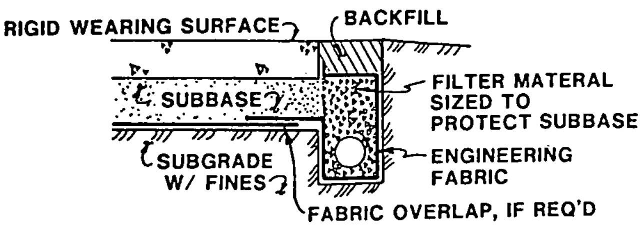
The subsurface drainage system is an integral part of the pavement structure and it should be integrated into the following overall structural design process:

1. Determine, from the overall highway design geometrics, the surface drainage facilities, subsurface drainage facilities, terrain conditions, and environmental conditions of the expected maximum free-water surface. Where the estimated free-water surface is closer than desirable to the subgrade surface, special additional drainage facilities (either part of or separate from the standard pavement subsurface design) should be investigated by the pavement designer in cooperation with other subsurface drainage specialists.

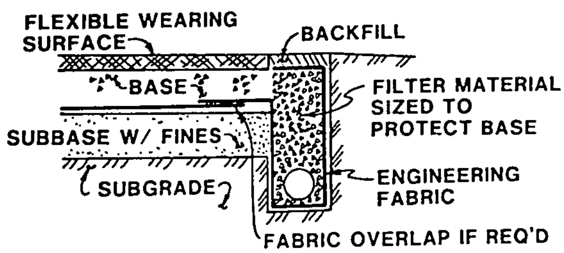
2. Determine the design subgrade moisture contents.



A. UNDERDRAIN ADJACENT TO PAVEMENT



B. SUBBASE DRAIN



C. BASE DRAIN

FIGURE 18 Various uses of engineering fabric to promote/enhance pavement structure design (*16*).

Tests to determine the strengths of subgrades should be run at these moisture contents or higher. These strengths will determine the minimum structural thicknesses required for the base and subbase materials. The designer may decide to use the base, subbase, or a new layer as the drainage layer.

3. Determine the permeability of the subgrade material.
4. Establish criteria for the amount of free water that will enter the pavement structure, and the rate at which it must be removed.
5. Using the free-water surface, the permeability of the subgrade, and the estimated amount of free water that will enter the pavement structure, decide how it is to be removed—vertically through the subgrade or laterally to a system of collectors and away from the pavement structure.
6. Using the principles of Darcy's law, design the drainage layer and/or the base and subbase to meet the criteria in item 4. If lateral flow is required and the design permeability is less than 1000 ft/day (0.35 cm/s) or if vertical flow is used and the design permeability is less than 2 ft/day (7×10^{-4} cm/s), the analysis and design criteria should be carefully reviewed.
7. Design the required filter system to assure long-term functioning of the drainage layer.
8. Base and/or subbase materials specifications should be checked to assure that permeability, strength, load-distribution, and construction stability requirements are met.
9. Design the subsurface drainage collection and removal system.

A pavement structure properly designed and constructed to drain away the free water, either laterally or vertically, will not be adversely affected by capillary moisture or condensation of vapor moisture.

CHAPTER FIVE

REHABILITATION OR MAINTENANCE OF EXISTING PAVEMENTS

Subsurface moisture conditions should be considered when planning the rehabilitation or maintenance of existing pavements. Repaving, overlays, recycling, or patching an existing pavement will be wasteful if the pavement distress is caused by moisture in the base, subbase, or subgrade materials and the existing surface and/or subsurface drainage conditions are not corrected.

The Asphalt Institute has posed four general questions that should be answered by surface and subsurface drainage investigations (*51*):

1. Is the original design adequate for drainage of the existing road?
2. What changes in design are necessary to ensure that drainage inadequacies, which may be a contributing factor to structural distress, are corrected?
3. If the original drainage system design was adequate, have environmental or structural changes taken place since it was built that require reconstruction of the system?
4. Does present or projected land use in areas adjacent to the road indicate that surface drainage flow patterns have changed or are likely to change, thus rendering existing drainage facilities inadequate?

When conditions indicate that moisture is a contributing cause of the pavement distress, the following questions should be addressed:

1. Is the surface drainage system adequate, functioning properly, and removing the surface water from the vicinity of the pavement structure?
2. Is the subsurface drainage system, other than that specifically for drainage of the pavement structure, adequate, functioning properly, and removing water from the vicinity of the pavement structure?
3. Is the structural design of the present pavement sufficient if the moisture problem is solved?
4. What are the permeabilities and capillary potentials of the base, subbase, and subgrade that are under the existing pavement, and how is the moisture entering the pavement structure?

Ring (*52*) identified the following categories of problems related to the above questions:

- Shallow side ditches.
- Blockage of subsurface drainage due to widening.
- Permeable shoulders and medians.
- Repaving rigid pavements.
- Impermeable aggregate drainage layers.
- Reduction of drainage capacity of curbed pavements because of overlays.
- Water in open-graded bases (trench section).
- Drainage of open-graded plant-mix seals.

LONGITUDINAL SUBDRAINS

The installation of pavement subdrains can, in most cases, improve the long-term load-carrying and load distribution properties of the base, subbase, and subgrade materials, but it cannot save a pavement structure that does not have sufficient design strength or thickness. When pavement longitudinal subdrains are installed in shoulders of existing pavements, it is important to know the permeability and capillary potential of the materials adjacent to the proposed drain. The success or failure of these drains depends on these properties and how the moisture is entering the structure. Figure 19 is a sketch of a typical longitudinal drain installation.

The rate at which the free water can drain from the base and subbase can be computed using the equations and charts included in the design section of this report. As stated by Moulton (*11*), it is impossible to increase the permeability of the existing base course. It should also be noted that the capillary potential of the longitudinal drain will approach zero and the drain will not remove moisture that is held by capillary forces from adjacent material.

When use of the longitudinal drain is considered, it is important to know which free water is to be drained. The free water that is entering the pavement structure at the pavement-shoulder joint can almost always be removed by longitudinal drains. Water entering the structure through

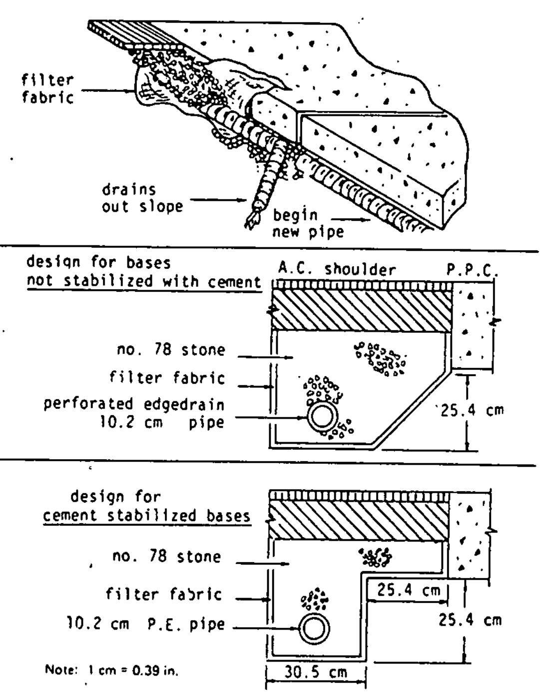


FIGURE 19 Edge drain details (*53*).

center-line joints and lateral cracks or joints that has to reach the longitudinal drain through the base or subbase will not be drained effectively if the permeability of the material is low.

Dempsey et al. (*18*) state that longitudinal drains will have some influence on draining bases or subbases that have permeabilities between 25 and 250 ft per day (8.8×10^{-3} and 8.8×10^{-2} cm/s) and appreciable influence when permeabilities are more than 250 ft/day. These permeabilities are substantially less than those indicated in Table 3.

Where there is some doubt as to the effectiveness of longitudinal drains, Cedergren et al. (*10*) recommend that test sections at least 200- to 300-ft (60- to 90-m) long be located in typical areas where it is thought that side drains will be beneficial. It is further suggested (*10*):

> that the test sections be monitored during and following showers and rainstorms for at least one wet season. Periodic pavement condition surveys should be conducted on adjacent and intermediate sections that do not contain edge drains. If noticeable flows occur at the outlets in trial installations during or after rains, or definite benefits in pavement performance can be observed in trial sections, it is likely that they will be of some benefit.

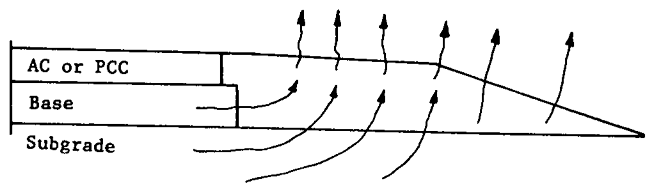
It should be noted, however, that flow from the newly installed drain does not in itself indicate an improved condition because in some cases the infiltration rate at the pavement edge has been increased during the installation of the drain.

The installation of longitudinal drains must be done carefully. A section of low-permeability material must not be left between the layer to be drained and the new drain. The strength and the support characteristics under the existing pavement should not be damaged.

There are conditions under which the seasonal moisture content under the pavement surface is affected by capillary flow, which slowly takes the moisture to the shoulder where it evaporates. The installation of longitudinal drains will increase the length of the capillary flow paths (Figure 20) and may cause an increase in the seasonal moisture content under the pavement surface. Longitudinal drains can remove only free water; in materials with high capillary potential the permeability is generally so low that the drains are not effective.

When longitudinal drains are installed under the above conditions, they will prevent moisture from entering the pavement structure from a wet shoulder area, but they will also block moisture from leaving the structure and may, in the balance, be detrimental. Where longitudinal drains will not function, extra effort should be put into sealing the pavement surface until redesign and reconstruction of the pavement incorporating the necessary pavement subsurface drainage facilities can be accomplished.

A. Without a longitudinal drain.



B. With a longitudinal drain. The capillary flow will be blocked by the drain.

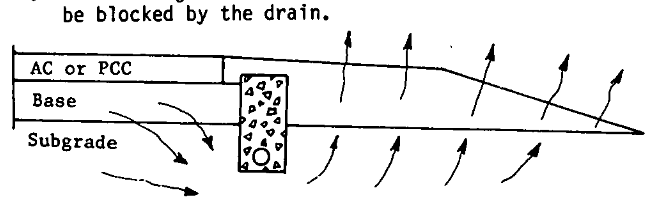


FIGURE 20 Path of evaporating moisture.

CHAPTER SIX

CURRENT INSTALLATIONS

NEW PAVEMENTS

California

Highway agencies have not generally adopted standard plans or designs for new pavements with subdrainage systems for infiltrated water. However, the California Department of Transportation issued a memorandum concerning structural section drainage (*45*). Designers are to consider the need for longitudinal edge drains to discharge infiltrated surface water and thereby reduce premature portland cement concrete pavement distress due to faulting. The revised standard plan is shown in Figure 21. California Department of Transportation Specification 68.20 T-6-24-81 requires that the permeable material for subgrade drains be either asphalt treated or cement treated. The memorandum (*45*) recommends that "guidelines for the design of subsurface drainage systems for highway structural sections included in the June 1972 Report No. FHWA-RD-72-30" (*9*) be used in the design of the subsurface drainage system.

It should be noted that the designs shown in Figure 21 are used in conjunction with portland cement concrete pavement and cement-treated base, lean-concrete base, or asphalt concrete base. There is little flow through these types of base materials. Almost all of the flow from the structural section reaches the drain through the joint at the edge of the pavement. Free water that enters the pavement structure at the center line or transverse joints can only reach the edge drain by flowing through small voids that exist at the interface between the pavement and base or by flowing in the transverse joint.

Pennsylvania

The Pennsylvania Department of Transportation (*54*) has installed five experimental sections of base/subbase materials under reinforced concrete (RCC) pavement on Route 66, a 4-lane divided highway, in western Pennsylvania. The materials ranged from impermeable to very permeable. The cross sections of the test sections designed with the four permeable materials are shown in Figures 22–24. Table 7 gives the density, porosity, and permeability of the materials.

Some of the conclusions from this study are (*54*):

1. Base material with significantly higher permeabilities (3 or more orders of magnitude) can be manufactured at reasonable cost.
2. Adequate stability to support construction equipment was provided by the more porous, open-graded base materials.
3. The three open-graded materials had adequately high permeabilities, but the permeability of the 2A subbase was unsatisfactorily low.
4. Porous material gradations used for drainage interlayers should have minimal material passing the 2.00-mm (No. 10) sieve.
5. The pavement is performing satisfactorily in all of the various base layer sections 1 yr after construction.

In the Pennsylvania cross sections, the base material immediately under the RCC surface is used as the drainage layer. The material in the drain (1B) is a pea gravel. When designs of this type are used, the designer must be sure that the filter requirements between the drainage layers and the adjacent materials are met; e.g., between the ATPM base and the 2A subbase materials and between the 1B material and the 2A subbase and the subgrade material (Fig. 22). If filter material is needed, either a fabric filter or an aggregate filter can be used.

Michigan

The Michigan Department of Transportation (*55*) has installed test sections using the cross sections shown in Figures 25 and 26. For the cross section shown in Figure 25, the average permeability of the subbase material was in the order of 10 ft/day (3.5×10^{-3} cm/s). The black base was dense graded. For the cross section shown in Figure 26, the drainage layer was the asphalt-treated porous material (ATPM) consisting of 9A stone with 2 to 3 percent 85–100 penetration asphalt and 2 to 6 percent fly ash to stiffen the mix. The permeability of the material was usually more than 3000 ft/day (1.1 cm/s). The subbase material adjacent to the drainage layer was examined and found to be satisfactory for filter material; thus no additional filter material was required.

Observations of the ATPM drain outlets indicated that large volumes of water were removed by the drains during and for a short time after each rain. The greatest source of water was thought to be at the longitudinal pavement-shoulder joint. The amount of the flow was considerably more than that originally expected.

The sections with the drain installed in the subbase material (Fig. 25) were not observed to carry water at any time. However, it has been noted that on superelevated sections, water infiltrating the higher longitudinal joint appears to be seeping between the pavement-base interface or along the transverse joint cracks to the lower longitudinal joint where it flows out and to the shoulder.

The subbase drains, ATPM, and black base were constructed without serious problems and could easily be used for standard pavement construction. The ATPM base was

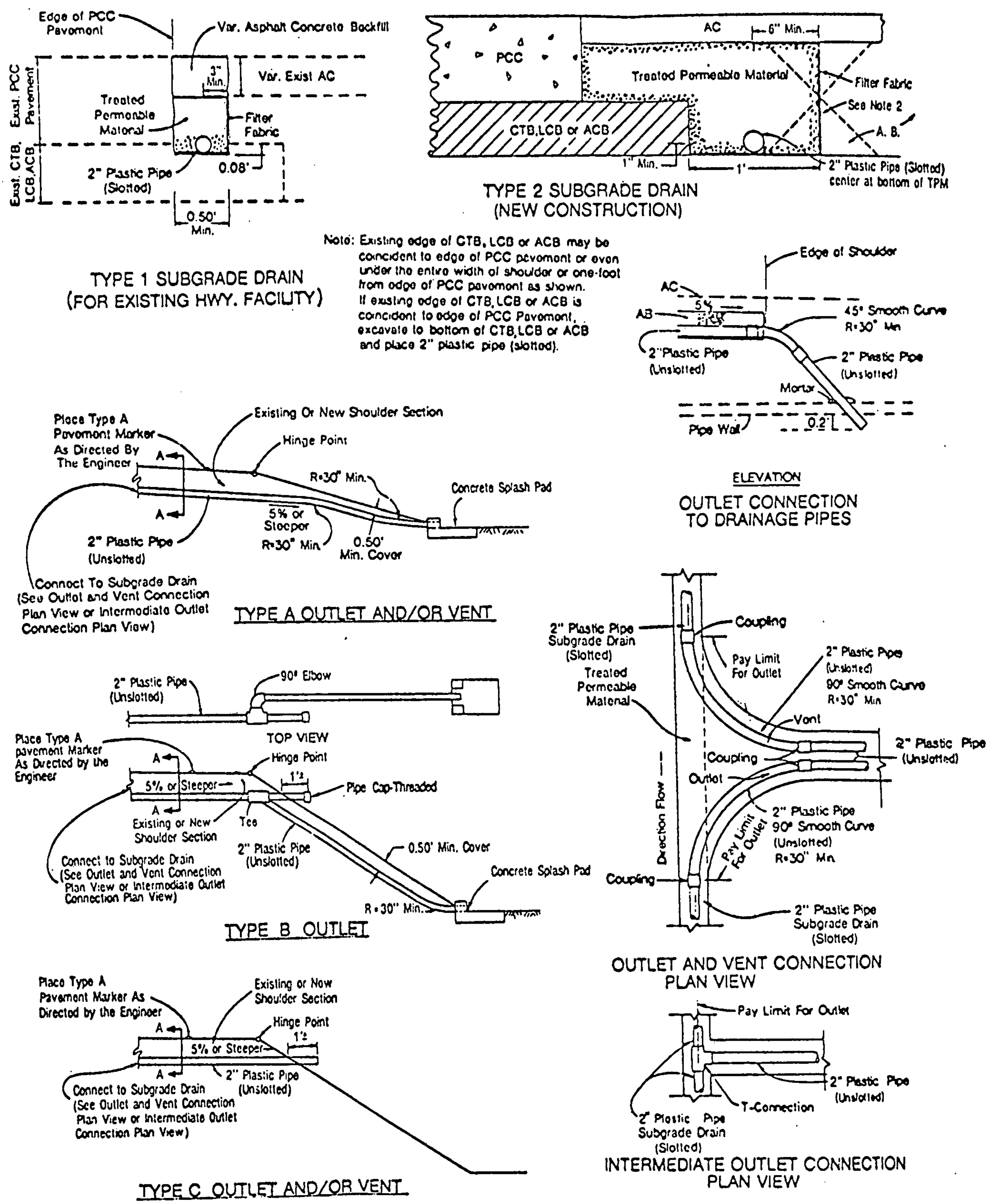


FIGURE 21 Portions of standard plan for longitudinal edge drains (California).

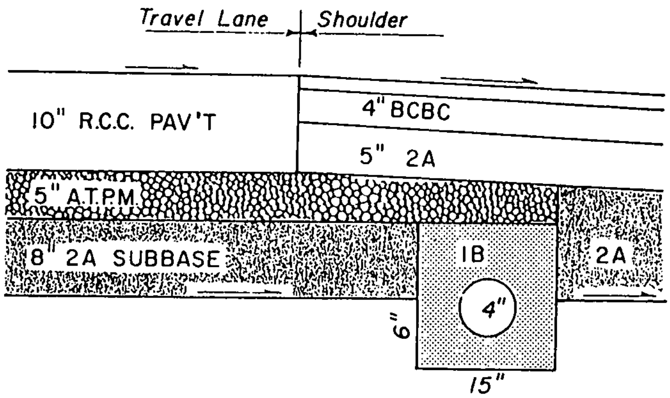


FIGURE 22 Pavement cross section (asphalt-treated permeable material test area) (Pennsylvania) (*53*).

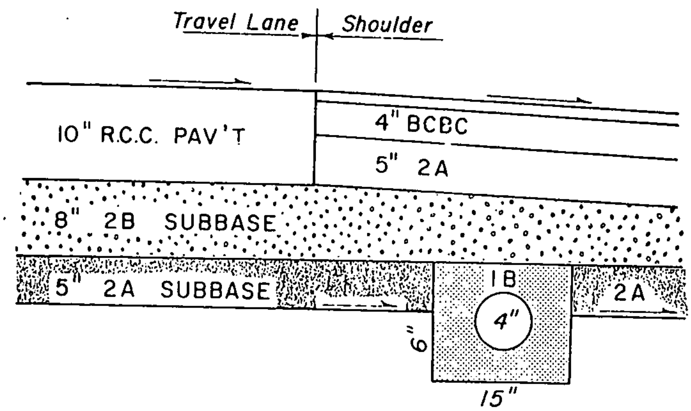


FIGURE 23 Pavement cross section (2B aggregate test area) (Pennsylvania) (*54*).

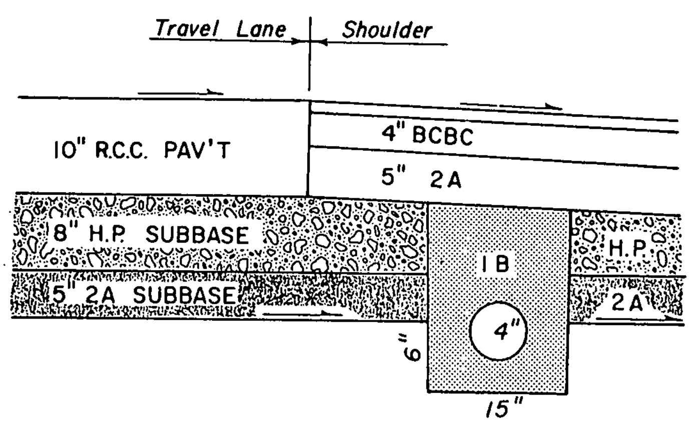


FIGURE 24 Pavement cross section (high permeability test area) (Pennsylvania) (*54*).

TABLE 7
PROPERTIES OF MATERIALS USED IN PENNSYLVANIA TEST SECTIONS (*54*)

Material	Density γ_d max.	Porosity n_{min} (%)	Permeability k (cm/sec)
2A subbase (control)	124.9	23	1.8×10^{-4}
ATPM[a]	112.7	31	2.4×10^{0}
HP[b]	110.0	32	6.4×10^{0}
2B subbase	102.9	37	7.6×10^{0}

[a]Asphalt-treated permeable material.
[b]High permeability.

easy to handle, extremely effective in removing infiltrated surface water, provided a stable platform on which to pave, and appears to be performing well. The black base has maintained its structural integrity with no signs of cracking at the time of this report was prepared.

Kentucky

The Kentucky Department of Transportation constructed a 5.17-mile (8.3-km) long experimental section of two-lane pavement using the typical cross section shown in Figure 27 (*56*). The drainage blanket is a Kentucky gradation No. 57 aggregate. It has an estimated permeability of more than 20,000 ft/day (7 cm/s). The dense-graded aggregate (DGA) met the necessary filter requirements; therefore, additional filter material was not required.

This project demonstrated the ability to design and construct a two-layer system of drainage within a flexible pavement that is cost effective compared to conventional designs and may offer considerable advantages in performance. The state of Kentucky, although not adopting this as a standard design practice, is planning to use this design in future experimental pavements.

PAVEMENT REHABILITATION WITH EDGE DRAINS

Several states have installed longitudinal edge drains along existing pavements that are distressed, or have the potential for distress, due to infiltrated water. The success of the underdrain and the conclusions of the studies vary considerably. Although it is not made clear in the reports, apparently the success of a longitudinal drain is primarily a function of whether or not the free water that is causing the distress can get to the longitudinal drainage system. Dempsey et al. (*18*) determined that drains will have some influence on draining bases or subbases that have permeabilities between 25 and 250 ft/day (8.8×10^{-3} and 8.8×10^{-2} cm/s) and appreciable influence when permeabilities are greater than 250 ft/day. (Note that these are considerably lower than any of the required permeabilities given in Table 3, but higher than the permeability of most base courses.) Another problem with the installation of longitudinal drains as a rehabilitation proj-

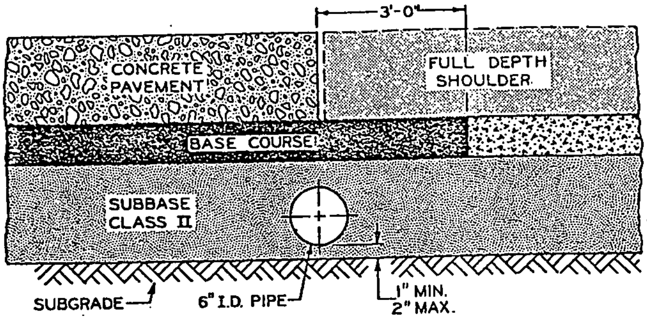


FIGURE 25 Cross section of subbase drain installation (Michigan) (55).

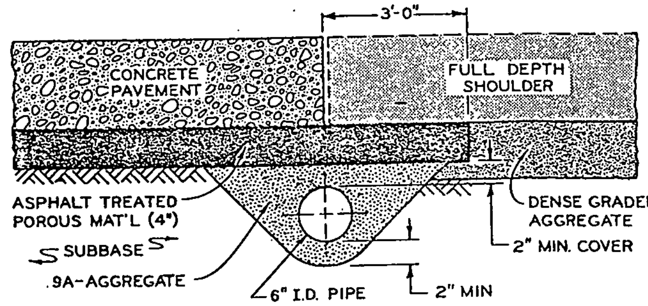


FIGURE 26 Cross section of asphalt-treated porous material (ATPM) drain installation (Michigan) (55).

ect is the disturbance of the pavement edge support when the drain is installed.

Georgia

The state of Georgia carried out an extensive study that included installing (between 1974 and 1979) edge drains on existing pavements exhibiting pumping and faulting (53). The final edge drain detail used is shown in Figure 19. The results of the Georgia study are as follows (53):

> Experience with some of the earlier installations and with the filter-fabric test sections indicates that the use of edge drains along concrete pavement may not be effective on a long-term basis. The Georgia DOT has a moratorium on any additional edge-drain installations until the performance of the existing 454 km (282 miles) of edge drains, especially those that use the current design, can be evaluated.

California

The California Department of Transportation (45) directs that longitudinal edge drains are to be considered along with other structural section drainage and other features in all new construction and in concrete pavement rehabilitation projects. The section adopted for the rehabilitation projects is shown in Figure 21; also shown is the section to be used for new construction.

The permeable material used in the drain is to be asphalt treated or cement treated. It should be noted that the drain is protected from clogging by the use of a filter fabric between the permeable drain and the subgrade or aggregate subbase material.

Although the success of these treatments can only be determined by long-term performance, Caltrans is confident that the current retrofit design will control the faulting problem (57).

France

Ray (58, 59) reported on recent longitudinal drains in France. Figure 28 shows a typical section of the drains used in rehabilitation work. Similar designs are used in new construction. The high-permeability material used in the French version is a porous concrete.

Some of the conclusions from 10 experimental test sections over a 1- to 4-yr period are as follows:

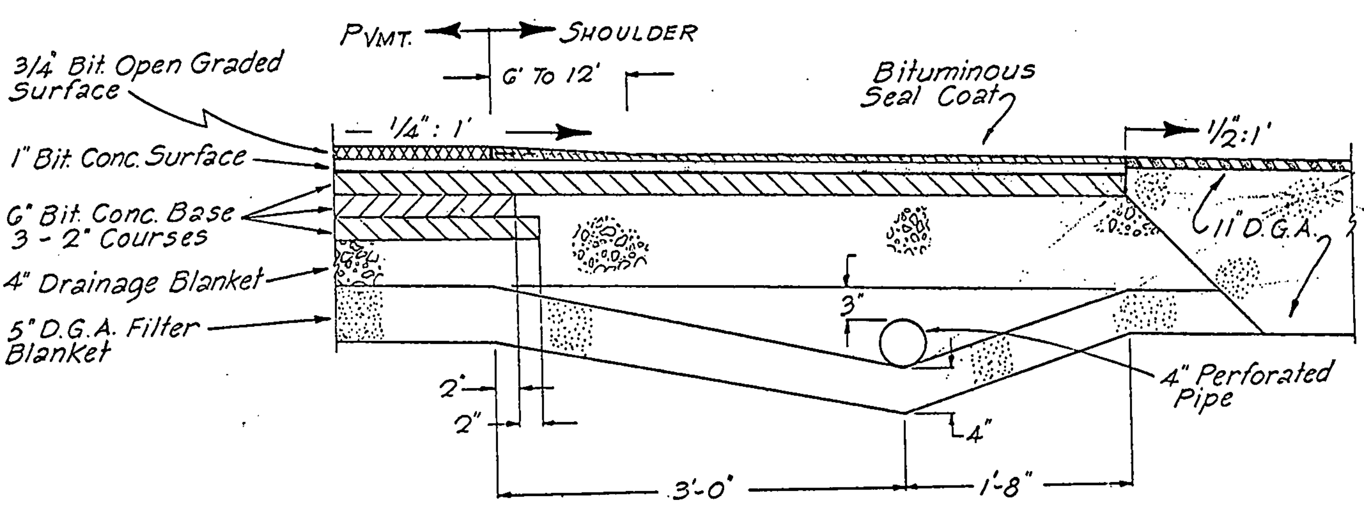


FIGURE 27 Experimental section with drainage blanket (Kentucky) (56).

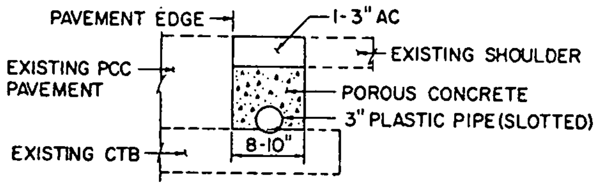


FIGURE 28 Edge drain used for rehabilitation in France (57).

1. The subbase should not be completely grooved (the trench should not go through the subbase) in order to avoid weakening the lateral support of the slabs. The slight grooving of 1 to 3 cm (0.4 to 1.2 in.) is intended to favor the rapid drainage of the concrete-subbase contact.

2. The fine particles produced by trenching should be removed by suction.

3. This type of trench is suited to existing pavements in good condition; it can retard or prevent the appearance of pumping and its consequences. On the other hand, such a device is to be avoided for an old pavement that has begun to deteriorate considerably, particularly when the cause of this deterioration is a high degree of erodibility in the subbase and water continues to enter the structure. In the latter case, the drainage trench accelerates the removal of the fines and leads to slab failure even more rapidly than without the drain.

4. Comparative measurements of approach and leave-slab deflections on old sections with and without drainage tend to show an increase in this characteristic after drainage, probably owing to a certain progressive removal of fines previously blocked under the approach slab and under the longitudinal edge of the concrete.

5. Faulting measurements would appear to show a stabilization of old pavements after drains are installed. For new construction, joint faulting will not develop if proper edge drainage is included in the design.

Iowa

The Iowa Department of Transportation (60) installed 13.6 miles (22 km) of longitudinal edge drain along a section of I-80 where many transverse joints were faulted and there was evidence of edge pumping. The design is shown in Figure 29. The porous back fill is a graded aggregate material.

Test results indicate that after 1.5 yr, the rate of increase of faulting is less than the rate of increase for adjacent pavement without subdrains; however, additional testing is necessary to verify the trend. There were no findings as to improvements of the pumping conditions.

CHAPTER SEVEN

CONCLUSIONS

The observation that many pavements are subject to moisture-related problems has convinced many engineers that subsurface drainage design criteria and principles should be part of the pavement structural design procedure. It is believed that better, more economical pavements can be designed and constructed if these criteria and principles become an integral part of the pavement design, construction, and maintenance.

The design of subsurface drainage for pavement structures is not difficult, but it is site-specific. Not understanding and/or not applying the basic concepts or principles can lead to uneconomic or poorly performing pavements. The main principles or concepts are as follows:

- Darcy's law for laminar flow is adequate for the design of subsurface drainage systems.
- Subsurface drainage systems will only drain free water from a pavement structure.
- The primary source of free water to the pavement structure is infiltrated water.
- Permeability requirements for lateral flow are very high because the hydraulic gradient is very low and the area of flow is small.
- Proper filters need to be included if the drainage system is to function properly for a long period of time.
- The permeability of the subgrade material and the location of the free-water surface (water table) must be known if removal of the free water by vertical flow is to be investigated.
- Wet soils or aggregates are not as strong as dry soils or aggregates under most circumstances. This is particularly true with the repetitive loading that occurs under pavements.

New pavement test sections incorporating subsurface drainage systems have been constructed in Kentucky, Michigan, New Jersey, and Pennsylvania. These pavements have both flexible and rigid surfaces. The drainage layer in these pavements is immediately beneath the pavement and is made of graded aggregate, asphalt-treated permeable material (ATPM), or porous concrete. Construction of these drainage

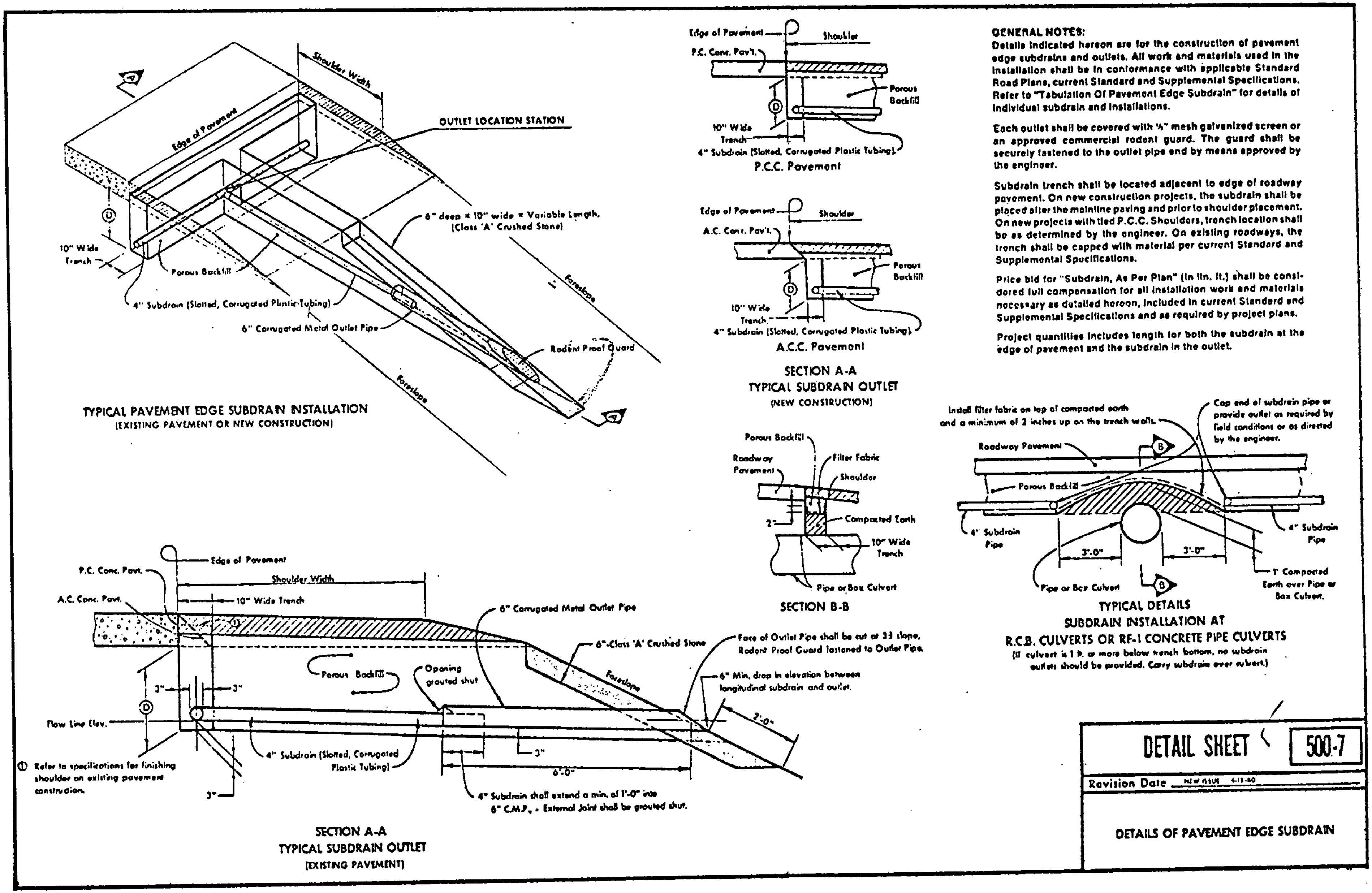


FIGURE 29 Details of longitudinal edge drain (Iowa) (*60*).

layers was not overly difficult and the cost of the in-place material was competitive with dense-graded aggregate materials. To date these materials have served satisfactorily as drains and as structural support for the surfacing materials. California has adopted a standard design for subgrade drains, and has issued a memorandum instructing personnel to consider the need for longitudinal drains in both new and existing pavements for the purpose of discharging infiltrated surface water to reduce pavement failures. California requires the use of either asphalt-treated (ATPM) or cement-treated (porous concrete) permeable material for longitudinal drains.

Longitudinal drains have been installed as edge drains in existing pavements in California, Georgia, and Iowa, and other states. The results of using longitudinal drains on rehabilitation projects have been mixed. There are two particularly important conditions that affect the successful use of these drains: (a) the edge support for the pavement must not be damaged when the drain is installed, and (b) the material that is adjacent to the drain and needs to be drained must be sufficiently permeable to allow the free water that is causing the problem to reach the longitudinal drain. Large rehabilitation projects incorporating longitudinal drains should be considered carefully. Cedergren (*10*) recommends the installation of trial sections. Where longitudinal drains will not work, it is important that extra effort be made to seal all joints and cracks.

The infiltration of free water into the pavement structure, its effect on material strength, and its removal by vertical flow or a lateral subsurface drainage system should be an integral part of the pavement structural design process.

REFERENCES

1. HAAS, R., and W. R. HUDSON, *Pavement Management Systems*. McGraw-Hill Book Co., New York (1978).
2. PANNELL, J. P. M., *Man the Builder—An Illustrated History of Engineering*. Crescent Books, New York (1977).
3. IZZARD, C. F., "A Rational Approach to Drainage of a Pervious Sub-Base." *Highway Research Board Proceedings* (1944) pp. 359–363.
4. CASAGRANDE, A., and W. L. SHANNON, "Base Course Drainage for Airport Pavements." *American Society of Civil Engineers, Transactions,* Vol. 117 (1952) pp. 792–820.
5. BARBER, E. S., and C. L. SAWYER, "Highway Subdrainage." *Highway Research Board Proceedings* (1952) pp. 642–666.
6. WOODS, K. B., *Highway Engineering Handbook*. McGraw-Hill Book Co., New York (1960).
7. YODER, E. J., *Principles of Pavement Design*. John Wiley & Sons, New York (1959).
8. CEDERGREN, H. R., *Drainage of Highway and Airfield Pavements*. John Wiley & Sons, New York (1974).
9. CEDERGREN, H. R., K. H. O'BRIEN, and J. A. ARMAN, "Guidelines for Design of Subsurface Drainage Systems for Highway Structural Sections." Final Report (Summary) No. FHWA-RD-72-30. Federal Highway Administration (1972) 25 pp.
10. CEDERGREN, H. R., K. H. O'BRIEN, and J. A. ARMAN, "Guidelines for Design of Subsurface Drainage Systems for Highway Structural Sections." Final Report No. FHWA-RD-73-14. Federal Highway Administration (1973).
11. MOULTON, L. K., "Highway Subdrainage Design." Report No. FHWA-TS-80-224. Federal Highway Administration (1980).
12. DEMPSEY, B. J., M. I. DARTER, and S. H. CARPENTER, "Improving Subdrainage and Shoulders of Existing Pavements—State of the Art." Interim Report. University of Illinois (1977).
13. BELL, J. R., et al., "Iterim Report for Evaluation of Test Methods and Use Criteria for Geotechnical Fabrics in Highway Applications." Department of Civil Engineering and Transportation Research Institute, Oregon State University (1979).
14. HEALY, K. A., and R. P. LONG, "Prefabricated Subsurface Drains." *Highway Research Record 360* (1971) pp. 57–64.
15. HEALY, K. A., and R. P. LONG, "Prefabricated Filter-Fin for Subsurface Drains." *ASCE Proceedings, Journal of the Irrigation and Drainage Division,* No. IR4 (December 1972) p. 543.
16. HALIBURTON, T. A., and J. D. LAWMASTER, "Training Manual on Use of Engineering Fabrics." Contract No. DTFH 61-80-C-0094. Federal Highway Administration (1981).
17. BARBER, E. S. and C. L. SAWYER, "Highway Subdrainage." *Public Roads,* Vol. 26, No. 12 (February 1952) pp. 251–268.
18. DEMPSEY, B. J., S. H. CARPENTER, and M. I. DARTER, "Improving Subdrainage and Shoulders of Existing Pavements." Final Report FHWA/RD-81/078. Federal Highway Administration (1982).
19. MAJIDZADEH, K., "Evaluation of Pavement Subsurface Drainage Conditions in Ohio." Report OHDOT-05-76. Ohio Department of Transportation (1976).
20. RIDGEWAY, H. H., "Pavement Permeability and Drainage." Ph.D. Thesis, Civil Engineering Department, University of Connecticut (1975).
21. RIDGEWAY, H. H., "Infiltration of Water Through the

Pavement Surface." *Transportation Research Record 616* (1976) pp. 98–100.
22. Winterhorn, H. F., and H. Eyring, "Theoretical Aspects of Water Accumulation in Cohesive Subgrade Soils." *Highway Research Board Proceedings* (1945) pp. 422–434.
23. Barber, E. S., and G. P. Steffens, "Pore Pressures in Base Courses." *Public Roads,* Vol. 30, No. 3 (August 1958) pp. 53–62.
24. Cedergren H. R., *Seepage, Drainage and Flow Nets.* John Wiley & Sons, New York (1968).
25. Taylor, D. W., *Fundamentals of Soil Mechanics.* John Wiley & Sons, New York (1965).
26. Terzaghi, K., and R. B. Peck, *Soil Mechanics in Engineering Practice.* John Wiley & Sons, New York (1967).
27. Lambe, T. W., and R. V. Whitman, *Soil Mechanics.* John Wiley & Sons, NewYork (1969).
28. Olsen, R. E., and D. E. Daniel, "Measurement of the Hydraulic Conductivity of Fine Grained Soils." *Permeability and Groundwater Contaminant Transport,* ASTM STP 746 (1981) pp. 18–64.
29. Moulton, L. K., and R. K. Seals, "Determination of the In Situ Permeability of Base and Subbase Courses." Final Report No. FHWA-RD-79-88. Federal Highway Administration (1979).
30. Healy, K. A., and R. Laak, "Site Evaluation and Design of Seepage Fields." *ASCE Proceedings, Journal of the Environmental Engineering Division,* No. EE5 (October 1974) pp. 1133–46.
31. Elzeftawy, A., and B. J. Dempsey, "Unsaturated Transient and Steady-State Flow of Moisture in Subgrade Soil." *Transportation Research Record 612* (1976) pp. 56–61.
32. Wallace, K., and F. Leonardi, "Theoretical Analysis of Pavement Edge Infiltration and Drainage." *Australian Road Research Board Proceedings* (1976) pp. 8–13.
33. Wallace, K., and F. Leonardi, "Theoretical Analysis of Pavement Edge Infiltration and Drainage." Parts 1, 2, and 3. James Cook University of North Queensland, Australia (Sept. 1975, May 1976, and July 1976).
34. "Roadway Drainage." *Proceedings of the OECD Symposium on Roadway Drainage.* Berne, Switzerland, May 22–24, 1978. Organisation of Economic Co-operation and Development (January 1980).
35. "Drainage of Highway Pavements." Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. (1969).
36. Oglesby, C. S., and R. G. Hicks, *Highway Engineering.* 4th Edition. John Wiley and Sons, New York (1982).
37. Transportation Research Board, "Roadway Design in Seasonal Frost Areas." *NCHRP Synthesis of Highway Practice 26.* National Research Council, Washington, D.C. (1974) 104 pp.
38. Simonsen, P., and S.-O. Hjalmarsson, "Influence of the Ground Water Table-Level and the Bearing of Capacity." OECD Symposium on Road Drainage. Organisation for Economic Co-operation and Development, Paris (1978).
39. Yoder, E. J., and M. W. Witczak, *Principles of Pavement Design.* 2nd Edition. John Wiley & Sons, New York (1975).
40. "Water in Roads: Prediction of Moisture Content of Road Subgrades." Organisation for Economic Co-operation and Development (August 1973) 75 pp.
41. Haynes, J. H., and E. J. Yoder, "Effects of Repeated Loading on Gravel and Crushed Stone Base Course Materials Used in the AASHO Road Test." *Highway Research Record* 39 (1963) pp. 82–96.
42. Rada, G., and M. W. Witczak, "Comprehensive Evaluation of Laboratory Resilient Moduli Results for Granular Material." *Transportation Research Record 810* (1981) pp. 23–33.
43. Darter, M. I., S. H. Carpenter, M. Herrin, E. J. Barenberg, B. J. Dempsey, and M. R. Thompson, "Techniques for Pavement Rehabilitation." Training course prepared for Federal Highway Administration and National Highway Institute (December 1980).
44. "Implementation Package for a Drainage Blanket in Highway Pavement Systems." Federal Highway Administration (May 1972) 25 pp.
45. "Memorandum—Highway Design Manual, Section 7-611.13, Structural Section Drainage." California Department of Transportation, Division of Project Development, Office of Planning and Design (March 17, 1980).
46. Steward, J., R. Williamson, and J. Mohney, "Guidelines for Use of Fabrics in Construction and Maintenance of Low-Volume Roads." Forest Service, U.S. Department of Agriculture, Washington, D.C. (1977). (Reprinted by Federal Highway Administration, Report No. FHWA-TS-78-205, 1978.)
47. "Sample Specifications for Engineering Fabrics." Report No. FHWA-TS-78-211. Federal Highway Administration (1978) 79 pp.
48. Haliburton, T. A., J. D. Lawmaster, and V. C. McGuffey, "Use of Engineering Fabrics in Transportation Related Applications." Implementation Division, Office of Development, Federal Highway Administration, U.S. Department of Transportation. Final manual for review by Task Force 25 of the AASHTO-AGC-ARTBA Joint Committee (1982).
49. Miller, S. P., "Filter Fabrics for Airport Drainage." Report No. FAA-RD-79-29. Waterways Experiment Station, U.S. Army Corps of Engineers. Prepared for Federal Aviation Administration (1979).
50. Bell, J. R., R. G. Hicks, et al., "Evaluation of Test Methods and Use Criteria for Geotechnical Fabrics in Highway Applications." Interim Report No. FHWA-RD-80-021. Oregon State University. Prepared for Federal Highway Administration (1980).
51. The Asphalt Institute, "Asphalt Overlays and Pavement Rehabilitation." Manual Series No. 17 (November 1969) 134 pp.
52. Ring, G. W., "Drainage and Pavement Rehabilitation." *Pavement Rehabilitation: Proceedings of A Workshop.* Report No. FHWA-RD-74-60. Federal Highway Administration (1974).
53. Thornton, J. B., and W. Gulden, "Pavement Restoration Measures to Precede Joint Resealing." *Transportation Research Record 752* (1980) pp. 6–15.
54. Hoffman, G. L., "Subbase Permeability and Pavement Performance." *Transportation Research Record 849* (1982) pp. 12–18.

55. Novak, E. C., Jr., "Drainage and Foundation Studies for an Experimental Short Slab Pavement." Michigan Department of Transportation, Testing and Research Division, Research Laboratory Section (1982).
56. DRAKE, E. B., "National Experimental Evaluation Program (NEEP-14)." Kentucky Department of Transportation. Prepared for Water In Pavements Workshops (1979).
57. MOORE, L. H., "Drainage Considerations for Rehabilitation of Portland Cement Concrete Pavements." *Proceedings of the National Seminar on PCC Pavement Recycling and Rehabilitation.* Federal Highway Administration, Report No. FHWA-TS-82-208 (December 1981) pp. 55–63.
58. RAY, M., "Recent Development in the Design of Rigid Pavements in France—Study of Performance of Old Pavements and Consequences Drawn from New Highway Construction." *Proceedings, International Conference on Concrete Pavement Design,* Purdue Univ. (1977) pp. 265–277.
59. RAY, M., "A European Synthesis on Drainage, Subbase Erodability, and Load Transfer in Concrete Pavements." *Proceedings, 2nd International Conference on Concrete Pavement Design,* Purdue Univ. (1981) pp. 27–39.
60. MARKS, V. J., "Use of Longitudinal Subdrains in the 3R Program." Progress Report, Project HR 509. Iowa Department of Transportation (1980).

APPENDIX

ASSUMPTIONS AND CALCULATIONS FOR TABLE 3

The design section used for drainage has a superelevation of 1 percent, two 12-ft (3.7-m) lanes, and subdrains at the edge of the bituminous concrete pavement. The minimum base thickness needed to distribute the load is 8 in. (200 mm).

The various criteria and equations used for the examples in Table 3 are given in Chapter 4. The equations to determine the required permeability of the drainage layer all assume saturated flow and that Darcy's law is applicable.

For all examples:

$H = H_d = 0.5$ ft
$L = 24$ ft
$\tan\alpha = s = 0.01$
$n_e = n'$ [A value of n_e is assumed for each calculation. However, the effective porosity (or yield) depends on gradation distribution and may need adjustment after selection of the gradation needed to obtain the required permeability.]

Criterion 1, Equation 1

$$k = \frac{n_e L^2}{2t_{50}(H + L\tan\alpha)}$$

$n_e = 0.05$
$t_{50} = 10$ days

$$k = \frac{0.05(24)^2}{2 \times 10(0.5 + 24 \times 0.01)} = 1.95 \text{ ft/day}$$

Criterion 1, Equation 2

$$k_d = \frac{(TF)n'L^2}{H_d t}$$

$TF = t/m = 0.33$ from Figure 13:

$U = 0.5$ (50% drainage)

$$S_1 = \frac{LS}{H} = \frac{24 \times 0.01}{0.5} = 0.48$$

$n' = 0.05$

$t = 10$ days

$$k_d = \frac{(0.33)(0.05)(24)^2}{(0.5)(10)} = 1.90 \text{ ft/day}$$

Criterion 2, Equation 2

$$k_d = \frac{(TF)n'L^2}{H_d t}$$

$TF = t/m = 2.9$ from Figure 13:

$U = 0.95$ (95% drainage)

$S_1 = 0.48$

$n' = 0.10$

$t = 1 \text{ hr} = 1/24 \text{ day}$

$$k_d = \frac{(2.9)(0.10)(24)^2}{(0.5)(1/24)} = 8000 \text{ ft/day}$$

$$t_{50} \text{ (equation 1)} = \frac{n_e L^2}{2k_d(H + L \tan \alpha)}$$

$$= \frac{0.10(24)^2}{2(8000)(0.5 + 24 \times 0.01)}$$

$$= 0.005 \text{ days} = 7 \text{ min}$$

$$t_{50} \text{ (Figure 13 and equation 2)} = \frac{(TF)n'L^2}{H_d K_d}$$

$$= \frac{(0.33)(0.10)(24)^2}{(0.5)(8000)}$$

$$= 0.005 \text{ days} = 7 \text{ min}$$

Criterion 3, Equation 3

$$k = \frac{qL}{H(sL + H/2)}$$

$q = q' \times 24 \text{ hr/day}$

q' = rainfall (Fig. 10) × global infiltration coefficient × 24 ft²/ft of pavement

= 1.4 in./hr (Washington, D.C.) ÷ 12 in./ft × 0.5 (asphalt concrete) × 24 ft²/ft = 1.4 ft³/hr/ft

$q = 1.4 \times 24 = 33.6$ ft³/day/ft

$$k = \frac{(33.6)(24)}{0.5(0.01 \times 24 + 0.5/2)} = 3300 \text{ ft/day}$$

$$t_{50} \text{ (equation 1, } n_e = 0.10) = \frac{0.10(24)^2}{2(3300)(0.5 + 24 \times 0.01)}$$

$$= 0.012 \text{ days} = 17 \text{ min}$$

Criterion 3, Equation 4

$$k = \frac{q}{Hs}$$

$q = 33.6$ ft³/day/ft

$$k = \frac{33.6}{(0.5)(0.01)} = 6700 \text{ ft/day}$$

$$t_{50} \text{ (equation 1, } n_e = 0.10) = \frac{0.10(24)^2}{2(6700)(0.5 + 24 \times 0.01)}$$

$$= 0.006 \text{ days} = 8 \text{ min}$$

Criterion 4, Equation 3

$$k = \frac{qL}{H(sL + H/2)}$$

$$q = 0.1\left(N + 1 + \frac{W}{40}\right)$$

$N = 2$ lanes

$W = L = 24$ ft

$q = 0.1(2+1+24/40) = 0.36$ ft³/hr/ft $= 8.6$ ft³/day/ft

$$k = \frac{(8.6)(24)}{0.5(0.01 \times 24 + 0.5/2)} = 850 \text{ ft/day}$$

$$t_{50} \text{ (equation 1, } n_e = 0.10) = \frac{0.10(24)^2}{2(850)(0.5 + 24 \times 0.01)}$$

$$= 0.046 \text{ days} = 66 \text{ min}$$

Criterion 4, Equation 4

$$k = \frac{q}{Hs}$$

$q = 8.6$ ft³/day/ft

$$k = \frac{8.6}{(0.5)(0.01)} = 1700 \text{ ft/day}$$

$$t_{50} \text{ (equation 1, } n_e = 0.10) = \frac{0.10(24)^2}{2(1700)(0.5 + 24 \times 0.01)}$$

$$= 0.023 \text{ days} = 33 \text{ min}$$

Criterion 5, Equation 2

$$k_d = \frac{(TF)n'L^2}{H_d t}$$

$TF = t/m = 1.35$ from Figure 13:

$U = 0.85$ (85% drainage)

$S_1 = 0.48$

$n' = 0.10$

$t = 5 \text{ hr} = 5/24 \text{ day}$

$$k_d = \frac{(1.35)(0.10)(24)^2}{(0.5)(5/24)} = 750 \text{ ft/day}$$

$$t_{50} \text{ (equation 1, } n_e = 0.10) = \frac{0.10(24)^2}{2(750)(0.5 + 24 \times 0.01)}$$

$$= 0.052 \text{ days} = 75 \text{ min}$$

THE TRANSPORTATION RESEARCH BOARD is an agency of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. The Board's purpose is to stimulate research concerning the nature and performance of transportation systems, to disseminate information that the research produces, and to encourage the application of appropriate research findings. The Board's program is carried out by more than 270 committees, task forces, and panels composed of more than 3,300 administrators, engineers, social scientists, attorneys, educators, and others concerned with transportation; they serve without compensation. The program is supported by state transportation and highway departments, the modal administrations of the U.S. Department of Transportation, the Association of American Railroads, the National Highway Traffic Safety Administration, and other organizations and individuals interested in the development of transportation.

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the Federal Government. The Council operates in accordance with general policies determined by the Academy under the authority of its congressional charter of 1863, which establishes the Academy as a private, nonprofit, self-governing membership corporation. The Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in the conduct of their services to the government, the public, and the scientific and engineering communities. It is administered jointly by both Academies and the Institute of Medicine.

The National Academy of Sciences was established in 1863 by Act of Congress as a private, nonprofit, self-governing membership corporation for the furtherance of science and technology, required to advise the Federal Government upon request within its fields of competence. Under its corporate charter the Academy established the National Research Council in 1916, the National Academy of Engineering in 1964, and the Institute of Medicine in 1970.

TRANSPORTATION RESEARCH BOARD
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

ADDRESS CORRECTION REQUESTED

NON-PROFIT ORG.
U.S. POSTAGE
PAID
WASHINGTON, D.C.
PERMIT NO. 42970

00001SM001
JAMES W HILL
RESEARCH SUPERVISOR
IDAHO TRANS DEPT DIV OF HWYS
P O BOX 7129 3311 W STATE ST
BOISE ID 83707