PB90266636

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA - RD - 73 - 14		
4. Title and Subtitle DEVELOPMENT OF GUIDELINES FOR THE DESIGN OF SUBSURFACE DRAINAGE SYSTEMS FOR HIGHWAY PAVEMENT STRUCTURAL SECTIONS		5. Report Date February 1973
		6. Performing Organization Code
7. Author(s) Harry R. Cedergren, Jorge A. Arman, Ken H. O'Brien		8. Performing Organization Report No.
9. Performing Organization Name and Address Cedergren/KOA, A Joint Venture 3745 Long Beach Boulevard Long Beach, California 90807		10. Work Unit No. 35C2-062 (FCP)
		11. Contract or Grant No. FH-11-7582
12. Sponsoring Agency Name and Address Federal Highway Administration Office of Research Washington, D. C. 20590		13. Type of Report and Period Covered FINAL REPORT
		14. Sponsoring Agency Code 5Ø216

15. Supplementary Notes

From the study "Development of Guidelines for the Design of Pavement Subdrainage Systems." FHWA Contract Manager: G. W. Ring HRS-14.

16. Abstract

The report presents results of interviews with State highway department personnel, field reconnaissance of pavements in 9 States and 9 case studies of selected pavements in the FHWA Regions. Problems with existing drainage design concepts and construction methods are pointed out, showing why many pavements are saturated with water for long periods of time each year. It is deduced that this saturation contributes to considerable shortening of pavement life. A new method of design is presented to take care of the infiltration of surface water. Inflow-outflow analyses and highway geometrics are included in a procedure utilizing a two-layer graded filter to rapidly remove any water entering the structural layers.

17. Key Words	18. Distribution Statement
Pavement drainage, pavement design, subsurface drainage, drainage analysis, collector drains, pipe outlets, drainage layers, open graded bases	Availability unlimited. The public can obtain this document through the National Technical Information Service, Springfield, Virginia 22151.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages
Unclassified	Unclassified	

Form DOT F 1700.7 (8-69)

All of the work required for this research and development study was accomplished by the Joint Venture of Harry R. Cedergren, Consulting Engineer, Sacremento, California, and Ken O'Brien & Associates, Consulting Engineers, Long Beach, California, under Contract No. FH-11-7582, dated June 26, 1970, between the Joint Venture and the Federal Highway Administration, Washington, D. C. The Joint Venture is responsible for the facts and the accuracy of the data presented in all of the Phase I and Phase II reports, including this "Final Report". The contents do not necessarily reflect the official views or policy of the Department of Transportation. This report does not constitute a standard, specification, or regulation.

PREFACE

The "Guidelines for the Design of Subsurface Drainage Systems for Highway Pavement Structural Sections" developed in this study, shows how to design pavement subsurface drainage systems capable of rapidly removing surface water, subsurface water, and water from any other sources that may enter structural sections. This report contains back-up information gathered in the study, supporting the conclusion that rapid drainage of pavement structural sections is usually necessary, practical, and economical.

In the "Interviews and Field Reconnaissance" phase of the project, only isolated examples could be found of pavements that had been provided with subsurface drains installed primarily to remove surface water. And those found had been installed under maintenance after water problems had developed. Yet, it is estimated that more than 90 percent of the major pavements in the United States may be periodically exposed to surface water inflows in sufficient quantities to cause significant saturation and flooding of pavement structural sections.

Ideally, if pavements could be kept tightly sealed, this would eliminate the need for most subsurface drainage systems. However, information presented in this report shows that the present State-of-the-Art does not ensure a high level of watertightness, even of new pavements.

Data presented in this report show that surprisingly large volumes of water can enter even narrow cracks and joints. Other data are given which show that the drainage rates of pavement structural sections constructed with the "standard" types of bases and subbases in widespread use are extremely slow draining systems. As a result, saturated conditions often can be sustained by rainfall rates as low as 0.01 in./hr or less, and many pavement sections can remain in an essentially saturated condition for days and even weeks after it stops raining.

Evidence that many pavements are slow draining systems can be seen by the bleeding and pumping of water out of joints and cracks, often several days after the rain has stopped. This condition has been observed in almost every part of the country. Those who worked on this project have personally seen it in more than 80 percent of the states.

Pavement life is being seriously shortened by slow drainage, resulting in increasing amounts of money being spent for mud-jacking and grinding to correct faulting, thick overlays, and extensive replacement of failed portions of comparatively new highway pavements.

The type of subsurface drainage system described in the "Guidelines" makes use of a layer of extremely permeable open-graded aggregate (pea gravel or coarser) under the full width of the traveled way, provided with pipes in collector and outlet drains. Although the idea that such systems ought to be designed rationally, as shown in the "Guidelines", seems to be rather new, the basic concepts for such designs are not new. John L. McAdam, back in 1820, very ably expressed the concept that good drainage is essential. And the theoretical concept on which these systems can be designed was developed by H. Darcy in 1856.

Although few examples can be found of truly well drained pavements, one of the Case Studies (Eureka site, Humboldt County, California) produced striking proof that rapidly draining systems of the kind proposed in the "Guidelines" are paractical, economical, and highly beneficial.

We want to take this opportunity to thank all of the State, County, and Federal personnel who cooperated in furnishing valuable information for this study. Special appreciation is expressed to Jorge Arman for his many technical contributions to this work, to William Dube' for his careful surveillance of the field work for the Case Studies, and to the many others who contributed to the preparation of the reports in both Phase I and Phase II.

Sacremento and Long Beach, California, October, 1972.

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THE DESIGN OF SUBSURFACE DRAINAGE SYSTEMS FOR
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FINAL REPORT
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1. INTRODUCTION

1.1 General

The damaging effect of water on road structural sections is well known to those involved in the design, construction, and maintenance of highways. Most of these damaging effects occur when free water gains access to the structural section and foundation soils, altering the mechanical properties of these materials by increasing the moisture content and allowing excess pore pressures to develop under impact of traffic. Free water reduces the frictional strength of structural section and foundation materials by creating buoyancy within these materials.

Considerable sums of money are expended every year to construct pavement structural sections of doubtful utility that are supposedly designed to protect the pavement systems against the damaging effects of water. If the low efficiency of these pavement systems (generally designed on empirical bases) has not become evident, it is largely because the mechanisms of water movement and removal from within the structural section are not generally understood. Drainage of roadbeds has been treated as an empirical or qualitative type of problem when in reality it is a quantitative problem requiring a specific design for each situation. Failure to design subsurface drainage systems as conveyors or conductors to remove water that infiltrates into highway pavement structural sections is largely responsible for a great deal of the premature damage occurring to pavements throughout the United States.

The sources of water in roadbeds include rainfall infiltrating through joints, cracks, unpaved shoulders and pervious pavements; ground water movement; localized springs or seepages; moisture transfer within soil masses; and thermodynamic or hydrogenesis processes. Of all sources, surface water is the most prevalent.

Numerous references are made in this report to the terms "excess water" or "free water". When these terms are used, they mean any water which (1) creates a condition of internal flooding of the pavement structural section with water available to produce hydrostatic pressures in cracks, voids, or other spaces; or (2) creates detrimental changes in the supporting characteristics of the structural layers.

1.2 Historical Background

The importance of proper drainage in road design was recognized as early in history as five centuries before Christ, and the Romans are generally credited with being the first highway designers of any importance. The first major highway system, comprising more than 48,000 miles of road, was constructed to facilitate the movement of officials and the army of the Roman Empire. The durability of those early day highways is proven by the fact that some of them still exist. One of the features responsible for the longevity of these roads is undoubtedly good drainage. In addition to constructing these roads on high, dry ground well above the water table, a sand layer was provided immediately above the subgrade and below the surface course of flat stones cemented together.

The next serious attempts to improve roads did not occur until 24 centuries later when Tresaguet, Metcalf, Telford, and McAdam (first half of the 19th Century) introduced important modifications to the then prevailing construction methods. One of the most important principles they "rediscovered" was that of "keeping" the roadbeds dry. These famous men recognized that the strength of the subgrade is one of the most single important factors when considering the load-carrying capacity of a road pavement section and that the strength of the subgrade is intimately related to moisture content. Therefore, it naturally follows that "keeping" the roadbed free of excess water is an extremely important consideration. Practically all the roads constructed under the direction of these pioneers of highway engineering were provided with ample side ditches, adequate cross slope, and subdrainage features. McAdam wrote, "It (water) penetrates through the whole mass and is retained in the trench whence the road is liable to give way in all changes of weather. It must, therefore, be obvious that nothing can be more erroneous than to provide a reservoir for water under the road where it is acted upon by frost to its destruction."

During the latter half of the 19th Century, very little attention was given to drainage of roadbeds. It was not until 1906 that attention was again directed toward proper drainage of highways as an inseparable element of good design. The significance of providing good roadbed drainage has been advocated many times through the centuries, but often unheeded by road designers. It is dramatized in H. Frost's book, "The Art of Roadmaking", written in 1910 which states, "A road on a wet, undrained bottom will always be troublesome and expensive to maintain, and it will be economical in the long run to go to considerable expense in making the drainage of the subsoil as perfect as possible."

In spite of the admonition of McAdam in 1820, of Frost in 1910, and others of the past, most modern highways are being built in trenches. For example, nearly all of the Case Study sites investigated under this project were prematurely damaged because their structural sections are reservoirs from which water escapes very slowly (see Case Study Investigations, Phase II - Development of Guidelines). When base courses and the interfaces between bases and pavements are filled with water, the supporting power is greatly reduced, and erosion of bases and the ejection of material out of structural sections can take place. As will be pointed out in more detail in subsequent parts of this report, each wheel impact on a structural section containing free water can be many times more damaging than each impact which occurs when no free water is present. Consequently, the prolonged presence of free water in bases can greatly shorten pavement life.

1.3 Objective of the Study

The objective of this study is to develop guidelines for the design of effective subsurface drainage systems for highway pavement structural sections.

Primary attention is directed to controlling surface runoff infiltrating downward through roadway surfacing, pavement joints or cracks, and pavement shoulders. In order to accomplish the objective, a detailed program plan was developed comprising four different items of work as follows:

1.3.1 Review of existing pertinent literature of the United States and foreign countries as related to subsurface drainage and associated subjects. (Refer to Appendix A, Literature Review Abstracts, Phase I - Final Technical Report.)

1.3.2 Interviews of nine selected State Highway Departments to probe extensively into materials, design, construction and maintenance practices in regard to subdrainage of roadway pavement structural sections. (Refer to Appendix B, Interviews and Reconnaissance, Phase I - Final Technical Report.)

Field reconnaissance of highway pavements under the jurisdiction of the selected State Highway Departments interviewed. During the field reconnaissance, highways were inspected where pavement distress had occurred due to inadequate subdrainage or where exceptional pavement performance could be attributed to good drainage. Hundreds of miles of both undistressed and distressed pavements were surveyed during the field reconnaissance.

Discussion with engineers of the selected State Highway Departments to determine the magnitude of subdrainage problems and how these problems are resolved.

1.3.3 A field testing program to evaluate environmental conditions and physical characteristics at a carefully selected site in each of the states visited. These investigations (Case Studies) attempted to determine the mechanisms of failure or distress of highway pavements presumably caused by inadequate subdrainage. (Refer to Case Study Investigations, Phase II - Development of Guidelines.)

1.3.4 Evaluation of different methods and development of guidelines for the design, construction, and maintenance of subdrainage systems.

1.4 Statement of the Basic Problem

Present highway pavement design practice generally assumes that pavement structural sections and subgrades will be saturated at least part of the time, and in that condition will have to support the loads of moving vehicles. Thus, the "saturated subgrade" has been assumed to be the "worst condition" for which pavements need to be designed. And the practice has been to determine strengths of subgrades and bases by static types of tests. Many of the pavements that have been designed on this basis have been deteriorating and failing after 6 to 15 years of use, whereas the expected life was in the order of 25 years. Although increased traffic volumes may be part of the problem, the increased damages that occur when free water is in structural sections is believed to be a bigger factor than has been generally recognized.

It has been known for many decades that damages to pavements during the "spring breakup" can be exceedingly severe if frost-susceptible materials occur within freezing depths. It has been less well recognized, however, that the impacts of wheels on structural sections that are saturated by rains can be many times more damaging than the impacts which occur when no free water is present. The pavement test track experiments of Barenberg and Thompson (Ref. 22, at end of text), for example, showed that rates of damage with excess water present were 100 to 200 times greater than when no excess water was present. One set of test pavements survived 700,000 wheel impacts with no visible damage at "as constructed" moisture contents, but failed completely under 12,000 impacts after the sections were saturated.

This experimental work, as well as the AASHO Road Test, the WASHO Road Test, and experience gathered in this study, demonstrate that pavements which are free of excess water can carry much heavier loads and larger volumes of traffic than the same pavements can carry when they contain excess water. It, therefore, seems probable that many of the slowly draining pavements which are showing distress and shortened life could have had much longer useful lives if they had been designed as rapidly draining sections.

1.5 Current Road Design Problems

Although it has been known for centuries that excess water is one of the basic road design problems, structural sections as built in the past few decades are slowly draining systems. The prevalent practice has been to put the emphasis on density and stability, rather than on drainability. Design practices are largely empirical; and after a design chart or formula has been in use for a number of years, it is usually modified to provide either thicker or thinner pavement systems, depending on the degree of success of the criteria used in the immediate past. In the last few decades, when design criteria have been found insufficient, design changes have generally resulted in slight modifications in thicknesses of pavements and bases, in the percent of cement or asphalt used in stabilizing bases, etc., but the drainability has not been increased. Base and subbase materials of high density almost always have low permeability. And, because of the low permeability of the materials used in compacted subgrades and shoulders, they generally act as dams or barriers that prevent the vertical and lateral flow of water out of structural sections.

If the damages from excess water in structural sections are to be minimized, it is evident that prolonged exposure to water must be eliminated. This report contains information demonstrating that rapid drainage can be obtained at little or no sacrifice in stability, and that well drained roadbeds are both practical and economical.

The number of only partially successful efforts to solve specific problems caused by water acting under pavements is an indication that new efforts toward the improvement of the subdrainage systems are needed. Subdrainage systems are integral parts of roads and should be incorporated in the careful design of basic roadway structural sections. The cost of a subdrainage system should be considered as part of the structural section, as well as are the surface drainage facilities, long recognized as a basic requirement in modern highway engineering practice.

When comparing the relative costs of alternate types of designs, the average annual cost of construction plus maintenance over the life of the system should be considered. It should be recognized that the construction of modern layered highway pavement systems of slow drainage capabilities, produces a mechanism for self-destruction. The pavement structural systems behave very much like diaphragm pumps: each heavy wheel impact forces water to move about at the interfaces between pavements and bases, causing erosion and physical movement of base materials which often results in material being ejected through joints and cracks. These actions cause loss of support, faulting, and accelerated damages which can substantially increase upkeep costs and shorten pavement life. The presence of excess water nullifies or reduces the advantages of intergranular friction in the supporting layers. It also increases problems of frost action.

The subsurface drainage system recommended in this report will greatly reduce and in most instances virtually eliminate detrimental water actions caused by dynamic loading and thus lengthen the useful life of pavement systems.

2. IMPLEMENTATION OF PROGRAM

2.1 Literature Review

A comprehensive search of existing literature on the general subject of underdrains, conducted during Phase I of this study, resulted in the publication of Appendix A, Literature Review Abstracts.

Appendix A contains abstracts of 255 articles, books, reports, and investigations published in the United States and in foreign countries.

During Phase II, the literature search was continued but with specific goals. These specific goals, which evolved as a result of the Phase I effort, included the development of criteria for estimating the amounts of surface water that are available for entry into pavements, and the amounts that can actually enter.

A considerable amount of the seepage and subsurface drainage information presented in Appendix A, Literature Review Abstracts, was found from sources not directly related to highway engineering. These other sources include the technical disciplines involving agriculture, irrigation and drainage, airfield pavement design, earthfill dams and levees, and railroad construction.

Research oriented towards developing a better understanding of the phenomena of subsurface drainage is rapidly increasing in the United States and in Europe.

Out of the 255 abstracts in Appendix A, 26 publications that are considered to be of particular value in understanding and solving subsurface drainage problems are labeled "Selected Reference", and are identified with an asterisk (*). Some additional items reviewed during Phase II of the study are given in a list of "References" at the end of the text of this report.

2.2 Interviews

Interviews of selected State Highway Departments were conducted during Phase I during the period of August to November 1970. State Highway Department officials and engineers of California, Connecticut, Georgia, Michigan, Missouri, Oklahoma, Pennsylvania, Utah, and Washington and representatives of the FHWA Field Regions and Headquarters were interviewed.

The purpose of the interviews was to become acquainted with the current practices in investigating and detecting possible problems requiring subsurface drainage, designing subsurface drainage systems, developing subsurface drainage materials specifications, and constructing and maintaining subsurface drainage systems in operation. Another objective of the interviews was to determine the attitudes of the engineers in the various State Highway Departments towards the use of subsurface drainage systems. The findings of the Phase I interviews are summarized in the following paragraphs

(Refer also to Phase I - Final Technical Report).

Summary of Interview Information

Soils or Pavement Design Engineers have the main responsibility for recommending the use of subdrainage systems during the design, and the Resident Engineers are responsible for actual installation of subdrainage systems. However, during construction Resident Engineers may recommend additions or deletions of subdrainage systems where field conditions warrant.

The detrimental effects of high ground water are generally clearly recognized and proper design care appears to be taken to try to avoid saturation of the roadbeds from ground water. However, the ineffectiveness of slow draining bases for water removal is not always fully appreciated.

The effects of rainwater infiltrating into the roadbed are not generally considered in design.

Concrete sand is commonly assumed to be an "adequately pervious material", and tests to evaluate its permeability are not considered to be necessary.

Permeability tests on materials to be used and soils to be drained are not routinely performed.

Sand blankets beneath PCC pavements are in use or have been used at one time or another in most States in an attempt to eliminate pavement pumping. The results have generally been disappointing.

In some States, the use of cement treated bases to support asphalt concrete pavements is being discontinued because of the problem of reflection cracking and the resulting shortened pavement life.

A large variety of pavement design methods are being used, making it difficult to compare the effectiveness of the various design methods as related to the effect of subdrainage conditions.

There are two basic approaches to the design of pavement structural sections. They are: 1) subgrade strength design and 2) design by soil classification. Drainage is usually not considered directly in the design procedure.

The average annual rainfall is not of itself an indicator of subsurface water caused problems. The severity of the problem appears to correspond more closely to rainfall duration and frequency.

Two distinct schools of thought concerning protection of roadbeds against infiltration of surface water prevail among Highway Engineers. The prevalent concept of protection is to provide an impervious surface and adequate cross slope to drain the water off the pavement. The second concept advocates the use of subdrainage systems to collect water and remove it from under the pavements as fast as possible. The latter assumes that it is not within reasonable cost and maintenance capabilities to maintain an effectively impervious pavement surface.

A good field identification/marking system for outlet pipes is essential in development of a comprehensive subdrainage systems maintenance program.

The field interviews indicate that there is a great diversity of opinion among Highway Engineers as to the concepts of subdrainage. There is a need for improved knowledge through education and training, especially with regard to sources and amount of water entering pavement structural sections and what constitutes a drainable, permeable material. The understanding of the concepts of design and need for implementation of subdrainage systems increases in proportion to the degree of direct involvement with field performance.

2.3 Field Reconnaissance

The field reconnaissance consisted of inspecting highway pavement areas selected by State Highway Engineers. These areas included some having subsurface drainage systems of various kinds, some experiencing subsurface drainage problems where pavement distress had presumably been caused by excess water accumulating in the structural section, and some that were in good to excellent condition. During the field reconnaissance and inspection of hundreds of miles of both undistressed and distressed pavements, additional locations were identified as having possible subsurface drainage problems.

The field reconnaissance trips were made in conjunction with the interviews as indicated in 2.2 and described in detail in Appendix B - Interviews and Reconnaissance, Phase I - Final Technical Report.

The primary objective of the field reconnaissance was to observe the efficiency of existing subsurface drainage systems and to determine if pavement deterioration is related to moisture conditions in the structural section. Special attention was directed to the inspection of pavements on embankments where they are theoretically free from high ground water problems and where existence of high moisture content or free water in the structural sections and subgrades could be attributed primarily to infiltration of surface water.

In each State visited, one or more highway pavement locations were identified where existing conditions would warrant further detailed investigations, and where it was reasonable to assume that useful data could be obtained by testing the materials in place. The selected sites were evaluated and analyzed in detail during the case study investigations as described in Case Study Investigations, Phase II - Development of Guidelines.

Some typical problems that were disclosed and/or observed during the field reconnaissance trips, and which are common to all geographical locations and independent of the pavement design methods utilized, are as follows:

Faulting of Portland cement concrete pavements.

Pumping of Portland cement concrete pavements.

Premature aging (cracking, increased permeability) of asphalt concrete pavements.

Apparent excessive moisture content of subgrades in embankments in special situations.

Evidence of excess water beneath pavement surfacing under certain conditions related to highway alignment, profile, and cross section.

Combining subgrades, subbases, and surfaces constructed of materials of different degrees of rigidity (i.e. use of rigid bases under flexible pavements), resulting in early cracking of pavements.

Need for improved subdrainage maintenance programs.

Occasional relaxation of the design requirements of the plans and specifications, sometimes detrimental to the end objective (i.e. omitting drains during construction because no water is evident during dry weather, but the structural sections become saturated during wet weather).

2.4 Case Studies

Nine (9) case study investigations were conducted in eight States: California, Connecticut, Georgia, Michigan, Oklahoma, Pennsylvania, Utah, and Washington. Seven of the case study investigations were performed on Interstate highways, one on a State highway (Washington), and one on a Federal-Aid secondary road (Eureka Case Study, Humboldt County, California).

The general procedure for the case study investigations consisted of initially selecting a short section of highway for detailed field investigation within an area in each State inspected during field reconnaissance visits. Although a reconnaissance inspection was made in Missouri, this State elected not to participate in the case study investigations. At the selected locations, diamond core holes and auger test holes were drilled through the pavements and into the underlying materials, and field tests were performed to obtain data in regard to subsurface conditions and materials characteristics. Selected samples were procured and subjected to laboratory tests to determine physical characteristics. The results of the subsurface investigation, field tests, and laboratory tests were then analyzed and evaluated to determine the causes of pavement distress at eight case study sites, and the reasons why there was no pavement distress at one case study site (Eureka Case Study, Humboldt County, California).

Descriptions of the case study sites and summaries of findings are given in Part 4, SUMMARY OF CASE STUDY INVESTIGATIONS, following Part 3, WATER ACTIONS BENEATH PAVEMENTS, so that the actions occurring to cause failure in the case study sites will be more understandable.

3. WATER ACTIONS BENEATH PAVEMENTS

3.1 General

Water is one of the primary causes of the failure of highway pavements. The mechanisms that lead to the destruction of the highway pavement systems have been studied from different aspects by a considerable number of investigators who have produced diagnoses of the problem and reported their findings. A considerable amount of research has been conducted on the subject of pavement distress and pavement failure caused by the actions of water in the structural section of a road. While this report emphasizes the need to rapidly drain roadbeds to prevent damages from external loads, good drainage reduces the potential for other types of damaging actions such as the pore pressures caused by thermal changes.

Review of existing literature, examination of records from road tests, and observations made during the progress of this project, provide the background for the following.

3.2 Sources of Water

The water found in the structural section of a road can originate from widely varied sources (see Fig. 1). The most abundant and often overlooked or underestimated source is undoubtedly atmospheric precipitation, supplying surface water from rain, snow, hail, condensing mist, dew, and melting ice.

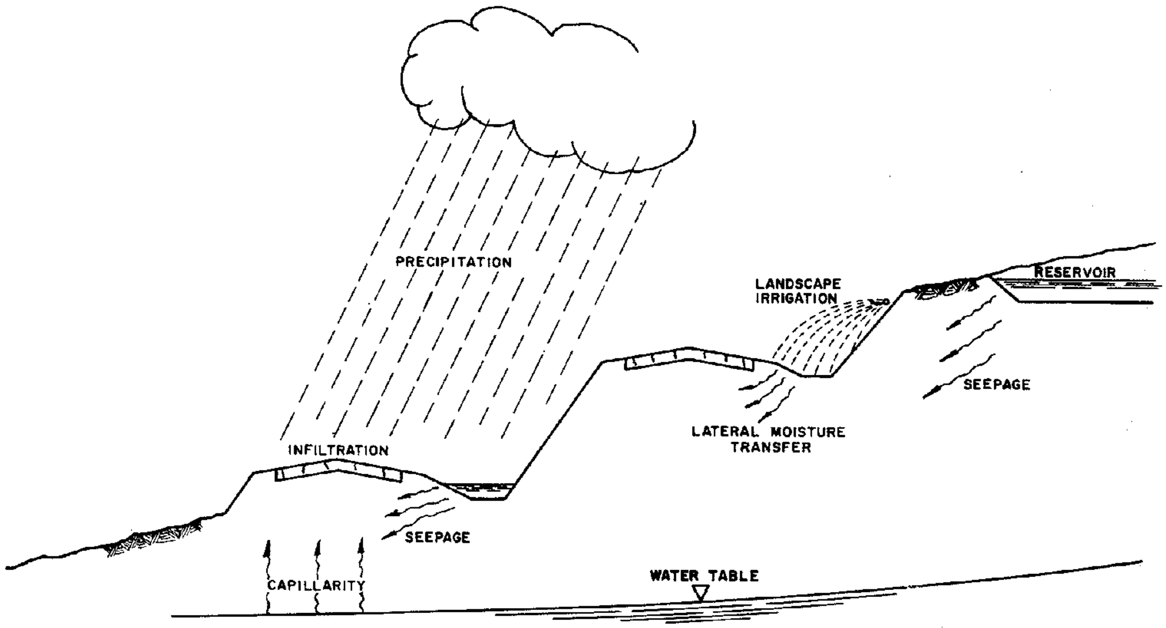


FIGURE NO. 1

SOURCES OF WATER INTO HIGHWAY PAVEMENT STRUCTURAL SECTIONS

In most of the areas that are subjected to severe snowstorms, State Highway Departments have adopted a "dry road" policy, and highways are cleared of accumulated snow as fast as is practical. Melting of the snow that accumulates in the roadside ditches and the area between the ditches and the shoulders of the highway can become a primary source of water by infiltrating from the areas adjacent to the shoulders and flowing downward and laterally towards the structural section. Where subsurface drains are provided for the removal of water from the structural section, snow or ice should not be permitted to block the outlets to these systems.

Rainfall is the primary source of water, and with the exception of a few areas in the western and southwestern

United States, is a persisting source through all seasons of the year.

Although usually less important than rainfall, other sources of water that can be extremely critical at times are ground water and water from manmade sources such as leaching fields, seepage from reservoirs, irrigation of roadside landscaping, etc.

In general, water from hydrogenesis and capillary transfer are not critical except under very special conditions, because the total quantity of water than can be added to the structural section from these sources is very limited. However, they affect the moisture content of the bases, subbases, and subgrades by raising the water content by 1 or 2 percent, thus making these materials more readily sensitive to other sources of water.

It was noted during the interviews and field reconnaissance that Highway Engineers generally consider high ground water tables to be the primary source of water in pavement structural sections. Underdrains are frequently installed to protect the pavement structural section from this source of water. It was also noted that many times after a highway has been designed and constructed, water problems are created by the construction of incompatible adjacent structures or incompatible activities. Examples of these types of problems are: (1) Seepage from a reservoir constructed adjacent to a highway, causing the subgrade to be virtually saturated at all times, so that flooding of the structural section takes place during practically every rainstorm. (2) Construction of an infiltration system to dispose of waste water into the soil adjacent to a four-lane highway in a cut section. The water from leaching fields overloaded underdrains and prevented them from performing as originally intended. (3) Extensive irrigation of intensively farmed areas located adjacent to highways. Lateral seepage from these irrigated areas can introduce water into the pavement structural section. Irrigation of roadside landscaping is also known to have introduced water into pavement structural sections during many months of the year. The effect of this lateral seepage is in essence a change of environment which normally occurs in areas of low precipitation.

A practically unlimited number of sources of water caused by manmade actions can enter into pavement structural sections, resulting in unanticipated poor performance of the structural sections and creating expensive problems for those responsible for highway maintenance. Subsurface drainage systems of the kind described in the "Guidelines" can safeguard pavements from all sources, both natural and manmade.

3.3 Points of Entrance of Water into Structural Sections

Of the total water available to enter pavement structural sections from various sources, only a percentage enters.

Portland cement concrete is practically impervious as are certain types of dense graded asphalt concrete mixes. Nevertheless, all types of pavements will eventually permit the downward passage of some water into the structural section. Surface water can infiltrate through porous pavement materials, unpaved shoulders and medians, through cracks and joints; and it can flow in laterally from the shoulders. Figure 2 shows the most common points of entrance of water into pavement structural sections.

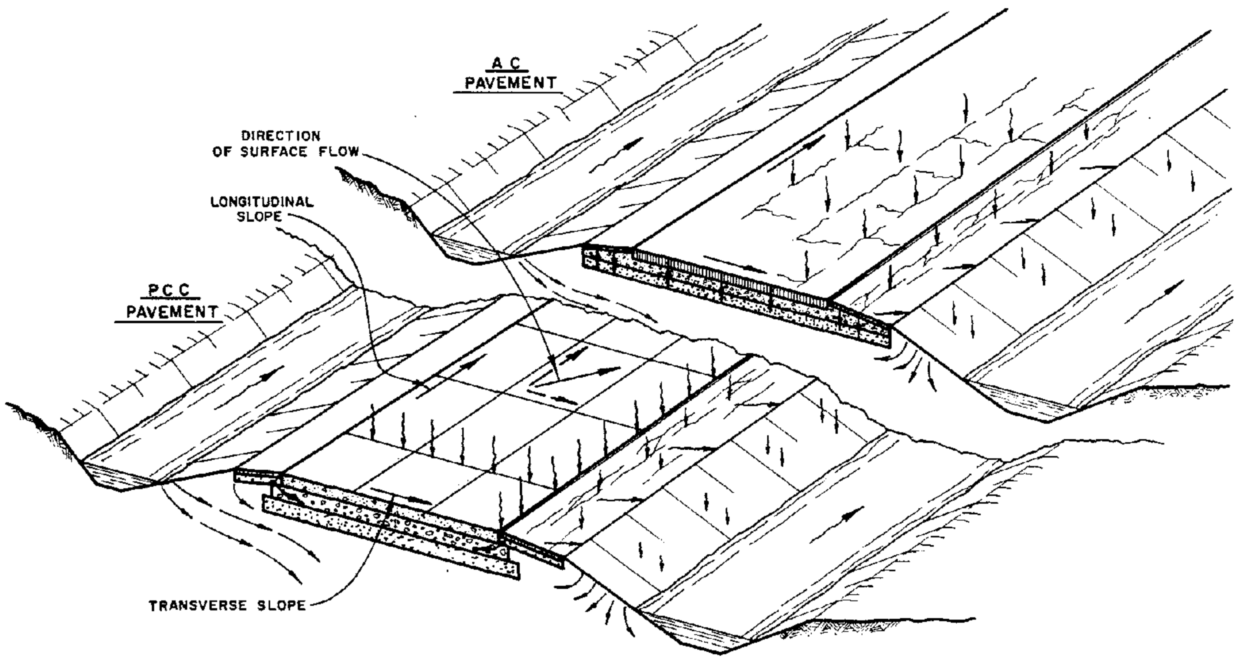


FIGURE NO. 2

POINTS OF ENTRANCE OF WATER INTO HIGHWAY PAVEMENT STRUCTURAL SECTIONS

In the case of Portland cement concrete pavements, as the slabs expand and contract with changes in temperature, the joints shrink or enlarge, with the result that most joint sealers will permit the entrance of some water after a short period of service. In addition, the asphalt-paved shoulders tend to separate from the edges of the traveled lanes, and it is quite difficult to maintain the longitudinal edge joint in a desired impervious condition.

In the case of asphalt concrete pavements, the natural permeability of the materials, porous zones at longitudinal joints, and subsequent cracking caused by aging, overflexing, or thermal changes can permit the entry of surface waters into the pavement structural section. The following tabulations (Tables 1, 2, and 3) indicate the range of hydraulic conductivity of cracks, joints, and pavement materials as determined by laboratory and field tests.

Table 1

Percolation and Air Permeability of Emulsified Asphalt Open Graded Mixes and Overlays*

Mix No.	Thickness (in.)	Density (lbs/ft^3)	Gradation Percent Passing 1"	3/8"	#8	#200	Percolation (ft/day)	Air Permeability (cm^3/min)
6	8	106	100	61	17	3	480	3,160
10	3	110	100	82	25	4	435	2,850
12	2	117	100	64	17	4	107	700
13	2	115	100	60	20	5	135	880
13	2	122	100	60	20	5	295	1,930

*Design and Construction of Emulsified Asphalt Open Graded Mixes and Overlays, Chevron Asphalt Company, Emeryville, California

Table 2
Permeability of
Asphalt Concrete Pavements

New Pavements

Source of Information	k (in./hr)
Kari & Santucci (US 101)[x]	75
Kari & Santucci (US 101 - left wheel path)[x]	23
Kari & Santucci (US 101 - between left & right wheel path)[x]	45
Kari & Santucci (US 101 - right wheel path)[x]	30
Cedergren	50
Reichert (Lessines, Belgium)	78
California Division of Highways Specifications	20

[x]Air Permeability

Old Pavements

Source of Information	k (in./hr)
Baxter & Sawyer (laboratory tests)	0.0001
Tomita (USNCEL, laboratory tests)	3.00
Breen (University of Connecticut - traffic lane)	0.75
Breen (University of Connecticut - shoulder)	2.25
Reichert (Lessines, Belgium)	3.50
South Africa (cracked surfaces)	1.00

Table 3
Runoff into Surface Cracks
Portland Cement Concrete Pavements*
(Precipitation Intensity - 2 inches/hour)

Crack Width (inches)	Pavement Slope (percent)	Percentage of 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

*Research by University of Maryland (laboratory test data)

The high rates of inflow given in Table 3 would apply to cracks that have no obstructions at the bottom side. In actual pavements, the rates of flow would probably be less when the cracks and the cavities under them became filled with water.

Shoulders generally are not designed to withstand as heavy a traffic load as the pavement proper. However, they often have to sustain a considerable number of heavy load repetitions, and this loading can cause cracking. Water then can infiltrate through these cracks into the structural section to saturate the materials and create an excess water condition. This condition occurs particularly in the right shoulder of a highway and its junction with the right lane.

Depressed medians of divided highways will pond runoff for prolonged periods unless they are adequately drained. Installation of a few widely spaced outlets often does not provide effective drainage; and in many instances, lined ditches are required to drain the water rapidly from the median to decrease infiltration. This is particularly true of grassed medians because of the retarding effects of turf on water flow.

Surface runoff from paved surfaces may infiltrate into the ground in considerable amounts if the slope of the area adjacent to the paved surfaces is not in the order of 1-1/2 to 2 times the slope of the pavement. In general, the required slope for the adjacent area is met. However, in a few instances, either safety considerations or deficient maintenance procedures have been major factors in producing a water trap at the outside edge of a pavement, literally creating a "spreading ground" adjacent to the paved portion of the road. This allows water to stand for prolonged periods of time over the junction between the paved surface and the adjacent ground where it can infiltrate and spread beneath the pavement, increasing the moisture content of the structural section and the subgrade near the edge of the right lane. This condition is known as border effect. A similar type of condition often exists at the longitudinal joint between PCC pavements and AC shoulders.

3.4 Factors Preventing Drainage

It is an acknowledged fact that widely variable amounts of surface runoff can enter into pavement structural sections through various points (see Fig. 2). In some highways, the infiltrated water will be drained from the structural section in a relatively short time. However, in the majority of existing highways, drainage of the roadbed is very slow.

Water can remain trapped for prolonged periods within structural sections for several reasons: relatively impervious or slow draining materials used for construction of bases and subbases can inhibit drainage either within the traveled way or beneath the shoulders; improperly designed underdrain systems can have insufficient capabilities for removing water; poorly maintained underdrain systems can retard the flow of water; and a variety of other causes peculiar to individual sites can increase inflow rates or retard outflow rates.

The sluggish nature of drainage out of pavement structural sections is probably not well understood. To aid in giving an understanding of the nature of the problem, the following example is presented:

Example: Assume a three-lane pavement (half of a divided freeway with the three lanes of each half sloping in one direction) has a 0.5-ft thick open-graded base under the three 12-ft lanes, a 1-ft thick daylighted aggregate ballast shoulder at the outside edge, a very impermeable subgrade, and no pipe outlets. According to the data in Table 3, it might be possible for more than 70 percent of the rainwater that falls on a pavement to enter into the structural section through cracks or joints if they are not tightly sealed. In this example, assume that 40 percent of the rainfall can enter into the structural section. Then, how much total rainfall at the beginning of a rainy season would be needed to fill the open-graded base, and how much time would be needed for it to be drained out sufficiently to eliminate an essentially saturated condition?

Assuming a porosity of 30 percent for the open-graded base, the volume of voids per foot of roadway would be 0.3 x 0.5 x 36 ft or 5.4 cu ft.

For an assumed rainfall intensity of 1 in./hr, the inflow per foot of roadbed would be (1 in./hr/12)(36 ft) x 40 percent = 1.2 cu ft/hr. And the time required to fill the open-graded base would be 5.4 cu ft/1.2 = 4.5 hours. Thus, a rainfall of 1 in./hr for 4.5 hours, or a total of 4.5 inches of rainfall, would be sufficient to completely fill the open-graded base with water.

After the base becomes filled, how much time would be needed for the saturation level to be significantly lowered?

Assuming a 3-inch average lowering of the free water level is required to eliminate an essentially saturated condition, the volume of water needing to be removed would be 5.4 cu ft x 3 in./6 in. = 2.7 cu ft.

For the very impermeable subgrade condition assumed, all significant discharge of water is out through the daylighted aggregate ballast in the lower shoulder. Use Darcy's law to estimate the discharge rates for various coefficients of permeability of ballast material having a thickness of 1 foot, and an average hydraulic gradient of 1.5 ft/18 ft = 0.083. Then, the discharge rate is $\underline{kiA} = \underline{k}(1.5/18)(1.0) = 0.083\underline{k}$. For various coefficients of permeability of the shoulder ballast, the time for a 3-inch lowering of saturation in the open-graded base would be as shown in Table 4.

Table 4
Time Required for
Drainage through Shoulder

Shoulder k ft/day	Discharge per day, cu ft	Time required for 3-in. lowering of saturation in base
1	0.083	32 days
2	0.17	16 "
5	0.42	7 "
10	0.83	3 "
20	1.66	1.6 "

Materials normally used in shoulder construction seldom have coefficients of permeability greater than a few feet per day; hence, where pipe outlets are not provided, roadbeds can remain in an essentially saturated condition for long periods of time, even if highly permeable materials are placed within the lower part of the roadbed structural section.

There exists a considerable amount of literature on the subject of permeability of granular materials as well as on drainage properties of granular bases (see Appendix A, Literature Review Abstracts, Phase I - Final Technical Report). The types of materials normally utilized to construct pavement structural sections usually permit subdrainage but so slowly as to be relatively ineffective. The capability of any material placed in the structural section to contribute to proper drainage is only as good as the perviousness of the material.

It is suggested that relative terms or numerical values be used exclusively when describing the draining capabilities of materials used in highway construction. Any reference to the permeability of a given material should be in specific coefficients (i.e. ft/min, or ft/day) or stated relative to adjacent materials. Thus, one might say, "Less pervious materials often are used for the construction of bases and subbases of highways than for the pavement surface . . .", but should not say, ". . . pervious materials are sometimes used in the shoulders of highways . . .".

Figures 3 and 4, that follow, demonstrate the wide range of permeability of materials used in highway construction.

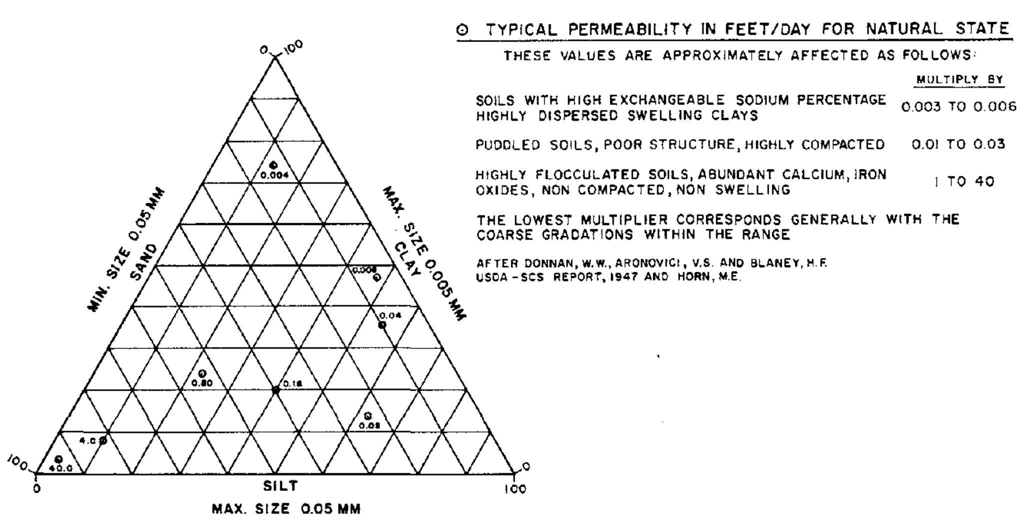
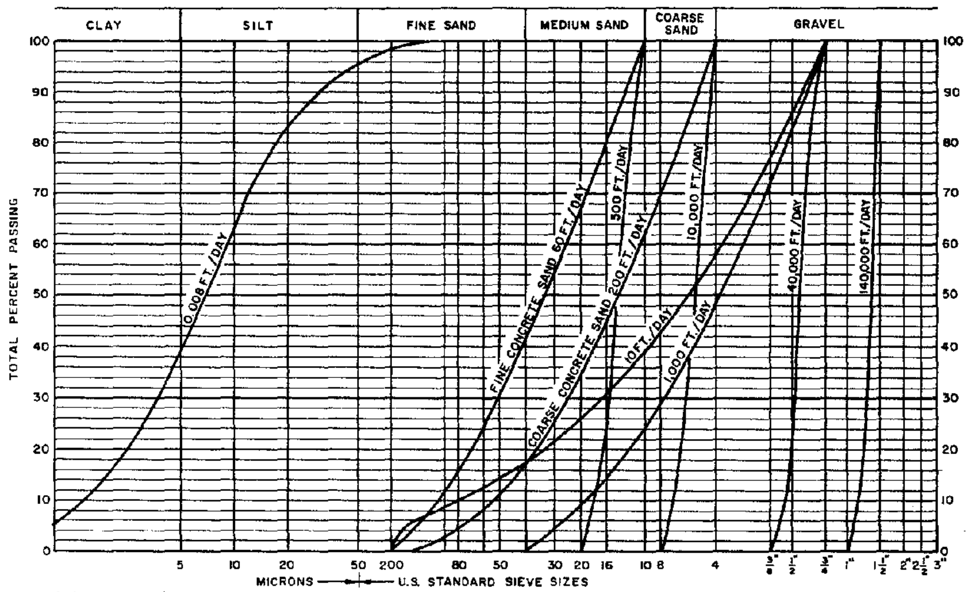


FIGURE NO.3
TYPICAL PERMEABILITY
RANGES FOR NATURAL SOILS

Where low permeability materials are used in the structural section, in shoulders, or in compacted subgrades, the actual discharge capabilities of the entire pavement section can be very low, and water that enters from surface infiltration or from any other source can be trapped and stored in all available spaces for long periods until drained by gravity (see Table 4).



NOTE: THE TOTAL RANGE OF PERMEABILITIES SHOWN IN THIS FIGURE IS APPROXIMATELY FROM 1 TO 20,000,000 TIMES

FIGURE NO. 4

TYPICAL PERMEABILITY RATES OF NATURAL AGGREGATES

Many of the underdrain systems constructed in the past have been somewhat functional but only partially effective because they drain so slowly. Although some drainage occurs, it may take so long as to permit new, infiltered water to replenish the supply before the last inflows have drained out. The type of system presented in this report and in the "Guidelines" will ensure the rapid drainage of water out of structural sections, and can eliminate problems with design details that tend to increase the amount of water that can accumulate in structural sections.

Things to avoid in design to eliminate the problems that occur with existing types of pavement-drainage systems are summarized here, some of which existed at all of the Case Study sites except Eureka.

Things to Avoid in Design:

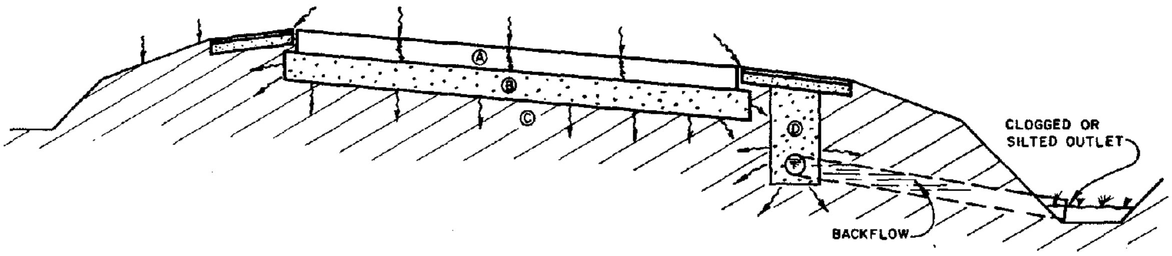
(1) Don't allow pavements to be built in trenches with no outlets to drain away the water that accumulates within the structural section.

(2) Don't overlook the need for pipe collectors and outlets. Where no outlet pipes are provided or they are allowed to become clogged with debris, grass, roots, silt, etc., the subsurface drainage system ceases to function and in effect becomes a water distribution system (or equalizing system) and spreads the supply of water along the trench or "bathtub".

(3) Avoid the construction of pavements which have obstructions to the free flow of water out of the roadbeds. These obstructions often exist in the form of discontinuous layers, and low permeability materials in shoulders or under the structural section, which in effect act as dams to obstruct flow both vertically and horizontally. Unfortunately, when longitudinal drains are installed, direct connection sometimes is not provided between the drain and the layers needing to be drained. Some examples of things to avoid are shown in Fig. 5. The edge drain in Fig. 5, for example, is separated from the base course by impermeable subgrade

material, and can assure literally no beneficial drainage of the structural section.

(4) Avoid locating outlet pipes so low in ditches that it is virtually impossible for maintenance crews to keep them unplugged. The outlet for the drain in Fig. 5 is too low, and its exit end can become completely blocked with silt and other debris.



NOTE: PERMEABILITY OF COLLECTOR TRENCH BACKFILL D > PERMEABILITY OF PAVEMENT A > PERMEABILITY OF BASE COURSE B > PERMEABILITY OF SUBGRADE C >

WATER IS STORED IN BASE COURSE B AND IN THE INTERFACES A/B AND B/C.

FIGURE NO. 5

AN INEFFECTIVE SUBSURFACE DRAINAGE SYSTEM (TYPICAL)

When the flow of water out of a structural section is blocked by any of the above conditions, a head builds up sufficient to cause the flow of water out through surface joints and cracks, or other exits. Not only does this blockage of drainage lead to many conditions detrimental to pavement life, but it is especially critical where the subgrade soils are swelling clays.

Only when the hydraulic conductivity of the different components in a pavement structural section increases substantially toward a suitable outlet can subsurface drainage be considered effective. Methods for designing effective systems and for determining the required conductivities of the different parts of drainage systems of roads are described in this report and in the "Guidelines".

3.5 Effects of Excessive Water

3.5.1 General Discussion

Water that is trapped in a pavement structural section can have many different effects on the materials in the section. The subgrade, subbase, or base can become saturated, lowering the effective weight and strength of the materials, and free water can fill the interstices between layers of different materials and be displaced under dynamic load impacts. The movement of water under load impacts can erode the materials of the structural section. Also, there is evidence that the pulsating surges of pore pressures building up and diminishing under wheel loads may disintegrate stabilized bases. At the California Case Study site, for example, the cement treated base under the interior of an uncracked PCC slab in the right-hand lane was so friable it could be removed with the fingers. In addition, frost action in structural sections can occur only when free water is available.

Design formulas for both PCC and AC pavements make the assumption that pavement and base layers are able to spread the loads through successively lower layers in such a manner that the strain or pressure at any level does not exceed the strain or compressive strength allowed for the particular material at that level. If water accumulates in structural sections to the point where free water is present, the normal load spreading assumptions are no longer valid as intergranular pressures are largely nullified. As a consequence, external traffic loads on structural sections in which excessive water is present introduce deviations to the otherwise considered normal assumptions for design and also modify the behavior and performance of the pavement systems.

One of the most significant deviations to normal design assumptions occurs when the pavement structural section components contain excess water in joints, cracks, and void spaces. If water is permitted to infiltrate into the structural section and no effective drainage is provided, then the base and subbase materials act as reservoirs and sources of water supply to prolong the detrimental actions that occur. Some of the kinds of actions that take place in structural sections containing excessive water are described in the following paragraphs.

While the pavement is unloaded (or intermittently traffic-impacted), the base and subbase become saturated by the water infiltrating from the surface through cracks, etc., and all the voids eventually become filled with water as the air in the voids is displaced, as shown on Fig. 6.

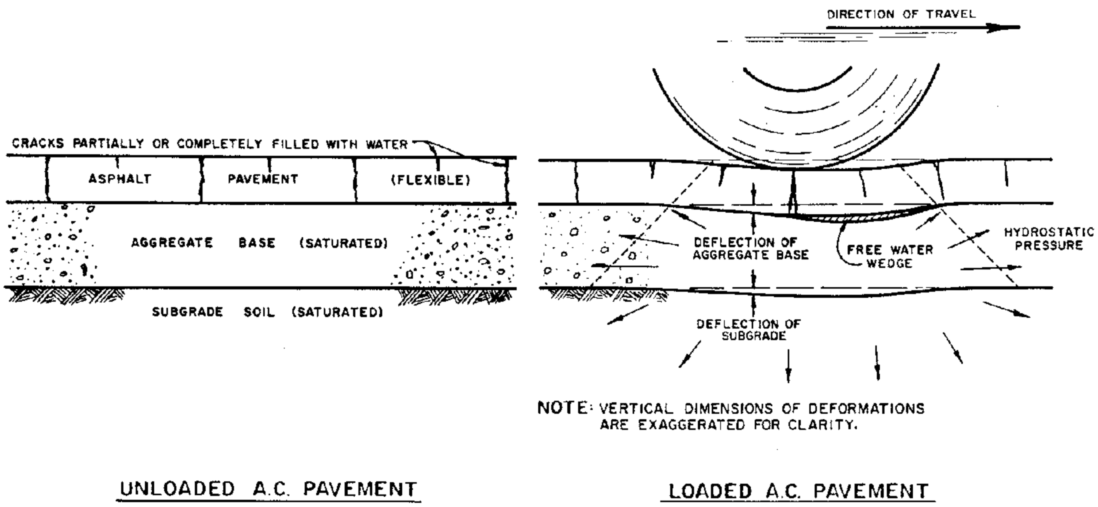


FIGURE NO. 6

ACTION OF FREE WATER IN
AC PAVEMENT STRUCTURAL SECTIONS
UNDER DYNAMIC LOADING

When heavy wheel loads (dynamic) are imposed on the pavement surface, the loading is transmitted through the successive layers of the structural section until it reaches the foundation subgrade soil (saturated). The foundation soil will tend to compress slightly under load; this compression will reduce the void spaces, slightly increasing the density of the soil. Minute amounts of water are forced out and temporarily become free water. The saturated subgrade material becomes temporarily supersaturated and high pore pressures can be developed (Ref. 6, 7, 8, 9, and 18). The degree to which this condition develops is dependent on the type of soil, its degree of compaction, the magnitude of the load, the number of load repetitions, and the stiffness of the structural section. It varies with the seasons and the aging of the pavement. Other factors which have not as yet been fully understood also have a contributing influence in the occurrence of this phenomenon (i.e., capillarity, hydrogenesis, etc.).

The moving pressure wave created by the dynamic action of the wheel loads on the pavement surface can create large hydrostatic forces within the structural section. Application of a force causes either a movement or a reaction. At least two different kinds of actions may occur when a pavement is subjected to dynamic pressure waves of heavy wheel loads. The most probable is forceful displacement of water within the structural section. The displaced water will often transport fines within the structural section and subgrade, affecting the gradation characteristics of various layers supporting the wheel loads. Often the void spaces in granular bases or subbases become filled with mud; consequently, the basic assumptions used in the design of the pavement system are modified because of the loss in supporting power (Ref. 10 and also Case Study Investigations).

Another type of action occurs at well defined interfaces between subgrades and bases or subbases when the adhesion at the interfaces is negligible. It occurs only when free water is present to act like a wedge to create a "slick" layer, similar to that found in rock faults, and which is highly susceptible to disintegration. Even though the thickness of the water layer may be only a small fraction of an inch, its rapid movement under pressure often amplifies the deflection of the pavement surface under dynamic loading.

Since water is practically incompressible, large hydrostatic pressures can develop where there is no escape available. Hydrostatic pressures are transmitted equally in all directions; the only reaction to the vertical pressure thrust is the weight of the pavement section above a given level. Any increase in deflection that occurs when the pavement loses support because of erosion of bases or rapid water displacement certainly is a potential factor in decreasing the useful life of the pavement system through larger magnitudes of stresses and accelerated fatigue accompanying them.

A common design assumption is that the various layers of materials in the road structural section are homogeneous and continuous. This assumption is not entirely true in many cases. The discontinuities in pavement surfaces (cracks) and in the bases and subbases (interstices, differences in relative permeability, etc.) usually act as reservoirs or barriers to hold and trap water for a time after surface runoff has subsided. When the pavement is deflected by the action of heavy moving wheel loads, these cracks and interstices tend to alternately widen and close, thus ejecting miniscule quantities of water or mud under pressure. Repetitive actions of this kind can lead to the stripping of asphalt from aggregates that have been stabilized with asphalt cement, destroy cohesion, and contribute to shrinkage cracking of AC pavements.

In some instances, the structural sections of existing pavements contain base materials that are of lower permeability than the asphalt concrete surfacing, and this combination is usually detrimental to the pavement system. Water which penetrates through the asphalt concrete surfacing tends to accumulate at the interface between the pavement course and the base. When this happens, the conditions are quite similar to those described in the preceding paragraphs, but more serious because the weight reacting against the vertical hydrostatic pressure caused by heavy moving wheel loads (or gravitational head) is only that of the asphalt concrete surface layer. As a consequence, water pockets may form at the interface and lift the pavement several inches before the water is released.

3.5.2 Factors Contributing to Pumping

Whenever water and dissolved matter or suspended matter are forced out of pavements under traffic impacts, the behavior is called "pumping", or "surging". In the Field Reconnaissance part of this project a limited number of asphalt concrete pavements showed unmistakable signs of pumping, although it is most commonly associated with Portland cement concrete pavements. The severity of pumping of PCC pavements is related to the design. Those with normal joints are most susceptible; those with effective load transfer devices that reduce elastic deflections are least susceptible. Pumping to some degree is practically unavoidable where effective subsurface drainage of the structural section is not provided. It cannot occur unless free water is present within the structural section. Some of the primary actions involved in the pumping of PCC pavements are described in the following paragraphs and shown on Fig. 7.

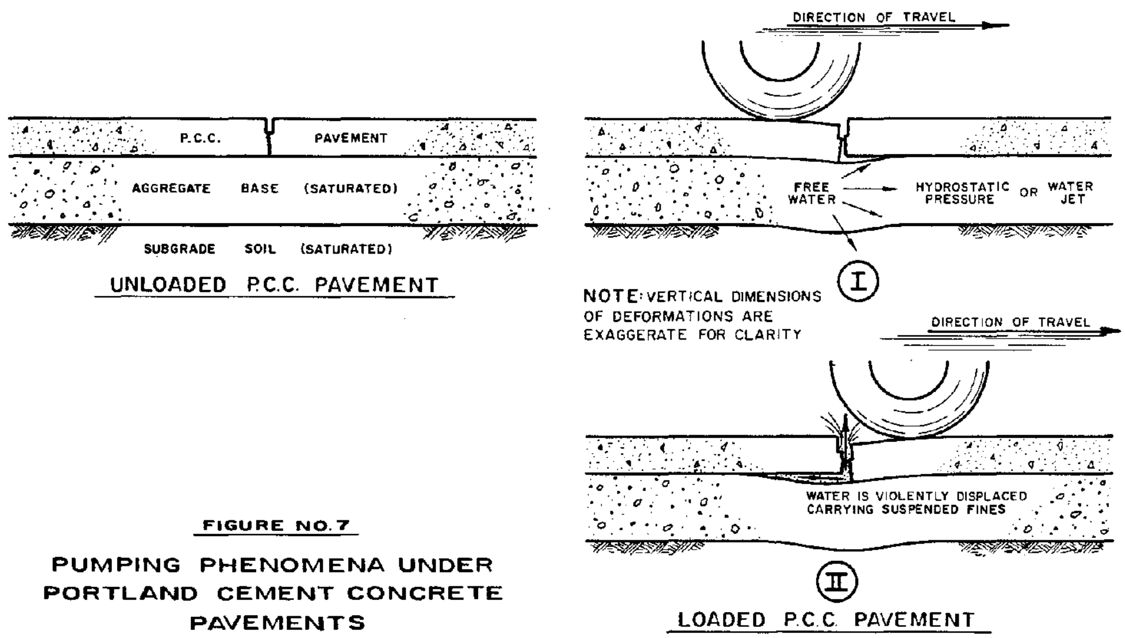


FIGURE NO. 7

PUMPING PHENOMENA UNDER PORTLAND CEMENT CONCRETE PAVEMENTS

Before any erosion or differential compaction of the base has occurred, spaces can exist under joints because of vertical, upward curl of the concrete slabs at joints, caused by temperature differences between the bottom and top of PCC slabs (see sketch of unloaded PCC pavement in Fig. 7). Then, traffic loads--with or without free water present--may create additional spaces between the pavement and underlying base, subbase or subgrade because of compaction or plastic deformation of the underlying materials. When free water is present, a heavy wheel load approaching a joint (see sketch I, Fig. 7) presses the trailing edge of the slab downward, sending a hydrostatic pressure wave or jet in a forward direction. After the wheel passes over the joint, the trailing slab bounces up as the leading edge of the next slab is pressed down (see sketch II, Fig. 7). The net result in situations like this is cavitation under leading edges and a buildup of material under trailing edges. The movements of free water and suspended fines caused by the deflections of the contiguous Portland cement concrete slabs on either side of a joint or crack are illustrated diagrammatically in Fig. 7.

When pavements are new the amounts of the movements and the spaces under the pavements may be very small, but the high pressure water has enormous erosional power and progressively pumps out more and more material, sometimes leaving PCC pavements entirely unsupported for appreciable distances.

As material is eroded out from under leading edges by pumping, and some is deposited under trailing edges, a very noticeable step-off occurs at the joints. This phenomenon is known as faulting. It can be very disconcerting to motorists and to truck drivers. It amplifies the impacts on the pavements, and often leads to severe break up of pavements (Ref. 10). A secondary factor that can increase the magnitude of faulting is differential consolidation of bases under PCC pavements.

Extensive pumping of Portland cement concrete pavements unavoidably leads to either faulting or failure of the pavements because of cracking. The sequence leading to failure has been extensively investigated over the past several decades and numerous reports have been written on this subject (see Section 4, Appendix A, Literature Review Abstracts, Phase I - Final Technical Report).

The use of load transfer dowels at the transverse joints reduces the seriousness of pumping by reducing deflections. Also, the use of continuously reinforced Portland cement concrete pavement usually eliminates all but edge pumping, except where the slab steel has broken at some cracks. Edge pumping is not critical except under unusual circumstances. And, continuously reinforced concrete pavements were found to pump only half as much as conventional pavements with plain joints (Ref. 12).

3.5.3 Excess Water and Frost Action

All types of pavements and shoulders are vulnerable to damage caused by frost action. In order for frost action to occur, water must be available; therefore, the relatively rapid drainage of most of the free water from a pavement structural section (probably within 15 to 20 minutes) would greatly increase the possibility of extending the useful life of many pavements. Most of the damage caused to pavements by frost action can be related to heaving caused by the formation of ice lenses, and to the release of excess water when the ice melts.

As in the case of pumping, a considerable amount of investigative effort has been dedicated to the explanation of the phenomena related to frost, and extensive literature on the subject is available (see Section 14, Appendix A, Literature Review Abstracts, Phase I - Final Technical Report; and Ref. 13, 14).

3.6 Damage Evaluation

Although considerable information has been gathered or developed concerning the performance of all types of pavements under various axle loads and loading patterns from full scale road tests, relatively little data have been obtained to establish correlations between presence of water in pavement structural sections, rainfall occurrence, and rate of deterioration of the pavement system.

Examination of records from the AASHO Test Road, the WASHO Test Road and the Road Test One--MD, however, provide indications that correlations may exist. The correlation patterns are evident for long observation periods, and they appear sufficiently valid to draw general conclusions. Unfortunately, no known road test has incorporated any well drained test pavement systems. Hence, it is necessary to analyze performance data for dry and wet seasons. This approach can be used for existing highways as well as for experimental road tests, and offers a sound basis for analyzing the relative damages occurring with free water present and with no free water in the structural sections. If adequate records of pavement condition, maintenance and replacement costs, or other indexes of serviceability were being kept in relation to wet and dry conditions, there would be no better way to assess rates of damage. Unfortunately, little such information seems to be recorded for highways.

Detailed records of damage or condition were kept for several road tests, such as the AASHO Test Road, the WASHO Test Road and Road Test One--MD, as previously noted. In addition, very useful and interesting information about the effects of excess water was obtained by Barenberg and Thompson, as noted in 1.4 (see Ref. 22).

Reports of the AASHO and WASHO road tests indicate that when comparisons were made for short periods of time (the worst few days compared with the best periods), the damages during the times when excess water was present were hundreds to thousands of times greater than during dry periods. When comparisons were made over longer periods of time, the relative damages with free water present were often in the range of 10 to 20 times greater than when no free water was present. The results of tests made by Barenberg and Thompson, which were intended to simulate conditions in the AASHO Test Road, showed damages 100 to 200 times greater with free water present than when no free water was present in the structural sections.

Values derived from the tests described in the preceding paragraph provide the first quantitative measurement of the damaging effect of excess or free water in pavement structural sections; but it is evident that there is a need for road tests specifically designed to evaluate the benefits of rapid drainage of roadbeds. Close observation of some of the Case Study sites during the next 2 or 3 years may lead to interesting and valuable conclusions and help to provide new parameters to evaluate the performance of the pavements in quantitative terms in relation to the degree of drainability provided. The recommended Case Study sites to be observed are: Kneeland Hill Road, Humboldt County, California; I-79 near Edinboro, Pennsylvania; and I-44 near Sallisaw, Oklahoma.

4. SUMMARY OF CASE STUDY INVESTIGATIONS

4.1 General

The general procedure for the case study investigations was mentioned in 2.4, Case Studies. Detailed reports on the investigations and the findings are given in Case Study Investigations, Phase II - Development of Guidelines. Those reports contain plans, cross sections, drill hole logs, field and laboratory test data, photographs, and detailed descriptions of conditions observed at the sites. Brief descriptions of the sites and summaries of the findings are given in the following part of this report.

4.2 Connecticut Case Study

The Connecticut Case Study investigation was conducted in the northbound freeway lanes of Interstate Highway 91, approximately 10 miles north of New Haven, Connecticut. The area of the freeway investigated consisted of a 200-foot section downgrade from a railroad overpass. In the area of investigation, the pavement section consisted of 9 inches of Portland cement concrete with wire reinforcing and dowelled transverse joints, constructed on 6 inches of sandy clay base course. The embankment, approximately 15 feet high, was composed primarily of clayey sand with some silt and plastic clay materials at upper levels. The shoulders consisted of asphalt concrete surfacing constructed on a sandy type base. Although the highway pavement at the Case Study site was approximately 8 years old at the time of the investigation, the reinforced concrete pavement within the site was extremely distressed with numerous slabs cracked transversely; and asphalt patching had been required to replace broken slab areas (see Photograph No. 1).

Photograph No. 1 - Connecticut Case Study Site

Precipitation appeared to be the main source of water in this Case Study site, as during the field investigation it was noted that the base course material became saturated and free water flowed downhill between the bottom of the Portland cement concrete pavement and the top of the base course after a moderate shower. Extensive void spaces caused by erosion reduced the support for the pavement, thus contributing to the severe faulting and pavement "break up" of the right traffic pavement lane that had occurred. Low permeability of the base and top layers of the subgrade prevented effective drainage of the structural section, extending the length of time that free water remains in the section after every rainstorm.

4.3 California Case Study

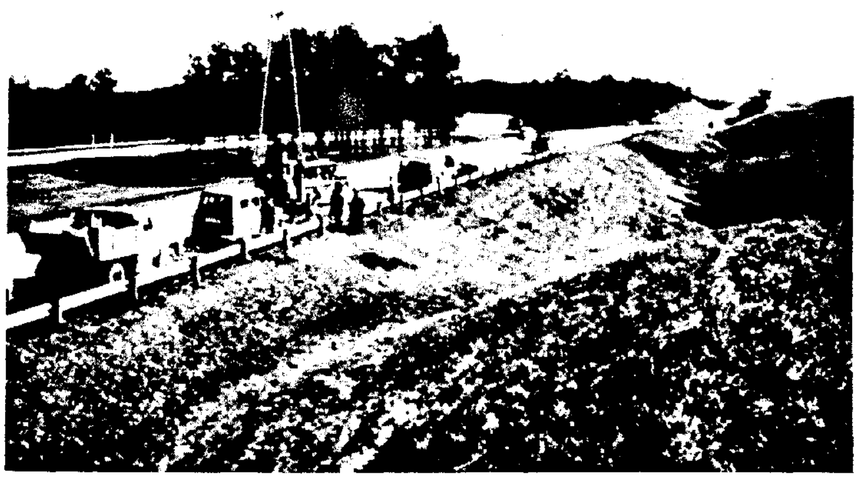
The California Case Study investigation was conducted in the westbound freeway lanes of Interstate Highway 80, approximately 6 miles south of the Carquinez Bridge near Vallejo, California. The area of investigation was in a 200-foot section of the westbound freeway lanes located near the center of a 60-foot high embankment. At the site, the pavement section consisted of 8 inches of undowelled and unreinforced Portland cement concrete over 2-1/2 to 3-1/2 inches of cement treated base. The embankment was composed of silty sand and clayey sand materials. The right lane of the Portland cement concrete pavement was badly faulted and the surface was cracked transversely across the approximate centers of a series of seven consecutive pavement slabs (see Photograph No. 2). An extensive amount of repair work had been required in the right traffic lanes of this highway, which was approximately 12 years old at the time of the Case Study investigation.

Photograph No. 2 - California Case Study Site

The faulting and other pavement distress was caused mainly by a combination of overloading and the action of free water within the pavement structural section. Surface water had entered the structural section through cracks and joints. The cement treated base in the right traffic lane (truck lane) was found to be friable, and entirely lacking in cohesive strength, possibly due to disintegrating actions of pulsating pore pressures. With the presence of free water between the cement treated base and the Portland cement concrete slab, channels and voids had developed by erosion due to the dynamic loading of heavily loaded trucks. The loss of support caused the Portland cement concrete slabs to crack and "break-up". The other lanes were essentially free of cracks; hence it appeared that temperature shrinkage cracking was not a significant factor at the site.

4.4 Georgia Case Study

The Georgia Case Study investigation was conducted in the northbound lanes of Interstate Highway 85, 2.9 miles north of Suwanee Road overpass and approximately 22 miles northeast of Atlanta, Georgia (see Photograph No. 3).



Photograph No. 3 - Georgia Case Study Site

The area investigated consisted of two lanes of Portland cement concrete pavement constructed on a 25-foot high fill section composed of clayey sand and silty sand that contained mica. At the test site, the pavement section consisted of

9 inches of Portland cement concrete placed over approximately 3 inches of plant-mixed bituminous stabilized subbase and 5 inches of plant-mixed soil stabilized subbase. Except for dowelling in the longitudinal and transverse construction joints, the pavement was not reinforced. The shoulders were paved with 1 to 1-1/2 inches of asphalt concrete. The Portland cement concrete pavement had faulted in the Case Study site area and adjacent areas. At the test site, the surface of the right pavement lane had cracked transversely with random patterns, and the bituminous stabilized subbase had been severely stripped.

Faulting and pumping of the Portland cement concrete pavements on this highway had been detected as early as 8 months after it was opened to traffic. It appeared that the pavement distress at this location was caused by conditions originating within the structural section, and it was apparent that surface drainage had entered the pavement structural section through joints and cracks. Because of the low permeability subbase material, the water that entered the structural section could not drain laterally and essentially remained trapped in the bituminous stabilized subbase materials. The hydrodynamic actions under heavy wheel loads gradually eroded and stripped the subbase materials, causing a loss of support of the pavement slabs.

4.5 Oklahoma Case Study

The Oklahoma Case Study investigation was conducted in the eastbound lanes of Interstate Highway 40, immediately east of the Cedar Creek Bridge which is approximately 1 mile south of Sallisaw, Oklahoma. The highway section investigated consisted of asphalt concrete pavement beginning at the east abutment of the Cedar Creek overpass and extending easterly approximately 1,250 feet (see Photograph No. 4). At the

Photograph No. 4 - Oklahoma Case Study Site

test site, the pavement section consisted of 1-1/2 inches of asphalt concrete surfacing, 3-1/2 inches of asphalt concrete base, 7 inches of black base course, and a select silty sand/clayey sand fill ranging in thickness from 12 to 54 inches. The shoulder consisted of 12 inches of asphalt concrete base course and black base course constructed on the select fill material. The highway pavement was approximately 4 years old at the time of investigation. This Case Study site was selected because of the distressed condition of the right pavement lane that was located on a fill section and included a sag point. Both wheel paths in the right traffic lane were severely cracked in longitudinal irregular patterns. Similar distress cracking patterns were noted at other locations not within the Case Study site.

The pavement distress seemed to be caused by the action of surface water which had infiltrated into the pavement structural section. Core holes and edge trenching showed that free water was standing in the asphalt treated base from the subbase to within three inches of the surface at some locations. When trenches were excavated at the outside edge of the shoulder of the right pavement lane, considerable quantities of water flowed from the asphalt treated base and black base course materials, indicating that water was trapped within the structural section.

The geometrics of the highway at the Case Study site eliminated the possibility of high ground water or lateral seepage from adjacent areas. Observations and tests indicated that the pavement structural section was constructed of low permeability materials so that in effect, the pavement is in a "bathtub" for long periods after heavy rains.

Water infiltrating into the sloping structural section was trapped and produced excess hydrostatic pressures at lower elevations in the sag of the vertical curve at the test site. The confined conditions allowed "artesian" pressures to build up within the roadway structural section.

At this Case Study location, the early deterioration of the asphalt concrete pavement can also be related to climatology. The area is subjected to temperature variations from $0^{o}F$ to $100^{o}F$, and the pavements are exposed to freezing temperatures during the winter, with precipitation in excess of 2 inches occurring during the months of December and January. Freezing and thawing of water entrapped within cracks and joints in the pavement structural section is believed to have contributed to the development of extensive longitudinal cracks in the wheel paths of the right traffic lanes. The authors feel that the cracking may be associated with freezing and the subsequent development of high pressures caused by ice expansion and the forces produced by heavy truck wheel loads.

4.6 Washington Case Study

The Washington Case Study investigation was conducted in the westbound lanes of State Highway 536, approximately 6 miles east of the town of Anacortes, Washington. The area investigated consisted of an embankment section beginning at the east abutment of a railroad overcrossing and extending

526 feet easterly (see Photograph No. 5). At the railroad

Photograph No. 5 - Washington Case Study Site

overcrossing the embankment was more than 30 feet high. The Case Study section was located on the high side of a superelevated horizontal curve with a downgrade of approximately 5 percent, and where the lower edge of the pavement cross section was adjacent to the median. The highway pavement structural section consisted of 3 inches of asphalt concrete placed in two layers, 6 inches of cement treated base, 2 inches of crushed surfacing top course, and approximately 10 inches of special granular borrow over relatively impermeable fill material.

Shoulders at the study site consisted of 2-1/2 inches of bituminous treated crushed surfacing top course and approximately 20 inches of special granular borrow. The highway pavement at the site, which was approximately 7 years old at the time of the investigation, was distressed and contained a combination of alligator and transverse cracks occurring in the right traffic lane of the westbound lanes. These distress patterns were concentrated within the truck traffic lane and were located at the high side of the pavement cross section.

The pavement distress occurring at the Case Study site can be explained as follows. The cement treated base, which evidently had a relatively high unconfined compressive strength, had cracked in a typical type of pattern (transverse cracking at intervals of 10 to 40 feet). The bond between the CTB and the asphalt pavement was broken and numerous voids at the interface were generated. The cracking that occurred in the CTB eventually reflected in the 3-inch layer of asphalt pavement and provided points of entry for surface water runoff. Water entering the cracks flowed directly downward into the crushed surfacing top course and special granular borrow, or after filling the vertical cracks, infiltered laterally into the voids at the interface of the pavement and CTB. The presence of water in the voids along the interface was a contributing cause of the general deterioration and the alligator cracking. Hydrostatic pressures under the weight of heavy traffic loads were created.

4.7 Eureka Case Study

The Eureka, California Case Study investigation was conducted in an experimental section constructed by the Humboldt County Public Works Department to test the feasibility of placing a highly permeable drainage layer under the full width of a road. After two prior failures, in just a few years, of conventionally designed pavements at this site, it was reconstructed in 1967 using a roadway structural section of 2-1/2 inches of asphalt concrete surfacing, 6 to 9 inches of aggregate base, 4-1/2 inches to 8 inches of gravel subbase, 8 inches of open-graded asphalt concrete drain material and 4 inches of filter material on the subgrade. A perforated metal pipe was installed as a transverse drain at the midpoint.

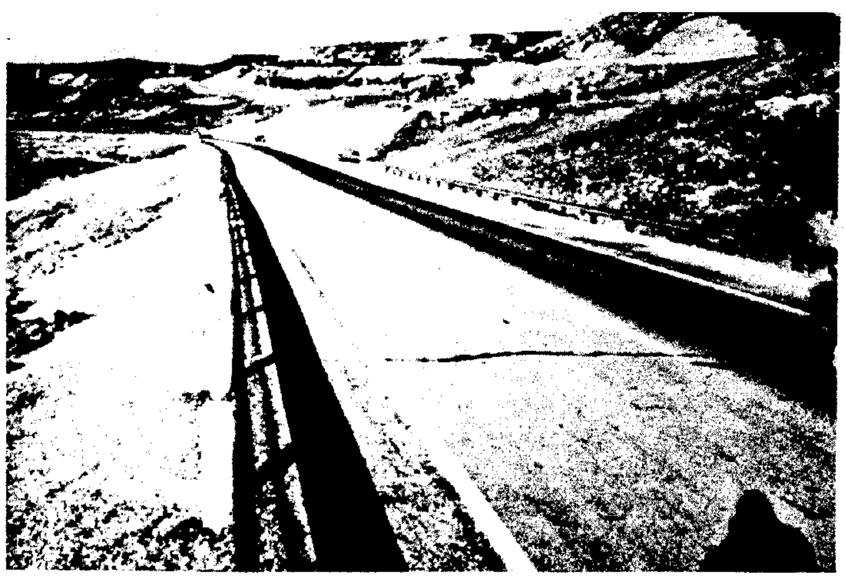
This Case Study site is situated within a section of two-lane asphalt concrete, on a County road, approximately 15 miles southeast of the town of Arcata. Geometrically located on a curved section of superelevated road with a 6.5 percent grade, the outside pavement edge of the descending lane is higher in elevation than the roadway centerline and the outside edge of the ascending lane. Rainfall in the area is in the range of 40 to 80 inches per year; and there was evidence of excessive ground water seepage at the site (see Photograph No. 6 for a general view of the site).

Photograph No. 6 - Eureka Case Study Site

Although the pavements beyond both ends of the 300-foot experimental section were severely distressed in both traffic lanes, the pavement within the experimental section was in excellent condition and showed no evidence of rutting, cracking, or shoving. Not a single, visible crack or other sign of distress could be found even though heavily loaded logging trucks frequently use the road. In contrast with these excellent conditions, there was evidence of general distress, presence of excess water, and the effects of heavy truck loads both upgrade and downgrade from this section. When test holes were drilled into the structural section within this Case Study site, the base and subbase layers were unbelievably free of excess water, in marked contrast with the other Case Study sites which showed evidence of excessive water. In-place percolation tests indicated that the open-graded drainage layer has a permeability in the range of 10,000 to 30,000 feet per day. Studies of the relative drainability of the various Case Study sites show that the Eureka (Humboldt County) site can drain hundreds to thousands of times faster (see Table 5, Section 4.11) than the conventionally designed roads.

4.8 Utah Case Study

The Utah Case Study site investigation was conducted in the westbound traffic lanes of Interstate Highway 80, approximately 9 miles west of the Utah-Wyoming State line near the town of Evanston, Wyoming (see Photograph No. 7). The area



Photograph No. 7 - Utah Case Study Site

investigated consisted of two asphalt concrete pavement lanes, 550 feet in length, with a grade of approximately minus 3 percent in the direction of travel (west). The entire Case Study was an embankment section that had been reconstructed approximately 2 years before the investigation.

Transverse cracks at the Utah Case Study site would lead an observer to conclude that the 1-1/2 inch to 2-inch thick asphalt concrete pavement had been reconstructed over a cement treated base, as the adjoining highway sections exhibiting similar cracking were constructed with a cement treated base. However, the investigation showed that the base course was 8 to 10 inches of asphalt concrete base course over a gravel base course which varies from 0 to 16 inches in thickness.

The pavement surface contained numerous irregularly spaced transverse cracks (generally 50 to 100 feet apart) extending through both traffic lanes. The transverse cracks ranged from 1/4 to 3/4 inch in width and generally extended across the traffic lanes and included the asphalt shoulders on both sides of the roadway. Longitudinal and alligator cracks occurred in both traffic lanes. Similar pavement distress occurred throughout adjacent portions of the Interstate Highway, both east and west of the site.

The subsurface investigation did not disclose an excess of water in the pavement structural section and therefore it was concluded that the primary cause of distress was probably not due to surface water infiltrating into the pavement section but instead to other factors. A combination of low temperature environment plus loss of rheological properties of the asphalt pavement are considered more likely to be the primary causes of the transverse cracking. Research of pavement cracking phenomenon similar to that which occurred at the Utah site has been individually conducted by the Universities of Connecticut, California, Massachusetts Institute of Technology; and the Universities of Alberta and Waterloo, Canada.

4.9 Pennsylvania Case Study

The Pennsylvania Case Study investigation was conducted in the northbound lanes of Interstate Highway 79, approximately 1 mile south of its junction with State Highway 6N near Edinboro, Pennsylvania. The area investigated was about 400 feet in length consisting of two lanes of Portland cement concrete. The highway pavement structural section consisted of 9-3/4 to 10-1/2 inches of dowelled Portland cement concrete constructed on 7-1/4 to 9-1/4 inches of gravel subbase. The subgrade was composed of a silty sand. The shoulders had 4 inches of asphalt concrete on 14 inches of gravel stabilized subbase. A 6-inch diameter perforated metal pipe subdrain had been constructed approximately 1-1/2 feet outside the right pavement shoulder edge and joint. At the time of the Case Study field investigation, the pavement was 2-1/2 years old (see Photograph No. 8).

Photograph No. 8 - Pennsylvania Case Study Site

Within the Case Study site location, there were only occasional distress cracks, although evidence of pumping was noted at several junctions of the pavement-shoulder edge joint and the transverse pavement joints. A significant separation existed between the edge of the Portland cement pavement and the asphalt concrete shoulder.

The field investigation revealed the presence of water in the pavement structural section, and early signs of pumping were observed in the Portland cement concrete pavement. Algae growth at one of the underdrain outlets indicates the presence of water at this location for a long period of time. Joints and cracks were sufficiently open to admit surface water. Slow draining materials used in the structural section have essentially created a "bathtub" for extended periods after each precipitation period. Although the pavement was relatively undistressed, the evidence of continuous moisture at joints, and fine materials being deposited on the pavement surface may be signs of early stages of pumping and future faulting.

4.10 Michigan Case Study

The Michigan Case Study was conducted in the two southbound lanes of Interstate Highway 196, approximately 5 miles north of its intersection with Interstate Highway 94 and 6 miles south of Coloma. The area of investigation, which was approximately 6 years old at the time of the investigation, began approximately 900 feet south of a concrete overpass structure and extended approximately 500 feet in a southerly direction. The pavement structural section consisted of 4-1/2 to 5 inches of asphalt concrete and 7-1/2 to 11-1/2 inches of aggregate subbase. The embankment was composed of a homogeneous fine to medium sand of relatively high permeability. At the site, the asphalt concrete pavement was severely distressed and had irregularly spaced (average about 6 to 12-inch spacing) alligator cracks and a continuous series of longitudinal cracks and rutting along the roadway centerline. The right pavement lane showed more distress (cracking) than the left pavement lane (see Photograph No. 9).

Photograph No. 9 - Michigan Case Study Site

The sandy embankment material under this road had a relatively high permeability, which made it difficult to relate the cause of pavement distress to excess water. The field investigation and subsequent laboratory tests on materials obtained at the site did not provide many clues as to the cause of the trouble. However, analyses of environmental phenomena revealed the following factors that are believed to be responsible for the pavement distress.

The maximum variation of temperatures recorded in the last 30 years in the Case Study site area is minus 19°F to 109°F. Temperatures are below 32°F a number of times each winter. The freezing index for the Case Study area is in the range of 600 degree-days. The hourly intensity of rainfall will reach 1.30 inches about once every 2 years. Normal rainfall for the area is approximately 31 inches per year, snowfall totals 34 inches per year, and the depth of frost penetration is 2 to 3 feet. During warm weather there probably is no problem as it is believed that the precipitation infiltrates through the cracked asphalt pavement surface and is rapidly dissipated into the sandy fill embankment. However, when the ground temperatures are below freezing, water that infiltrates to the subbase and sandy fill embankment freezes, and alternating freezing and thawing cycles can cause the build-up of free water in the structural section.

At low temperatures, the water introduced into the roadbed remains as ice during the winter season and may or may not damage the pavement from heaving. As the temperatures rise in the spring, the reverse process occurs. During the warmer periods, ice entrapped in the upper layers of the structural section melts, but the water cannot drain downward because of the still frozen condition of the lower layers. Some lateral drainage takes place above the frozen sand, but the permeability of the sandy material, while undoubtedly satisfactory for vertical drainage, is too low to permit the water to drain laterally in a relatively short period of time. Thus, hydrodynamic forces under the action of heavy wheel loads can develop within the pavement structural section while it contains free water. While this explanation is somewhat hypothetical, it is felt that it is compatible with the behavior of the pavements at the site.

4.11 Relative Drainability of Case Study Sites

As noted in the above summaries and described in more detail in the section of the Final Report, Case Study Investigations, Phase II - Development of Guidelines, all of the Case Study sites had pavements constructed with "standard" types of pavement and base layers, except the Eureka (Humboldt County, California) site, which was selected because it had been constructed on a full-width, highly permeable, open-graded base course connected with an outlet pipe. Water problems in varying degree had been experienced at all of the sites, except the Eureka site. The damages that had been occurring at most of the State Highway sites were ascribed to the slowness of the drainage of the roadbeds at these sites. On the other hand, the exceptionally good condition of the County Highway site was attributed to its unusually fast drainability. A basic conclusion from the Case Study investigation is that rapidly drained roadbeds are vastly superior to poorly drained roadbeds, and will suffer considerably less damage.

To compare the relative drainability of the various Case Study sites, estimates were made of the time required for excess water to drain out of the structural sections after it stops raining (see Table 5). Taking into account all available permeability and soil properties data and the physical conditions at each site, approximate calculations were made with Darcy's law to estimate the length of time after a rainstorm the structural section would remain essentially saturated (see second column, Table 5). The basis for estimating the times for drainage was the assumption that a total volume of water equivalent to 0.01 ft of water over an entire pavement area has to drain away before free water is substantially drained from the cracks, joints, spaces at interfaces, and pore spaces in the upper levels of the structural sections.

The theoretically calculated times for all of the State sites were multiplied by estimated factors less than 1.0 to try to allow for all beneficial drainage considered possible at each site, including water pumped out by passing trucks, flow along joints, etc. Thus, the estimated amounts of time in Table 5 for the State sites are all less than the theoretically calculated values using subgrade permeabilities. Although the times given in Table 5 may be somewhat approximate, it is felt that the <u>relative</u> amounts of time give a conservative basis for comparing the one site with "rapid drainage" with the sites having "slow drainage". Thus (see third column, Table 5), it seems reasonable to conclude that seven of the State Highway sites will remain essentially saturated

Table 5

Estimated Length of Time Structural Section Remains Essentially Saturated after It Stops Raining

Case Study	Estimated Time, Days	Relative Time (Eureka = 1)	Special Notes
California	20	2000	Section is on 50-60 ft high clayey sand embankment
Connecticut	15	1500	Section is on low side of superelevated curve; clayey subgrade layers over sandy fill
Eureka (Humboldt Co. Calif.)	0.01	1	Has highly permeable drainage layer under full width of traveled way, with an outlet pipe
Georgia	12	1200	Section is on clayey sand-silty sand fill; crushed aggregate subbase is blocked by soil on fill slope
Michigan	0.2 (unfrozen) Infinite (frozen)	20 Infinite	Section is on sand fill; subbase is daylighted; subbase and top of subgrade become frozen at times during winter
Oklahoma	15	1500	Has black base which is not directly drained; section is on clayey sand fill
Pennsylvania	12	1200	Section is on silty sand fill; has 6-inch diameter underdrain pipe under subbase, which is also daylighted
Utah	8	800	Section is on clayey sand fill; base course is daylighted
Washington	5	500	Section is on high side of superelevated curve; has 2-inch thick porous subbase which is not daylighted; is on silty sand-clayey sand fill

hundreds to thousands of times longer than the Humboldt County Highway site (Eureka). The Michigan site, on a clean sand fill which evidently drains quite rapidly under normal conditions, can be completely non-draining during periods of cold weather when it becomes frozen; hence this is a special case.

5. DESIGN OF SUBSURFACE DRAINAGE SYSTEMS

5.1 General

The basic objective of subsurface drainage systems for highway pavement structural sections is to prevent or greatly reduce both in quantity and duration the presence of free or excess water in roadbeds. The subsurface drainage systems, as considered in this report, are concerned primarily with surface waters that infiltrate through pavement surfaces into the highway structural sections, although the design method can make allowances for free water from any and all sources.

In the past, subsurface drainage systems for pavement structural sections have been concerned primarily with ground water, and other underground sources; but there is considerable evidence that surface waters often are the primary if not the only significant source of water in pavements. For this reason, it is frequently not possible to make any major distinction between subsurface drainage requirements of roads constructed on fills or in cuts (except for the additive effects of high ground water, springs, seepage, etc. for roads constructed in cuts).

The appearance of cracks and other openings that allow inflow of water are largely unpredictable (except joints in Portland cement concrete pavement); hence, the only completely positive manner in which to protect roadbeds from damage caused by free or excess water is to provide full width, rapid subsurface drainage of the entire roadbed. Although these systems can rapidly remove free water from structural sections, they cannot remove retained or absorbed water (such as that held in capillary suspension), as these forms of water can be removed only by application of external physical forces.

Two basic approaches are available to reduce the harmful effects of water that is available to infiltrate into pavement structural sections. The first involves improving the surface runoff areas by reducing the effective permeability of the pavement surface and increasing the cross slope. The second provides the necessary subsurface drainage systems (as outlined in the "Guidelines") to convey the water out of the roadbed within a reasonably short period of time.

Only limited improvements of surface drainage can be obtained by steepening the cross slopes because there are geometric limitations imposed by highway design criteria (such as safety requirements, and limits in areas subjected to icy pavement conditions). And, as previously stated in this report, no instances were found during the Field Reconnaissance or Case Study investigations to substantiate the assumption that pavement surfaces, either asphalt concrete or Portland cement concrete, can be made permanently impervious to infiltration of surface water. Cracks, joints, and construction imperfections eventually allow substantial amounts of water to infiltrate into the pavement structural sections. As stated in 1.5, Current Road Design Problems the water that gets into roadbeds can greatly shorten pavement life. Consequently, the second approach--that of providing the necessary subsurface drainage systems as outlined in the "Guidelines"--is judged to be superior to the first because it is based on realistic considerations.

5.2 Subsurface Drainage Systems Analysis

During the search for a suitable subsurface drainage system, some basic principles were developed to provide preliminary guidelines for the design of such systems. These principles recognize the fact that the amount of water which can infiltrate through any type of pavement is difficult to predict and generally depends on many variables such as road geometry, type of asphalt concrete mix, type of Portland cement concrete joint construction, environmental conditions at the time of construction, type of shoulder material, traffic volumes, quality of control during construction, precipitation, and many other factors. Because of the difficulty of accurately predicting the amounts of water that can enter pavement structural sections, subsurface drainage systems should be designed to have large water-removing capabilities, rather than minuscule capabilities. Some large-capacity systems may cost no more than small-capacity systems.

In recognition of these facts, the Guidelines for the

Design of Subsurface Drainage systems for Highway Pavement Structural Sections , developed in this project, presents a design method that makes exact knowledge of the effective permeabilities of pavements relatively unimportant. By this method, subsurface drainage systems are designed for estimated maximum probable rates of inflow that can enter into pavement structural sections from all possible sources. Surface infiltrations are estimated by multiplying a "design precipitation rate" by a factor somewhat less than unity. To allow for inherent inaccuracies in estimating inflows through pavements, the minimum <u>required</u> conductivities of drainage layers are multiplied by a factor of safety of 4 or 5. The method produces designs having inherently large water-removing capacities. When this method is used, the determination of accurate inflow rates for subsurface drainage systems is much less critical than for systems having small capacities such as those in widespread usage at the present time. Nevertheless, knowledge of the effective permeability can be of value in narrowing down the discharge requirements of subsurface drainage systems.

Research workers in Europe use the term "global permeability" ($\underline{k_g}$) to represent the average or effective permeability of a given pavement area, including not only the intrinsic permeability of the surfacing material, but also the discontinuities such as joints, cracks, and any other openings of whatever nature that allow water to enter the structural section.

Because of the diversity of variables, it is necessary to use a probabilistic rather than a deterministic method to evaluate the amount of infiltration through most pavement surfaces. Although the intrinsic permeability of a pavement surface material can be tested in the laboratory, the global permeability of a pavement cannot. To experimentally determine the permeability of any material, it is necessary to measure the volume of water that goes through that material under a known amount of head loss. With most pavements, the head losses and volumes of water going through large areas cannot be measured; hence probabilistic methods must be used. This can be an arduous and difficult task. But, if pavements are constructed on highly permeable, open-graded bases with pipe outlets, as advocated in the "Guidelines", outflows from known amounts of pavement areas can be measured directly, both during and periodically after heavy rainstorms. In effect, the systems are large permeameters. By making such measurements at various times, it is possible to determine variations in global permeability with age and type of pavement, type and condition of joint fillers, and all other factors influencing rates of infiltration into pavements. This information would aid designers in making realistic estimates of the quantities of surface water having to be removed by subsurface drainage systems.

Historically, granular bases and subbases have been advocated for roads because of economical structural characteristics. Although these materials may offer good structural support for pavements, they often act more in the manner of a reservoir than a drainage layer as intended by designers. Sands and sand-gravel blends do not provide an effective capillarity break or even good drainage. The movement of infiltrated water in such layers, from a point directly beneath the crown or high side of a road to a suitable drainage outlet located at the lower pavement edge, can be extremely slow, often requiring weeks. The Field Reconnaissance and Case Studies have shown that the use of bases and subbases constructed of sands and sand-gravel blends is not only inefficient from the drainage standpoint, but can be deleterious by retaining water for long periods of time.

Observation of the performance behavior of a few existing truly open-graded bases, even in instances where they were not designed to act as subsurface drains, clearly indicates their potential for subsurface drainage systems. Previous investigations have indicated the advantages of utilizing open-graded aggregates to construct self-draining bases. The results of the Case Study Investigation at the Humboldt County, California, site indicated that bituminous coated, open-graded bases have the ability to rapidly drain structural sections and support traffic loads (see 4.7, Eureka Case Study). The design concepts for subsurface drainage systems advocated in this report are based on the use of open-graded aggregate bases that can be either untreated or stabilized with bituminous materials.

The need to protect roads against infiltration of water into pavement structural sections is well recognized by Highway Engineers when the sources of water are known to be active springs, ground water, capillary water or floodwater. However, protection against precipitation and snow melt is seldom provided. To include these inflow sources, the rational approach to the design of subsurface drainage systems proposed in this report can be expressed mathematically in the form of a general equation:

$$\Sigma O \geqq \Sigma I \qquad (1)$$

where, I = all sources of water inflow
O = water outflow capability

Equation 1 can also be written as:

$$O_E + O_S + O_P + O_D \geqq I_s + I_c + I_T + I_H \qquad (2)$$

where, O_E = surface evaporation
O_S = loss by lateral seepage
O_P = loss by vertical percolation
O_D = water removal by subsurface drainage
I_s = surface infiltration

I_C = capillary water from water table

I_T = water transfer from adjacent wet areas or from underlying ground water

I_H = hydrogenesis

Under normal circumstances, the terms $\underline{I_H}$, $\underline{O_E}$, and $\underline{O_S}$ can be neglected. The term $\underline{I_T}$ is dependent on the subgrade material, soil profiles, ground water occurrence, road geometry, and existence of manmade water sources; and in the majority of cases, its numerical value is small when compared to $\underline{I_s}$. However, it should be carefully evaluated before a decision is made concerning its consideration in the treatment of the design problem. Capillary water, $\underline{I_C}$, is not drainable, but it does contribute to the saturation of the subgrade. The term $\underline{O_P}$ depends on the vertical permeability and depth of subgrade material and the depth to the water table. As with $\underline{I_C}$ and $\underline{I_T}$ careful consideration should be given to $\underline{O_P}$ before excluding its effect from the design problem; and where it is significant it should be included. In addition, it is of particular importance to recognize the possible effects of frost action in reducing the permeability of the subgrade (see 4.10, Michigan Case Study). A simplified equation for drainage of surface infiltration only, can now be written as

$$O_D \geqq I_s \tag{3}$$

which states that the amount of water removed by a subsurface drainage system should be larger than the surface infiltration.

It is suggested that a safety coefficient C be introduced to reflect the possible inaccuracy of the probabilistic approach. Equation 1 thus becomes

$$\Sigma O \geqq C \Sigma I \tag{4}$$

And, Equation 3 becomes

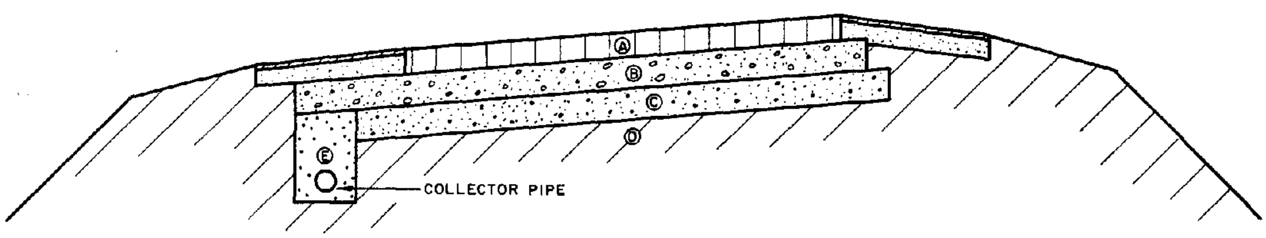
$$O_D \geqq C I_s \tag{5}$$

The numerical value to be assigned to C depends on the reliability of the data available for design but should not be less than 4 or 5 in any case. Although this seems like a large safety factor, subsurface drainage systems can have built-in apparent safety coefficients of 10 or more at little or no more cost than systems having safety coefficients considerably less than unity.

The preceding rational approach is based on the premise that a subsurface drainage system cannot adequately protect a structural section unless the hydraulic conductivity of the various components of the system increases, starting at the pavement surface and progressing to the outlet. Any restrictions or blockages at the outlet or exit regions can render subsurface drainage systems ineffective and can even be detrimental.

There are two fundamental requirements of drainage layers in roadbeds: (1) The design of the drainage layer should be based primarily on its ability to convey a certain rate of water flow (calculated peak flow) without developing harmful hydrostatic head (free surface flow). (2) The gradations of the drainage layer aggregates should be related to the gradations of the subgrade soils to prevent soil migration into and through the drainage system. If necessary, filter layers should be provided between drainage layers and subgrade soils to satisfy filter requirements and prevent soil migration (basic filter requirements are discussed under 5.4.2, Perforated or Slotted Pipes).

On the basis of the studies conducted in this project, it has been concluded that the optimum location for a subsurface drainage layer is directly beneath the primary pavement layer, whether it be asphalt concrete or Portland cement concrete (see Fig. 8). Therefore, it is important that the



NOTE: USE FILTER CLOTH WHEN NECESSARY TO PREVENT SAND, SILT, UNCONSOLIDATED CLAY, SOFT SHALE, ETC FROM CLOGGING THE COLLECTOR TRENCH BACKFILL.

- Ⓐ PAVEMENT LAYER
- Ⓑ DRAINAGE LAYER
- Ⓒ SUBBASE MATERIAL
- Ⓓ SUBGRADE SOIL
- Ⓔ TRENCH BACKFILL

FIGURE NO. 8

SUBSURFACE DRAINAGE SYSTEM CONCEPT

drainage layer (permeable base) have sufficient stability and durability to support traffic loads without compacting or deteriorating; only strong, durable aggregates should be used in these layers.

In a study of the "optimum" properties of granular drainage layers, Dr. Hans Winterkorn (Highway Research Record No. 203, 1967, pages 1-7) uses granulometric principles to evaluate physical properties such as permeability and strength of various kinds of granular mixtures. Dr. Winterkorn emphasizes that "in drainage systems, the primary concern is the rate of flow of water", and "the size of the pores and hence the component particles should be as large as possible" and "the compatibility of these conclusions must be checked with the required mechanical strength properties of the system."

Dr. Winterkorn states, "The bearing capacity of such systems (noncohesive granular systems) may be defined as their ability to resist single and repeated loadings without rupture or excessive deformation including volume change by internal readjustment or consolidation."

In discussing systems of two, three and more components of different sizes up to the so-called continuous gradation, as employed in concrete technology and soil stabilization, Dr. Winterkorn concluded that "the obvious lesson for granular drainage structures is the use of single-sized coarse aggregate of maximum feasible dimensions to be protected externally by suitable filter layers."

Dr. Winterkorn's overall conclusion is that "Evaluation of available practical and theoretical information on the permeability and strength properties of granular systems makes it clear that these properties can be optimized by using the largest feasible aggregate of single size or very narrow size range. The aggregate should be of sufficient strength, toughness, abrasion resistance and durability to retain its integrity under service conditions, and its packing should be such that no further densification will occur."

Dr. Winterkorn's observations have been widely proven by the service records of roads that have been constructed utilizing macadam types of aggregates. It is extremely fortunate that this type of material not only is an optimum type from the drainage standpoint, but also has good strength and serviceability properties. In the studies that were made for the development of the "Guidelines", cases were found where a very permeable open-graded asphalt concrete layer had given exceptional service although it was covered with less than an inch of dense-graded wearing material. Other references were found to cases where highly permeable open-graded asphalt concrete bases were still in excellent condition after several decades of service.

The exceptionally good drainage capabilities of single-sized aggregates are illustrated in Outflow Capabilities of

Drainage Layers, (Figure No. 8), Guidelines for the Design of Subsurface Drainage Systems for Highway Pavement Structural Sections. That chart shows, for example, a 3-inch thick, open-graded base having a permeability (k) of 10,000 feet per day has a drainage capacity about 200 times greater than that of a 12-inch thick layer of sand with a permeability (k) of 10 feet per day.

To be effective in draining structural sections, the open-graded drainage layers must be provided with adequate collector pipes and outlet pipes. Extension of the subsurface drainage layer to the exterior slope of the road section is a convenient way to provide an outlet for the drainage layer; however, it is not often advisable to construct a subsurface drainage system in this way. There are many reasons to avoid the daylighting of subsurface drainage layers in this manner, such as: (1) the drainage layer will be exposed to contamination from roadside materials that will reduce its hydraulic conductivity, (2) there is the possibility of the mechanical disruption of the drainage layer due to external forces, and (3) there is the possibility of freezing in some localities.

A more efficient subsurface drainage system can be developed by providing a means for the water to leave the structural section quickly and with a minimum head loss. Usually this can best be accomplished by utilizing perforated or slotted pipes to collect and convey the drained water to suitable outlet pipes. Normally, collector pipes can drain by gravity flow to low points along the road alignment, but in locations where gravity flow cannot be relied upon (such as at bridge underpasses and other depressed sections) sumps and pumping may be required.

The Interviews and Reconnaissance (Phase I) revealed a wide variety of types of perforated metal or slotted PVC pipes are in use for highway drainage. In any given area, the selection of a particular type of pipe should be based on local experience which is influenced by the chemical composition of the water to be drained; gradation, type and physical characteristics of the local subgrade soils; and economic considerations. In cold regions, the discharge ends of collector and outlet pipes may have to be enclosed in manholes or box structures to obtain as much protection as possible from freezing when water needs to be discharged during periods of cold weather.

A detailed analysis of the basic elements involved in the design of pavement subsurface drainage systems follows. The proposed design procedure is presented in the "Guidelines for the Design of Subsurface Drainage Systems for Highway Pavement Structural Sections", also called the "Guidelines" in this report.

5.3 Inflow Analysis

5.3.1 Sources of Water

There are a number of possible sources of free or excess water in pavement structural sections; but surface water--that which falls on pavements, shoulders, medians, etc.--offers an abundant and almost instantaneous supply, irrespective of whether or not the roadbeds are in cut or fill sections. The detailed investigations made in this study have indicated that most roadbeds behave similarly whether they are constructed in cut or in fill sections as far as the effects of surface water infiltration are concerned. Of course, portions of roadbeds in cut sections with active springs or high ground water, or with extraneous sources of water such as seepage from reservoirs and irrigation of areas adjacent to shoulders, have additional water problems. Various sources of water (springs, ground water, seepage, etc.) will combine with any surface water that enters through the pavement surface or along its edges to create possible detrimental effects on the structural section, unless drained.

In most cases, the main sources of water in pavement structural sections are surface infiltration ($\underline{I_s}$) from atmospheric precipitation and ground water ($\underline{I_T}$). Highway Engineers in general know how to cope with the problems caused by high ground water and are aware of the many methods available to eliminate this type of subdrainage problem. Appendix A, Literature Reviéw Abstracts, Phase I - Final Technical Report contains many references regarding subdrainage of ground water.

The subject of surface infiltration, however, is not generally understood nor has it been adequately analyzed. A thorough understanding of the mechanism of surface infiltration and the methods used to estimate the quantity of water that may infiltrate into a pavement structural section is essential for the design of subsurface drainage systems for pavement structural sections.

Although surface waters can enter essentially every highway pavement structural section, the significance of surface water as a prime source of water in roadbeds is not always recognized. During a precipitation event, pumping of joints or cracks and other hydraulic actions are not easily detected due to the profuseness of the water supply, but after the surface supply of water has drained away, the pumping phenomenon occurring at cracks and joints becomes very apparent. Frequently, it is possible to observe water being pumped from nearly every transverse joint or crack during the passage of heavy moving wheel loads. Sometimes the emergence of water will continue for several days or weeks with a small amount of water being physically forced out of the roadbed for each impact loading by heavy moving wheel loads.

Water that is pumped from new highway pavements generally contains little or no base or subbase materials; but as the cycles of pumping continue to occur, the erosional action within the pavement section may cause the transport of significant amounts of material with the pumped water. If fines or stabilizing materials such as cement are being eroded by the water, staining will usually be seen on the surface of the pavement and shoulder after drying. Often, fine material can be discerned in edge joints, and sometimes water carrying solids can be observed flowing out of cracks in pavements. The common step-off or faulting of pavements is a telltale sign of serious pumping of structural section materials (see 3.5, Effects of Excessive Water).

The quantity of surface infiltration depends on the rate of supply, ponding factors (or surface runoff factors), time of exposure and the global permeability of the pavement as defined in 5.2, Subsurface Drainage Systems Analysis.

Precipitation normally extends over areas that are large in comparison with roadway areas and can be considered constant for a given roadway surface. The numerical value of the global permeability of a pavement at a given time determines the maximum amount of surface infiltration that can enter a given roadway at that time. This concept can be expressed in mathematical form as follows:

$$I_s = P \leqq k_g \tag{6}$$

where, k_g = Global permeability of pavement
I_s = Surface infiltration
P = Rate of water supply

It is evident that the maximum inflow condition for which a subsurface drainage system needs to be designed is reached when $\underline{k_g}$ is equal to or greater than the amount of water that is available to enter into a pavement. Until such time as the State-of-the-Art permits dependable estimates to be made of global permeabilities, it is recommended that the subsurface drainage system design be based on an approach that utilizes a rainfall rate that will be exceeded only a small percentage of the time each year. The rate used in the method described in the "Guidelines" is the 1-hour duration, 1-year frequency rainfall; the method described should give the desired degree of protection to pavement structural sections, although modifications should be made when warranted by local conditions.

5.3.2 Inflow Water Paths

It is important to try to visualize the paths followed by the water infiltrating into the road structural section in order to find the most effective point of interception.

The possible points of entrance of water into structural sections are described in 3.3 and are shown graphically on Fig. 2 (page 22) for asphalt concrete and Portland cement concrete pavement sections. The tabulations on pages 23 and 24 give permeabilities of old and new asphalt concrete pavements, and runoff into surface cracks of Portland cement concrete pavement. Even well maintained pavements can absorb surprisingly large volumes of water which can be highly detrimental if not rapidly removed.

The infiltration of water into the pavement structural section is not uniform and follows the lines of least resistance, such as construction joints, minute fissures, and temperature and stress cracks in and through the pavement surface. Uncracked Portland cement concrete slabs between joints and cracks are considered to be impervious as are certain types of dense graded asphalt concrete mixes.

In the analysis of infiltration of water in special cases (i.e. unusual highway geometrics, proximity of structures that may concentrate water into road structural sections, short radii reverse curves, etc.), a simple inventory should be made of all possible entrance points.

Once free water has infiltrated into a structural section, it will flow by gravity toward the areas of lower elevation, such as sag-vertical curves, the low side of superelevated curves, and bridge approaches. It can build up artesian pressures when forced to flow under pavements for long distances on long, steep grades. Points such as these often are the first trouble spots on highways.

The general way that water can flow in pavement structural sections is illustrated in Fig. 9, following.

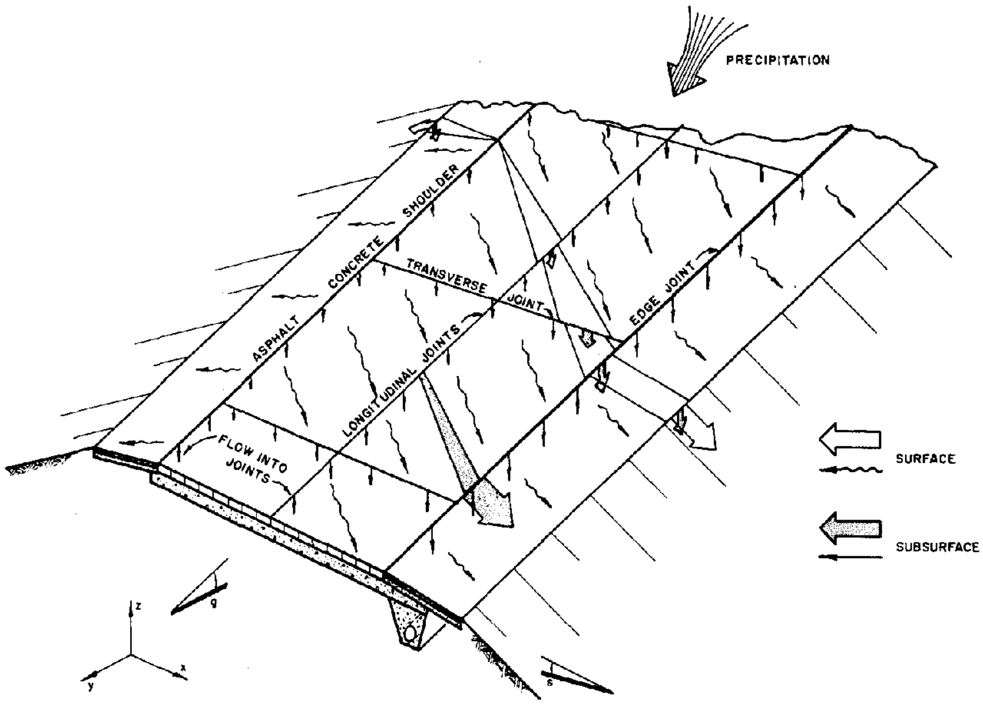


FIGURE NO. 9

PATHS OF FLOW OF SURFACE WATER IN PORTLAND CEMENT CONCRETE PAVEMENT STRUCTURAL SECTION

Movement of the subsurface water can take place through base or subbase materials if they are relatively permeable and, where the base or subbase is relatively impermeable, it flows through the voids created at the interface of two relatively different materials inadequately bonded together. The paths selected by the water and the quantities of flow will depend upon the hydraulic resistance of the various elements involved. It is evident that unless an interface void is of hairline dimensions, most of the water will tend to spread and flood the interface before it starts to percolate into the base or subbase materials. This phenomenon is accentuated when the base materials are dense and impervious.

The tendencies for concentrations of water problems at interfaces between pavements and bases provides one of the main justifications for the installation of drainage layers beneath the primary pavement layer (such as directly under PCC pavements) rather than beneath a stabilized base which can partially block the flow of water to the drainage layer. Another justification for placing the drainage layer under the primary pavement layer is the need to rapidly remove water before it can infiltrate into other structural layers.

Examples of the potential benefits of keeping the saturation level down within structural sections were seen at several of the sites investigated in this study; others have been observed at various places throughout the country. Cases of roads on superelevated curves have been noted where the lanes at the lower side of the superelevated curve were periodically being subjected to artesian pressures as evidenced by "bleeding" whereas the water level in the higher lanes only infrequently rose to the pavement surface. In one such case, although the "passing lane" was at the lower side, and had been subjected to only a small number of truck repetitions, it was severely damaged from excess water, whereas the "truck lane", on the high side of the curve, showed little or no pavement damage, demonstrating the benefits of lowering of the saturation level in the structural section only a few inches. A multitude of examples could be cited of pavements showing increased damage in areas where water completely fills the structural section appreciable amounts of time each year.

A common error to be avoided in the analysis of subsurface water movement is that of not combining the grade and cross slope of the structural section at the depth under consideration. The factors involved are detailed in Fig. 10.

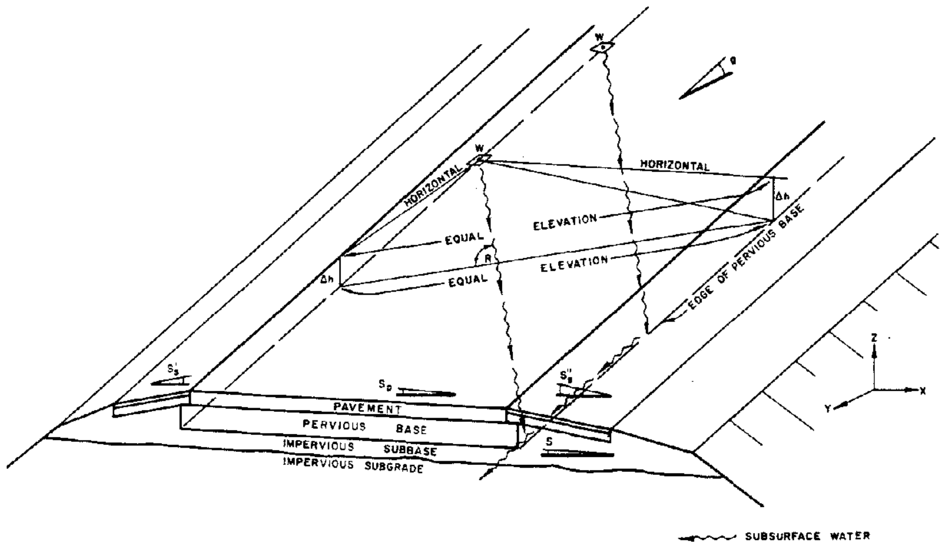


FIGURE NO. 10
PATHS OF SUBSURFACE WATER

If the longitudinal grade of the road at the surface is g, it can normally be assumed that the base, subbase, and subgrade will have the same grade; as the cross slope of the pavement surface, S_p, and the cross slope of the base, subbase, or subgrade surfaces are generally the same. The cross slope at an interface of two materials, the lower material being less pervious than the material about it, should be considered in the analysis of subsurface water movement. The cross slope at this plane is designated as s.

Elements of water entering the structural section at points called W tend to flow in a direction perpendicular to the lines of equal elevation that could be imaginarily traced on the flat surface. The flow lines will have a slope of i and will have the maximum possible drop in elevation between the point W and the lower edge of the pervious base as shown on Fig. 10.

The flow lines are perpendicular to the centerline of the highway when the grade is zero; they are at 45 degrees to the centerline when the grade equals the cross slope.

In hilly terrain, the flow paths in subsurface drainage layers should never be allowed to reach excessive lengths. To prevent this, it is recommended that cross drains be required wherever needed to prevent the flow paths from exceeding approximately 150 feet. For divided highways, this requirement will necessitate the use of cross drains (connected with longitudinal drains along the lower side of the roadway) approximately as follows:

Number of lanes in each direction	Steepest grade not requiring cross drains
2	5%
3	4%
4	3%

5.4 <u>Outflow Analysis</u>

5.4.1 Drainage Layers

Layers of granular material have been placed beneath pavement surfaces for many purposes.

Sandy or gravelly materials are often placed to serve as a structural layer; sometimes they are placed at the subbase level to protect the roadbed against heaving due to frost action. Sand blankets have been used to protect roadbeds against capillary action where the water table level is near the embankment subgrade, although as previously noted, sand is of limited value as a capillarity "break".

Coarse sand and sandy gravel layers are presently being used by a number of State Highway Departments for internal drainage of roadbeds, although their capabilities for this purpose are often very limited.

In a few isolated instances observed in the field reconnaissance, clean gravel, crushed rock or bituminous coated coarse aggregate had been placed beneath the pavement surface to serve as a structural layer to support the pavement. In most of these cases, these granular material layers were not provided with positive outlets, or the outlets had become plugged, and they served as "bathtubs" to store water; consequently the results have been disappointing to those who expected the granular drainage blanket to protect the pavement section against saturation.

Studies performed in Europe and reported by R. Van Ganse during 1967 (Ref. 15) have demonstrated that a sand drainage layer placed on top of a cohesive subgrade will supply water to the soil even if the water in the sand layer is not free water but is capillary water. Contrary to the widely accepted belief, the sand layer will not reduce the quantity of water that will infiltrate into the foundation material (subgrade soil), but instead will <u>increase</u> the quantity because the sand will act as a reservoir and continue to supply water to the subgrade soil between precipitation events (Ref. 15 and 16). This phenomenon is due partly to the soil having a high capillary potential in relation to the sand, plus high reservoir capacity and permeability of the sand.

It should be stressed that the foregoing analysis is of general application and includes sand layers provided with positive outlets as well as those having no outlets.

Although coarse aggregate materials are not often utilized as drainage layers, a few roads have been designed and constructed with such layers under the pavements as part of the structural section, as already noted. The State of Washington has used coarse aggregate materials beneath pavements or in shoulders for a number of years. Figure 11 indicates the typical gradations of these materials used in that State.

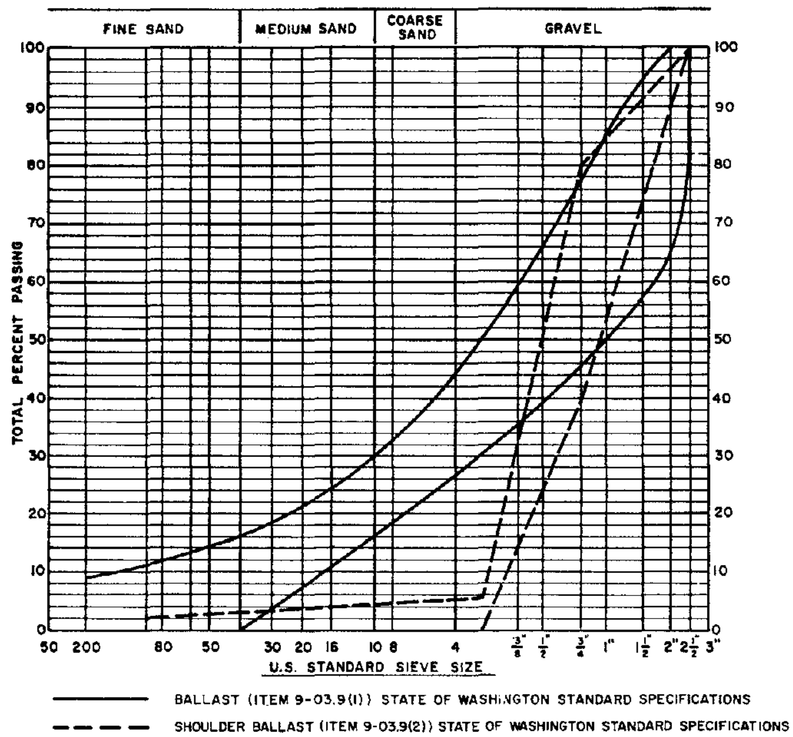


FIGURE NO. 11

GRADATION OF COARSE AGGREGATE MATERIALS
STATE OF WASHINGTON

Angular materials have very high stability in such layers; however, when non-angular, rounded aggregates must be used in roadbed drainage layers, they should generally be plant mixed with a hot, paving grade asphalt to ensure a high level of stability.

To prevent the clogging of these coarse, open-graded drainage layers by intrusion of fines from subbases and subgrades, attention should be given to the placing of suitable filter layers or utilizing overlying and underlying materials that have proper gradations to prevent such intrusion of fines into the drainage layer (see 5.4.2 for a discussion of filter criteria). When open-graded coarse aggregate materials are properly placed and protected from the intrusion of fines, these drainage layers are vastly superior to sand and sandy gravel layers for roadbed drainage (see also 5.2 and the "Guidelines").

It follows that the sensible approach with regard to subdrainage is to combine the best properties of both coarse and fine materials to develop optimum systems. Drainage layers consisting of open-graded coarse aggregate have been "sandwiched" between layers of specially processed filters of sandy material or structural layers satisfying the filter requirements of individual sites. The optimum combination of materials is a filter of minimum thickness to keep subgrade soil out of the drainage layer, and a drainage layer constructed of materials providing good stability and high permeability. A variety of filter cloths, meshes, woven felts, etc. are on the market and can be substituted for a sand filter layer; however, the cost of these types may be relatively high. Cost comparisons will establish the most economical solution in a given subsurface drainage design situation.

An alternative to the use of filter layers is the application of an asphalt penetration treatment to the subgrade prior to constructing the open-graded drainage layer. Also, if the subgrade has been subjected to suitable lime or cement stabilization treatments or dense graded aggregate bases or subbases which meet filter criteria are being used, it may not be necessary to place a filter layer between the subgrade and the open-graded layer.

Adequate stability of structural layers must always be assured. When required, open-graded, coarse aggregates with a low coefficient of uniformity and high permeability can be stabilized with asphalt cement. The Vermont, New York, Tennessee, and Indiana State Highway Departments have utilized open-graded, coarse aggregates that are stabilized with asphalt cement as base courses. These asphalt stabilized, open-graded, coarse aggregates have both sufficient stability and strength to serve as base courses and sufficient permeability to serve as drainage layers. Figure 12, that follows, indicates the

PERMEABILITY OF OPEN GRADED BASES

SYMBOL	—·—	— — —	———	—··—
STATE	VERMONT	TENNESSEE	NEW YORK	INDIANA
SPECIFICATION NO.	213	#2-308	45 SX	
GRADATION 3"	—	—	—	
2½"	—	—	—	
2"	—	100	—	
1½"	100	90	100	
1"	80	—	70	
¾"	61	61	—	
½"	45	—	28	
⅜"	—	—	—	
#4	20	12	13	
#8	13	—	6	
ASPHALT CONTENT %	3.5 − 4.5	3.0 − 4.0	2.0 − 4.2	
CORE PERMEABILITY FT./DAY	4,200 TO 5,500	3,000 TO 4,000	800 TO 950	

TESTS PREFORMED ON SAMPLES PROVIDED BY THE STATE HIGHWAY DEPARTMENT

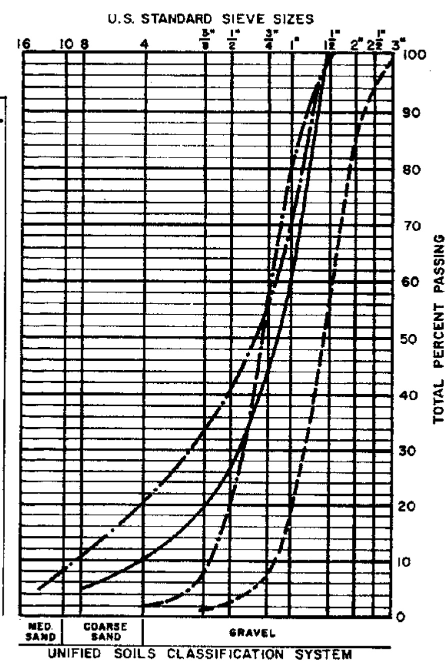


FIGURE NO. 12

TYPICAL GRADATION OF OPEN-GRADED BASE AGGREGATES

STATES OF VERMONT, TENNESSEE, NEW YORK AND INDIANA gradation of the above open-graded, coarse aggregates, the typical asphalt content used to stabilize the materials; and the resulting permeability of the stabilized base course.

Seepage analysis methods should be used to determine the thickness and permeability of an open-graded layer that will be sufficient to ensure a discharge capability exceeding the maximum predicted inflow with an appropriate safety coefficient (see "Guidelines"). To minimize construction control problems and to allow for some loss in permeability at the top and bottom of the open-graded drainage layer, a minimum thickness of 3 or 4 inches is recommended. The coarse layers must be protected from contamination by the use of suitable fine filters whenever they are placed on erodible, fine-grained soils. The decision concerning the minimum thickness of a subsurface drainage layer for a given project should be based upon technical as well as economical considerations. Where frost penetration is a factor, the total depth of drainage and filter layers may be governed by frost criteria.

Four important parameters that must be considered in designing the materials specifications for subsurface drainage layers are: stability, durability, permeability, and effective porosity.

As described elsewhere in this report, any materials placed within a structural section must have sufficient stability to withstand the traffic for which the road is designed. The permeability of the materials used will determine the minimum thickness of the drainage layer required and will control the velocity of the water flowing through the materials and the period of time it will take the water to drain from the structural section. Porosity influences the volume of water that will fill the pores in a given material, and the speed of flow of water in that material. Step-by-step procedures for analyzing the flow out of subsurface drainage systems are presented in 8.3.

5.4.2 Perforated or Slotted Pipes

Water conveyed by subdrainage layers toward the lower (generally outside) edge of the pavements must be collected and rapidly removed from the roadbed. The most efficient way to remove the collected water is to use a system of perforated or slotted, corrugated or smooth collector pipes placed in trenches alongside the edge of the pavement (with cross drains, where required, as explained in 5.3.2). The perforated or slotted collector pipe should be laid on filter material approximately 2 or 3 inches above the bottom of the trench, with the perforations or slots down. Collector pipes perforated or slotted for their entire periphery perform satisfactorily; however, in all instances, the perforation and slot widths must be sized to prevent intrusion of fines into the pipe in accordance with filter criteria. The respective locations of the proposed subdrainage system components are shown on Fig. 13.

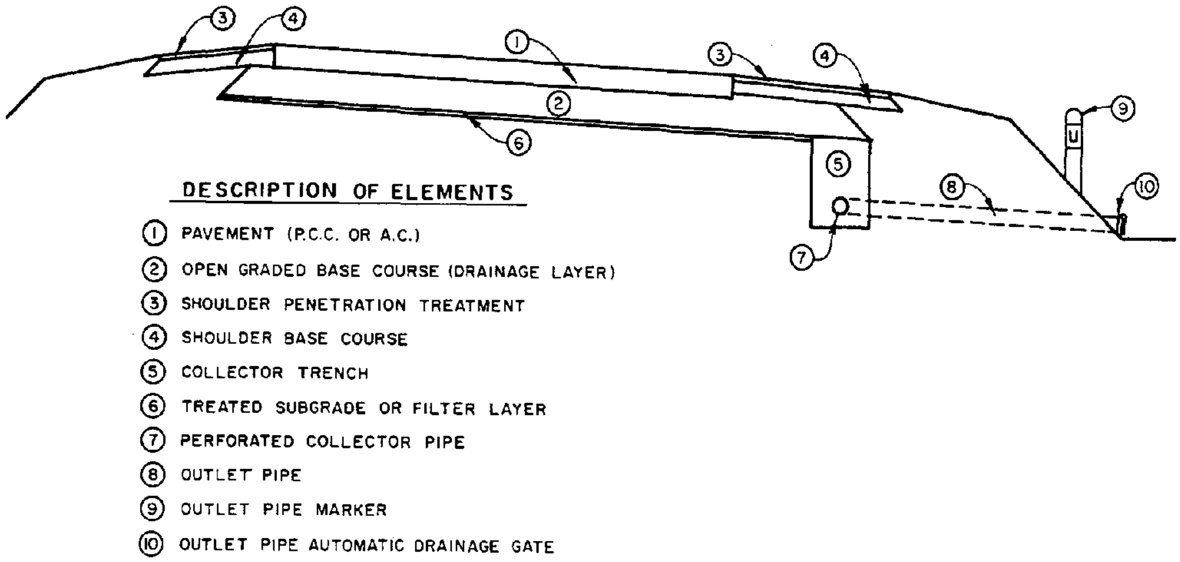


FIGURE NO. 13

RECOMMENDED SUBSURFACE DRAINAGE SYSTEM

The collector trench must be wide enough to permit installation of the pipe and must provide the hydraulic capacity (i.e. sufficient permeability of the material placed in the trench) required to convey water from the pervious base course to the perforated or slotted pipe. This hydraulic capacity is a function of the permeability of the filter material. In cold regions, collector pipes and outlet pipes should be placed as deep as practicable to minimize problems with freezing of water in the pipes.

Perforated or slotted collector pipe normally should be installed at a slope paralleling the grade of the road centerline, except that in no case should the slope of the pipe be less than 1 percent for smooth bore pipes and

2 percent for corrugated pipes.

There is a considerable amount and variety of criteria regarding the minimum diameter of perforated or slotted pipe that should be utilized in collector systems. The reasons given are extremely diverse. Evaluation of the existing criteria (both USA and foreign countries) seems to indicate that the majority of the designers fear a loss of waterway due to siltation. Siltation in a perforated or slotted underdrain can occur only if the material surrounding the pipe, or the perforations and slots do not comply with filter and compatibility criteria. Common objections to the use of relatively small diameter pipes are not usually justified. Perforated or slotted pipes should be dimensioned in the same manner that storm drain pipes are dimensioned. The rational approach to the design of pavement subsurface drainage systems excludes rule-of-thumb techniques. From a practical standpoint, however, it is desirable that a minimum diameter of 3 inches be adopted for slotted or perforated PVC pipes and 4 inches for all others.

The selection of a specific type of perforated or slotted pipe should be based on practical and economical considerations. Existing ASTM and AASHO specifications and manufacturer's design recommendations should be followed by the designer to make a proper selection based on soil conditions, loads, and durability requirements.

Two different granular materials may be required to backfill the trenches where perforated or slotted pipes have been installed. The filter material placed around the pipes should be compatible both with the diameter of the perforations and the gradation of the trench backfill material. The trench backfill material should be compatible with the adjoining subgrade embankment soils. Some applicable filter criteria that will prevent soil migration are summarized as follows:

For circular holes in pipes:

$$\frac{D_{85} \text{ size of filter material}}{\text{hole diameter}} > 1.0 \qquad (7)$$

For slots in pipes:

$$\frac{D_{85} \text{ size of filter material}}{\text{slot width}} > 1.2 \qquad (8)$$

To prevent the movement of particles from the protected soil into or through the filter or filters:

$$\frac{D_{15} \text{ size of filter material}}{D_{85} \text{ size of protected soil}} \leqq 5 \qquad (9)$$

$$\text{and} \quad \frac{D_{50} \text{ size of filter material}}{D_{50} \text{ size of protected soil}} \leqq 25 \qquad (10)$$

The foregoing filter criteria are applicable for the design of protection to layers of materials against intrusion of fines from other adjoining erodible types of materials. They were developed largely by G. E. Bertram, the U. S. Corps of Engineers, and the U. S. Bureau of Reclamation.

5.4.3 Outlets

Underdrain pipes can be either drained directly into roadside ditches or into clean-out boxes which can also double as junction boxes. The use of clean-out boxes is recommended where the highway subsurface drainage system is located in an urban or suburban area or where rapid urbanization is predicted.

If subsurface drainage systems are to drain into a common junction box with a storm drain, it is imperative that the flow line of the subsurface drainage system pipe be at least 6 inches higher than the maximum predicted water surface in the junction box to avoid storm water backing up into the subsurface drainage system. Subsurface drainage and storm drain systems should not be constructed in a common trench. But, if they must be constructed in a common trench, the subsurface drainage system pipe should be lower than the storm drain pipe to avoid subsurface drainage water flowing in the backfill of the storm drain pipe. In all such cases, gravity drainage from both pipes must be assured at all times.

The majority of the problems that interfere with the normal operation of properly designed and constructed subdrainage systems occur in the outlets. As previously stated in 3.4, a free draining outlet is absolutely necessary to ensure the efficient operation of the subdrainage system.

Outlets should be carefully located to eliminate the possibility of clogging and should be protected against intrusion of small animals. The outlet end of outlet pipes should be at least 12 inches above the flow line of the roadside drainage ditch and 6 inches above the base of the clean-out box, if utilized. Many State Highway Departments prevent small animals from crawling into outlet pipes by installing a wire mesh over the end of the outlet pipe. Unfortunately, the wire mesh cover tends to trap silt and debris; and in a short time, weed growth starts and often the outlet is completely blocked. An inexpensive flap gate, as shown in Fig. 14, is a better way to protect outlet pipe openings.

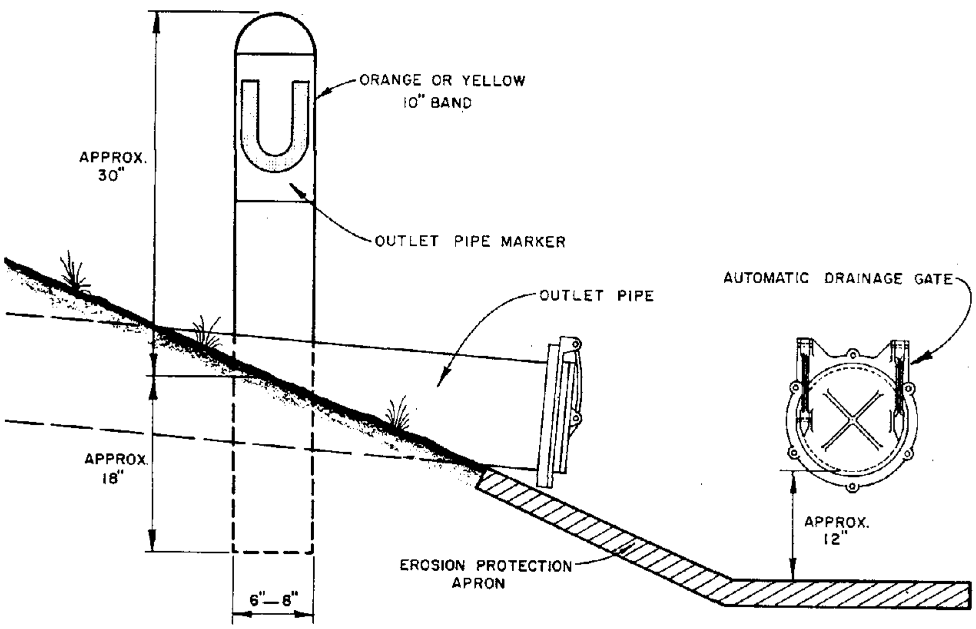


FIGURE NO.14

OUTLET PIPE AND MARKER

Locating outlet openings for maintenance purposes sometimes proves to be difficult because in many cases they become buried by debris, etc. To avoid accidental damage or blockage, outlet opening locations should be marked with a stake or post of suitable material and dimensions. If inadequate markers are used, they gradually disappear because they have insufficient size and strength to withstand the abuse received during roadside maintenance operations.

A most effective outlet opening identification marker is a 6- or 8-inch-diameter wood post, not less than 4 feet in length, embedded approximately 12 to 18 inches into the ground adjacent to the outlet (refer to Fig. 14). The post should be treated to resist termites in termite areas. In areas of ground freezing, a heavy wood post can become a safety hazard and the use of a weaker, yielding post is justified.

5.5 Related Factors

5.5.1 Freeze-Thaw Effects

Pavements become most vulnerable to degradation and loss of strength during the spring thaw. When air temperatures are above freezing for longer periods of time, the ice near the surface of the pavement is first melted. At that time, the highway pavement structural section is still frozen to some depth. Surface cracks in the pavement are open and permit water from the melting ice to infiltrate farther into the structural section. If the water in the base, subbase, subgrade and corresponding interfaces is still frozen, the water supplied by melted ice during the early stages of the thaw cannot escape except as surface runoff.

The thawing action proceeds from the exposed pavement surface to depth, and eventually all of the ice in the structural section is melted. Initially, melted ice on the pavement surface or in the cracks of the pavement remains as free water above the first interface, and is trapped because the base material is still frozen. Under the action of traffic loads, this water is pressurized because ice has filled all the voids of the base material and rendered it completely impervious. When melt water is trapped by underlying ice in the pavement, the phenomenon occurring is similar to that which takes place on low-permeability bases (see 3.5, Effects of Excessive Water), regardless of whether nonfrost susceptible materials have been used in the pavement structural section.

It is believed that the ice-barrier situation can be alleviated somewhat if an open-graded base is utilized beneath the pavement surface, although there is need for more performance information on this type of installation. By utilizing an open-graded base of high permeability, as proposed in the "Guidelines", infiltrated water can drain and leave the structural section before it can freeze.

In areas subject to long periods of freezing, precautions should be taken to assure the best possible performance of subsurface drains. Wherever possible, the collector pipes should be placed at a depth to exceed frost penetration, both vertically and horizontally; the outlet must be isolated from the collector trench backfill by utilizing native soil or other non-pervious material to backfill around the outlet pipe for the last portion of the outlet trench; the underdrain outlets must be placed above the elevation at which ice and snow may collect in the roadside ditches, if possible; and, the open-graded base should be protected against cold air drafts that may lower the temperature in this material below the freezing point before the infiltrated water has had time to drain. Outlet flaps are an important requirement for drains in cold regions as they will keep cold air out of the discharge ends of the pipes.

5.5.2 Highway Geometry

A thorough understanding of the principles governing subsurface water flow within highway pavement structural sections is required in order to analyze special cases involving subsurface drainage of complicated horizontal alignments, vertical alignments, and interchanges. The governing principle is that water always flows downhill and tends to follow the paths of least resistance.

Figure 15, on the following page, indicates the subsurface drainage for a superelevated curve to the left. Water infiltrating into the pavement section above the superelevated curve flows toward the right outside edge of the pavement. In the curved section, the low side of the pavement is on the left side; therefore, and depending on the grade of the highway, water will flow to the right side and then to the left, as shown on Fig. 15. Interception of the subsurface flow must be accomplished by a combination of interceptor drains and longitudinal drains, located as required to prevent the accumulation of water in the structural section.

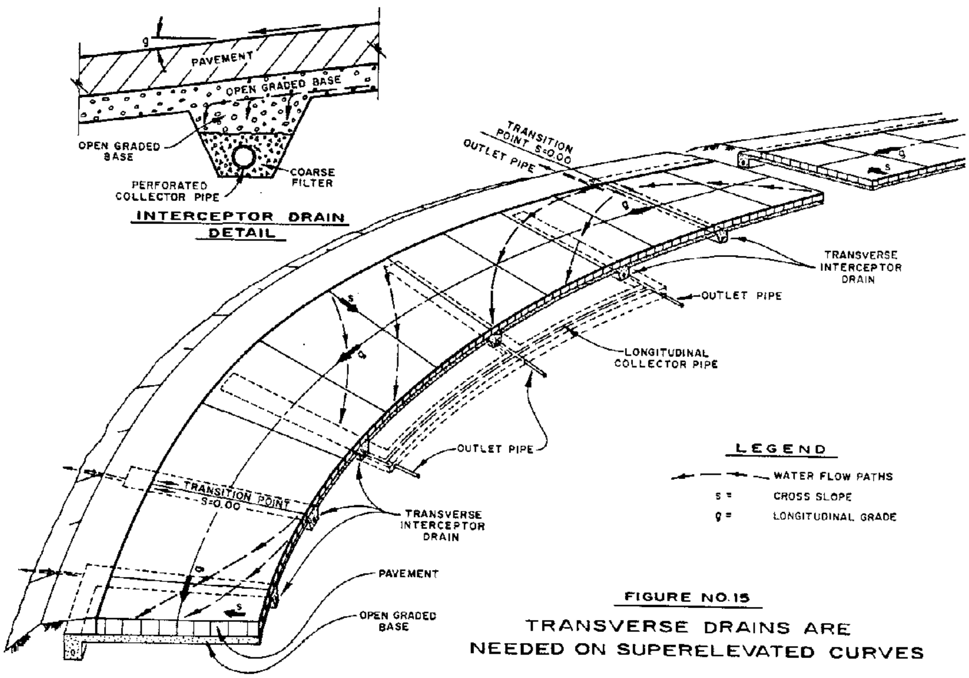


FIGURE NO. 15
TRANSVERSE DRAINS ARE NEEDED ON SUPERELEVATED CURVES

This situation becomes more complex in the case of reverse curves because the succession of the opposite cross slopes may prevent the water from reaching one of the longitudinal drains. Therefore, careful detailed analyses are unavoidable in order to design an effective interceptor subdrainage system.

In the case of sag-vertical curves, it is important to prevent the accumulation of water at the low point. Installation of one or more interceptor drains is usually required at such locations, as shown on Fig. 16.

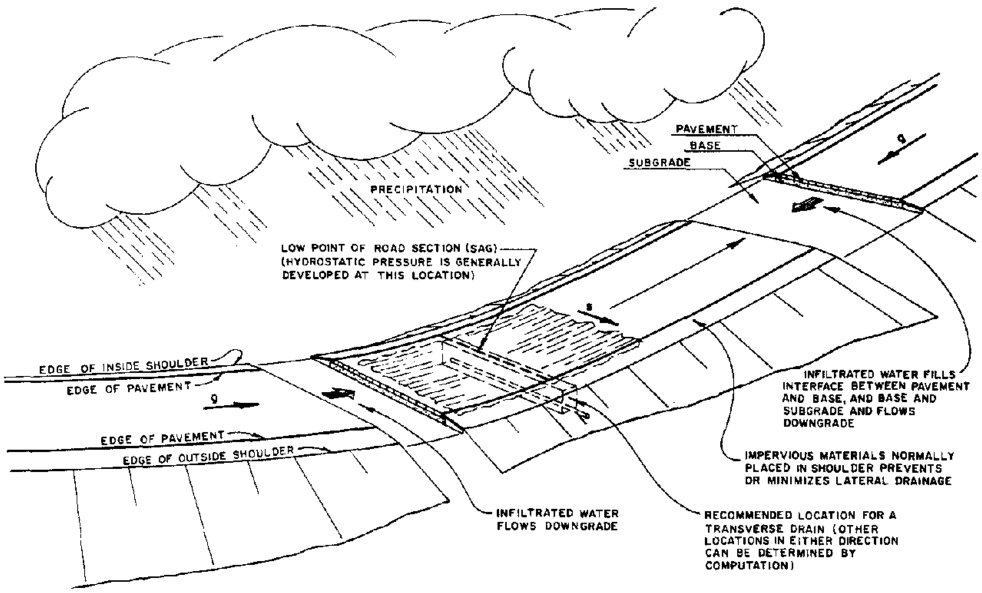


FIGURE NO. 16

UNDRAINED ROADWAY SECTION ON VERTICAL CURVE (SAG)

Subsurface water from interchange ramps that are situated at higher elevations than the adjoining multilane highway are very often the cause of pavement distress in the adjacent lanes of that highway. The subsurface water flow from interchange ramps should be intercepted before it can percolate downward. Otherwise, the adjacent lanes should be protected by underdrains to intercept subsurface water flow. This can be accomplished by utilizing trench drains of suitable depths and dimensioning the perforated collector pipes to accommodate the additional quantities of water originating from the on-ramp areas.

5.5.3 Shoulders

Frequently shoulders "break up" in a very short time after a highway is opened to traffic.

Heavy trucks being passed by another heavy vehicle tend to move to the right, and in many instances this shift causes the wheels on the right side to track on the shoulder pavement. This fact was observed during the field reconnaissance phase of this study and was also reported during interviews with Highway Engineers. Because of these actions, the continuity of the edge joint between Portland cement concrete pavement and asphalt concrete shoulders is very difficult to maintain. Also, temperature related dimensional changes cause the edge joint to open and permit easy entrance of water into the pavement structural section and under the shoulder. Since shoulders are not generally designed to support full traffic loads, they become particularly vulnerable to failure when their bases and subgrades are subjected to heavy wheel loads while in a saturated condition. In addition, shoulders are often very sensitive to frost action, and vertical heave of 1-1/2 inches more than the pavement is very common in areas subjected to severe winters. When shoulders become higher than the adjacent pavement, this forms a barrier that traps surface water, and aggravates the inflow problem.

It was observed during the field reconnaissance phase, that shoulder deterioration is a very serious problem in those highway areas that have a combination of heavy truck traffic and below freezing temperatures. A breakdown of shoulder pavements jeopardizes entire pavement systems by interfering with surface drainage and allowing surface water to infiltrate into pavement structural sections. The foregoing problems can be reduced by extending the open-graded base 3 or 4 feet under the outside shoulder.

5.5.4 Landscaping

Although landscaping generally enhances the appearance of highways, it may sometimes adversely affect the performance of pavement systems.

During preliminary highway design, it is desirable that careful consideration be given to the extent of landscaping and the required irrigation and maintenance operations. Heavy irrigation of planted slopes can raise the moisture content of certain types of subgrades to undesirable levels, and increase the amount of excess water that enters into pavement structural sections.

Subsurface drainage problems associated with landscaping of highways can be reduced if the landscape designers are made aware of the possible consequences of improper design. It is important that landscape designers and highway designers coordinate their efforts. Landscaping involving grading, cut-and-fill operations, and the spreading of topsoil should be under controlled supervision, so that the final conditions are conducive to good subdrainage.

For highway safety reasons, wide gently sloped areas extending beyond the paved shoulder are presently required and may cause problems in the highway design. For example, areas that are covered with turf beyond the shoulder should be lowered 1 to 2 inches below the edge of the shoulder to compensate for future grass growth and accumulations of silt and organic matter. If the shoulder is constructed to the same elevation as the adjacent gently sloped safety surface that is turfed, surface drainage will eventually be impaired. Also, care must be exercised when spreading topsoil along roadside slopes so that the flow of water from daylighted base courses is not impaired or blocked.

Drainage problems from landscaping activities are minimized, if not completely eliminated, by the use of underdrains of the kind described in the "Guidelines".

5.6 Summary

Roads have large surface and subsurface areas exposed to inflows of water under substantial hydraulic gradients; consequently, large quantities of water can infiltrate into highway pavement structural sections. Because roads are relatively flat and pavement layers thin, low exit hydraulic gradients exist, and highway pavements are inherently difficult to drain. And, the magnitude of the drainage problem increases rapidly with the width of the pavement, being many times greater for modern multilane highways than for the older, narrower roads.

It is important that all possible sources of significant water inflow be identified and estimated so that subsurface drainage systems can be designed realistically. Known or suspected sources of water inflow into highway pavement structural sections include: (1) gravity flow of water into pavements through surface cracks, joints, porous pavements (i.e. rainfall, snow melt, melting ice, landscape sprinkling, and other extraneous sources); (2) pressure or artesian flow from springs or underlying water-bearing permeable zones; (3) capillary water introduced from underlying high water tables; and (4) condensation due to temperature fluctuations under roads, or water of "hydrogenesis".

Capillary water and water of "hydrogenesis" may in some cases contribute to subsurface drainage problems; however, the most obvious sources (surface inflows by gravity or pressure flows from springs and high ground water) can quickly overtax inadequate subsurface drainage systems. Within minutes after the start of heavy precipitation, all surface joints and cracks can become filled and overflowing, and signs of hydraulic actions can often be detected by the naked eye under the impacts of heavy wheel loads.

Culverts, water supply pipes, sewer lines, etc. are all designed for estimated inflow rates, and hydraulic calculations are made to determine the sizes of the pipes or culverts required. Subsurface drainage systems for roads are collectors and conveyors of water and as such should also be hydraulically designed. In the past, it has not been the general practice for Highway Engineers to calculate the quantities of water that need to be removed by subsurface drainage systems; however, the present State-of-the-Art of Soil Mechanics and Seepage Theory permits this type of approach to be used. Even though some of the important factors may have to be estimated, a conscious effort to examine the discharge needs of subsurface drainage systems is fully warranted.

The basic procedure of designing subsurface drainage systems involves the following steps: (1) identify all potential sources of inflow and estimate probable inflow rates; (2) estimate any beneficial outflows from vertically downward seepage into subsoil, out through shoulders, flow to side ditches, evaporation, etc.; (3) design subsurface drains capable of removing all excess rates of inflow with reasonable factors of safety to allow for uncertainties in the estimates. This concept is mathematically expressed in 5.2, Subsurface Drainage Systems Analysis, Equations 1 to 5.

Use of this concept in the design of subsurface drainage systems will reveal that in most cases the underdrains should contain an interior core of open-graded, highly permeable pea gravel or coarser aggregate material, usually protected by fine filters. Such underdrains are known as "graded filters" or "layered drains" and are extremely efficient. For example, a 6-inch thick layer of 3/4-inch to 1-inch stone constructed on a 2 percent cross slope can remove over 500 cubic feet of water per day per linear foot of road. When provided with a collector pipe and outlet pipe, this subsurface drainage system could protect a 40-foot wide pavement from 140 inches of water infiltration per day.

Flow nets, seepage theories, or Darcy's law should be used to calculate inflow and outflow quantities from various sources and through subsurface drains. Darcy's law is of great practical value, provided reasonable values can be assigned to the terms of the equation:

$$Q = kiA \tag{11}$$

In Darcy's law, $\underline{Q}$ is the seepage inflow or outflow rate; $\underline{k}$ is the coefficient of permeability of the soil, formation, or drainage layer; $\underline{i}$ is the average hydraulic gradient; and $\underline{A}$ is the cross sectional area normal to the direction of flow. Frequently, reasonable values can readily be assigned for $\underline{i}$ and $\underline{A}$, although determination of a reasonable value for permeability $\underline{k}$ is more difficult because it is the most variable factor.

Since the permeability of soils, formations, and drainage layers is the primary factor affecting rates of inflow and outflow, working values to be used in the calculations should be realistic and conservative.

The basic principles of hydraulics and seepage should be used to develop typical solutions to various phenomena of water flow onto or into roadbeds, such as: (1) gravity or artesian flow from subgrades or underlying highly permeable water-bearing zones, (2) inflow downward through cracks or joints of various widths, and (3) inflow downward and inward through porous pavements and shoulders.

Darcy's law can be used to estimate seepage quantities and to design various types of subsurface drainage systems for different conditions, such as: (1) lateral flow through "pervious" shoulders, (2) flow through horizontal drainage blankets under pavement structural sections, (3) downward flow to pipes in collector drains, and (4) analysis of flow in drainage layers due to artesian inflow from concentrated springs.

In the analysis of the design of subsurface drainage systems, basic inflow conditions should be analyzed for: (1) cut sections with springs or ground water inflows to which should be added the surface inflows through cracks, joints, or porous pavements, and (2) fill sections where there is only surface water inflow and no inflow from springs or ground water.

Subsurface drainage systems can be designed that will accommodate the various inflow conditions. The conventionally designed sand layer drain of well graded, low permeability fine aggregates is capable of removing infiltrated water at only miniscul rates. The fine aggregate layers tend to store water after saturation and release it to the underlying soil, as previously discussed.

Free, unobstructed discharge from subsurface drainage systems is absolutely mandatory. To ensure the proper performance of the subsurface drainage system outlets, the following procedures should be observed: (1) gravity flow is highly desirable but sumps and pumps should be provided, if needed; (2) the required sizes of perforated or slotted pipes and the optimum distance between outlets should be rationally determined; and (3) outlets should be adequately marked and protected from damage.

The design of pavements and required subsurface drainage systems should be integrated and should take into account all relevant factors and practices influencing the design and operation of these systems.

During the Interviews and Field Reconnaissance phase of this study, some very significant factors and practices were revealed regarding pavement distress caused by inadequate subsurface drainage: (1) Road geometry including the number and width of lanes, cross and longitudinal slopes, steepness or flatness of side slopes, depths of side ditches, height above swampy ground, design of interchange loops and groin areas, etc. are important factors to be considered in the design of subsurface drainage systems. (2) Surface Deterioration including the opening of joints between pavement and shoulder, cracking of pavements, consolidation or settlement of subgrades, etc. caused by cyclic weather changes combined with the action of traffic. These forms of pavement deterioration, which vary with the type of pavement and the detailed design, are further aggravated when free water is introduced into the structural section through the openings and cracks. (3) Safety and aesthetic requirements such as flattened side slopes, shallow ditches, etc., and landscaping and slope erosion control--irrigation, blockage of drain blankets with impervious topsoil, etc.--will often entirely modify the assumed conditions used for subsurface drainage design. All of these problems will be minimized when pavements are provided with underdrains designed in accordance with the procedures described in the "Guidelines".

6. CONSTRUCTION OF SUBSURFACE DRAINAGE SYSTEMS

6.1 General

The basic factors involved in the design of an efficient subsurface drainage system are explained in Part 5, DESIGN OF SUBSURFACE DRAINAGE SYSTEMS. By taking into account all important factors, drainage systems can be designed that will adequately protect pavements against the actions of both surface infiltration and subsurface flows of water from all sources. But, the best designed subsurface drainage system may perform poorly if adequate care and control are not exercised during its construction.

Several precautions must be taken during the construction of a road that includes a subsurface drainage system. Some of the precautions are general in nature, and some refer specifically to certain items or phases of work. Every component of a highway roadway should be provided with maximum cost-effective protection against excessive water; this can be accomplished best by providing properly designed and constructed subsurface drainage systems.

6.2 Subgrade Requirements

Compaction of subgrades and embankments to a specified percentage of the "maximum density at optimum moisture content" should always be required, to assure the long-time performance of roadbeds without the development of sags that will trap water and weaken subgrades. To prevent the formation of built-in water traps, the grading operations must be true to the lines and grades specified in the drawings. In addition, stripping of unsatisfactory foundation materials and preconsolidation of all compressible foundations is mandatory to minimize post-construction settlement that can cause sags in the highway grade.

6.3 Collector Pipes

The first elements of a subsurface drainage system to be installed in-place are the perforated or slotted collector pipes. The function of the pipes is to collect and rapidly convey away the water that infiltrates into the structural section. Longitudinal and transverse collection pipes and lateral exit pipes are vital parts of an effective subsurface drainage system.

Prior to installation, the collector pipes should be inspected to assure that they are undamaged. The interior of the pipe should also be inspected to make sure that no foreign objects obstruct the pipe opening.

Before installation of the pipe in the trench, a bedding layer of filter aggregate must be placed and properly compacted. Where subsurface flow from springs or ground water exists or is expected, a fine filter layer is generally required between the coarse aggregate bedding layer and the soil. Certain types of filter cloths may be substituted for the fine filter layer to prevent erodible soils from being carried into the coarse open-graded aggregate drainage layer. Perforated pipes should be placed in the trench with the perforations on the bottom to reduce the possibility of sedimentation and also to reduce the potential static level of water in the trench by almost one-half the diameter of the pipe. When slotted PVC pipes are used, the widths of the slots should be sufficiently small to prevent the surrounding material from entering into the pipe. Slots can be staggered intermittently around the circumference of the pipes. See Equations 7 and 8, page 102, for filter criteria.

During installation, care must be exercised to avoid collapsing or breaking the pipes and clogging with debris that may accumulate and impede or block the free flow of water. The longitudinal gradient of the pipe should be frequently checked to assure that a uniform positive gradient is maintained in the direction of flow, and that the installed conditions are in accordance with the requirements of the plans and specifications. After the pipes are installed, it is desirable to test the continuity of the pipe waterway before the trench is completely backfilled.

6.4 Pipe Trench Backfill

After the collector pipe has been installed in the trench, backfill material should be placed immediately to prevent contamination by other construction materials, debris, mud, etc. <u>At no time during the construction of the subdrainage</u>

system and the pavements should foreign matter be allowed to contaminate any of the drainage layers.

The coarse filter material surrounding the collector pipe should be placed carefully to avoid segregation, utilizing conveyors that can be lowered into the trench for placement of the coarse filter, or other methods that assure uniformity of the placed materials. The construction specifications should indicate that all segregated, contaminated, or otherwise unsatisfactory materials must be removed and replaced with materials that will comply with the specifications after placement in the work. The specifications should clearly indicate that tests for compliance with gradation requirements shall be made on samples taken after the drainage materials have been placed and compacted. Many materials apparently degrade or become contaminated during placement and compaction.

The collector pipe trench should be backfilled to the top with fine or coarse filter material complying to the requirements of the specifications. Care to avoid contamination of the filter and drainage materials is necessary during the storage and handling of all of these materials. The introduction of even small amounts of fines into the fine filter material by wind or handling can greatly reduce the permeability of the material. As shown in Fig. 17, on the following page, increasing the clay fines from zero to a level of 3.3 percent reduces the permeability to 1/100 or 0.01 of its former value. The base aggregate used in preparing the mixtures in Fig. 17 ($\underline{k}$ = 12 ft/day) was uniformly graded from 3/4 inch maximum size to a No. 200 sieve.

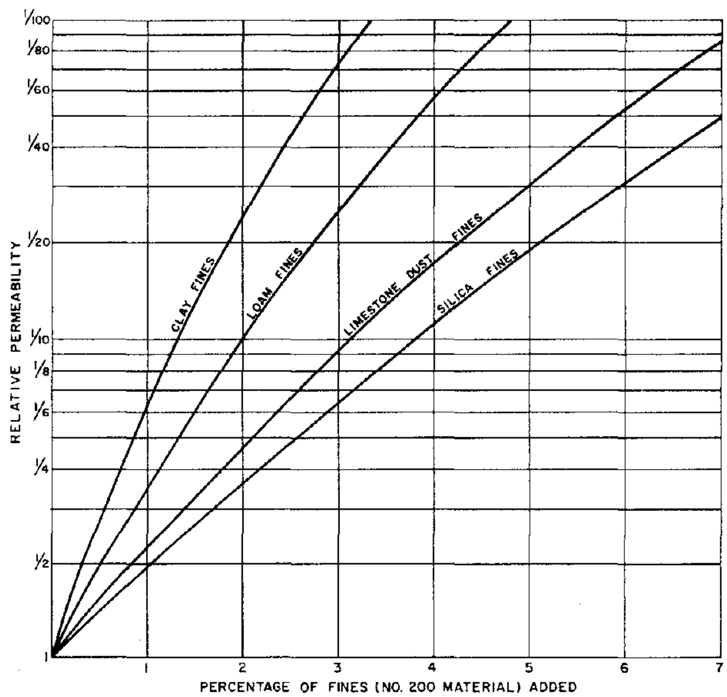


FIGURE NO. 17
EXAMPLE OF THE EFFECT OF FINES ON PERMEABILITY OF BASE MATERIAL

If collector trench backfill material has been in place for an extensive period of time prior to constructing the open-graded base drainage layer, the top 2 inches of the trench backfill should be removed and replaced with new material. During the Interviews and Reconnaissance phase, several State Highway Departments reported instances where trench backfill material had been placed and surface runoff was observed flowing over the supposedly pervious filter material without infiltration. This was probably due to an increase in density and reduction in permeability of the upper materials because of the introduction of fines (dust) and compaction by equipment. Low permeability layers located at any level within a collector trench must be avoided if the subdrainage system is to function as intended.

6.5 Open-Graded Base and Filter Layers

As indicated in 5.4, a filter layer may be required between the subgrade and the open-graded base drainage layer. The purpose of the filter layer is to prevent intrusion of fines into the open-graded base and the resulting reduction of its permeability and strength.

Three basic methods can be utilized to prevent contamination of open-graded bases by intrusion of soil fines. The first and most common is the installation of a thin layer of fine graded material (complying with the filter criteria given in 5.4.2) on top of the subgrade. After this thin layer of filter material has been placed, care must be exercised to avoid disturbing it or contaminating it with fines. This type of filter material is highly susceptible to variations in permeability, and precautions must be taken during storage and handling to avoid contamination and degradation. The fine graded filter material must have sufficient permeability to permit the free flow of water (i.e. ground water or lateral seepage) from the subgrade; otherwise the effectiveness of the subsurface drainage system is nullified. This is particularly important in areas of large ground water flow. The basic methods used for establishing the permeability requirements of the various elements of subsurface drainage systems are described in 5.4 and 5.6.

The second method for preventing contamination of open-graded bases is by the installation of a fabric or mesh on top of the subgrade. There are several mesh and plastic products that appear to be sufficiently strong to withstand heavy traffic loads without rupturing. Reasonable care must be taken during construction of the open-graded base to avoid ripping of the fabric or mesh. Mesh or fabric filter materials have been widely utilized in other types of construction projects (dams, levees, cellars, etc.) but there is only limited experience with the use of manmade filters in road construction. The U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, made rather extensive tests of the suitability of plastic cloths for filters (see Ref. 23).

The third method that will prevent foreign materials from filtering into open-graded bases utilizes an impervious membrane under the base in lieu of the filter layer. This method of protection is limited to cases where only surface water is expected to infiltrate the structural section. In such cases, thin PVC or other plastic sheeting can be used or an application of a bituminous treatment is also effective.

Any filter or impervious layer placed between a subgrade and an open-graded base is susceptible to damage by carelessness during construction of the base. Disruption of the specified physical properties of the layer can lower the efficiency of localized portions of the subsurface drainage system; therefore, close supervision of the construction of the open-graded base is important.

The installation of the open-graded base layer is a relatively simple operation when this material is placed with an asphalt paving machine.

6.6 <u>Daylighting of Drainage Layers</u>

Although drainage systems, under the traveled lanes, with pipe outlets are usually the most economical types of systems, drainage layers are sometimes extended across shoulders and daylighted to drain. Where construction of daylighted drainage layers is specified, care must be taken to avoid segregation of the material in the area exposed to the atmosphere. Segregation can occur during construction due to the difficulties inherent in placing a drainage layer to the slope line. After placement, heavy equipment should not be allowed to traverse across the exposed material as this can damage the drainage layer. Overcompaction of the drainage layer must be avoided to preserve the desired permeability and water removal capabilities of the layer. Where drainage layers of high permeability are daylighted, pipe outlets may not be required.

6.7 Clean-Out Boxes

In addition to the normal care required during the construction of clean-out boxes or manholes, they should be immediately covered and protected until the concrete has set and formwork has been removed, to avoid introduction of debris into the perforated pipes. The tops of the clean-out boxes should be above the elevation of the surrounding ground or, if this is not possible, protected in some way against flooding during precipitation. The permanent cover should be installed as soon as possible. Continuity of the collector or outlet pipe waterway should be verified to assure that no extraneous matter has accumulated in the pipes.

6.8 Outlets

Outlet pipes should not be perforated as their purpose is to conduct water away from the collector pipes and trenches. The outlet pipes should extend from a convenient junction or clean-out box to the exterior of the embankment slope or roadside ditch. Backfill material surrounding the outlet pipe should specifically be selected to have low permeability when compacted in place to preclude any possibility of piping along the pipe or trench. If such materials are unavailable, cut-off collars should be constructed at proper intervals along the outlet pipe.

Outlet pipe openings must be protected by installation of permanent protective attachments to prevent the entrance of small animals or foreign materials.

Figure 14 (page 104) indicates the care that is recommended in the location of outlet pipes to avoid accumulations of mud, sedimentation, erosion, etc. below the pipe openings along the slopes and roadside ditches. Heavy construction equipment should be prevented from entering areas where outlet pipes have been installed, particularly where the cover over the pipes is insufficient to support heavy wheel loads.

6.9 Markers

Outlet pipe markers should be installed as soon as the outlet pipes are in place. Installation of suitable, permanent markers should be a very simple task consisting of drilling a power auger hole to a depth of 18 to 24 inches, installing a treated marker pole or metal pole, and backfilling the void space between the pole and the hole.

6.10 Landscaping

Landscaping is normally one of the last items to be accomplished on highway construction. Most highway projects require that topsoil be spread over areas that will be turfed; generally including areas where subsurface drainage outlets are located. The prompt emplacement of permanent markers, as noted in 6.9, should help to prevent the covering of outlet pipes with topsoil during landscaping. Indiscriminate spreading of topsoil has caused unmarked outlets to be covered with several inches of relatively impervious soil; thus blocking water flow out of the subsurface drainage system.

6.11 Testing of Materials

Materials utilized in filter and drainage layers, and trench backfills should be thoroughly tested for compliance with the construction specifications. Gradation and permeability tests should be routinely performed on samples taken from stockpiles and also on samples extracted after placement and compaction. The construction specifications should be written to indicate that acceptance tests performed shall be on representative materials after they have been placed and compacted. As previously noted, significant degradation and loss of permeability of certain materials can occur during placement and compaction.

Gradation tests on materials can serve as indicators of the range of permeability of these materials. Possible losses in permeability due to degradation are illustrated in Fig. 17 (page 123). If the functional properties of filter and drainage materials are to be preserved, it is important that strict restrictions be placed on gradation requirements, particularly on the maximum allowable content of fines. Permeability of a material is directly related to the amount of fines the material contains.

Relatively simple field permeability tests should be devised that can be used as field control of the permeability and hydraulic conductivity of the materials. These tests should be correlated to more accurate laboratory tests.

Materials that have been placed and do not comply with minimum permeability, gradation, and soundness requirements must be removed and replaced, because the performance of the subsurface drainage system will be jeopardized if they are allowed to remain in the work

7. MAINTENANCE OF SUBSURFACE DRAINAGE SYSTEMS

7.1 General

The maintenance of highway appurtenances is of significant and particular importance in assuring the intended performance of constructed facilities and safeguarding the capital investment. The following paragraphs present principles that should be observed in order to maintain subsurface drainage systems in good operational conditions at all times. Special effort has been made to avoid overlapping into recognized pavement maintenance procedures even though pavement maintenance exerts a significant influence on the performance of subsurface drainage systems.

7.2 Preventive Maintenance

7.2.1 Collector Pipes

The principal function of the perforated or slotted collector pipes is to receive water that enters the subsurface drainage system and to convey it to outlet points.

In urban areas where clean-out boxes are provided, it may be desirable at times to flush the subsurface drainage system collector pipes by introducing large quantities of clean water into the pipes. Flushing may be necessary when self-cleaning of the collector pipes does not occur, which may be due to a combination of the pipe gradient and heavy sediment load. Flushing of outlet pipes is recommended to remove any excessive sediment that may have accumulated. When drains are properly designed and constructed, very little sediment should get into the pipes.

7.2.2 Outlets

Outlets are the most critical element of a subsurface drainage system because they are exposed and subject to damage that can impede the free flow of water out of the system. Weed growth, observed during the field reconnaissance to be a major cause of the blockage of outlets, is fostered and sustained by the high water content of the soils near the outlet and by siltation due to erosion in the roadside ditch or adjacent slopes. In only a very few instances had maintenance equipment crushed the outlet pipe openings.

The primary objective of performing preventive maintenance on outlets is to keep them open. Inspection of the outlet pipe openings does not demand an inordinate amount of time since they are exposed. Weed growth near the outlets should be discouraged and the minimum vertical distance between the flowline of the outlet and the bottom of the drainage ditch or slope, as shown on Fig. 14 (page 104), should be maintained to avoid plugging.

By flushing outlet pipes, extraneous objects that may have been introduced into the pipes usually can be detected and removed.

Light gage flap gates installed on outlets, as shown on Fig. 14 (page 104), prevent the entrance of small animals.

Also, these gates make it difficult for floodwaters in the roadside ditches to intrude and deposit sediments and debris into the outlet pipes. Maintenance crews should periodically check flap gate pivots and the tightness of flap gate collar to pipe.

7.2.3 Markers

Outlet pipe markers are sometimes damaged by maintenance operations and vandalism, and should be periodically inspected at the same time the outlet pipes are inspected. A marker of the type recommended in this report will be durable, is not vulnerable to destruction, and thus its maintenance is simple. The wooden marker recommended can sustain a great deal of abuse without suffering apparent damage and without having its function impaired. In cold regions where deep frost penetration would rigidly anchor wooden posts and create a hazard to motorists, less rigid metal posts should be used. Markers constructed of light gage steel shapes are frail and require frequent replacement.

There are two basic objectives for the maintenance of outlet pipe markers: (1) to assure the presence of a marker at each outlet pipe, and (2) to ensure that the markers are easily identifiable from the traveled way or the shoulder of the highway.

7.2.4 Mowing

Mowing and other roadside maintenance operations have a direct bearing on the performance of subsurface drainage systems. To prevent damage to outlet pipes and markers from maintenance equipment (especially mowing equipment), weed growth near the outlets and markers can be eliminated by constructing erosion protection aprons, as shown on Fig. 14 (page 104), or by sterilizing the adjacent soil with chemicals.

7.2.5 Summary

Subsurface drainage systems that have been properly designed and constructed do not generally require extensive maintenance, but periodic inspections should be scheduled to identify any potential problems in order that remedial action can be taken.

Roadside maintenance work should be carefully performed to avoid damaging outlets and markers.

7.3 Drain Installations for Pavement Rehabilitation

Highway pavements that show signs of structural weakness or distress generally should be programmed for overlays or other protective work before the distress progresses to the point where irreparable structural damage occurs. The reduced load-carrying capacity and early distress of highway pavements are often caused or worsened by the presence of excess water in their structural sections. In some cases, the damage caused by excess water can be reduced or minimized by applying seal coats or by taking other action to reduce the amount of water that enters into pavement structural sections. Such measures often are more effective if performed when the pavements are relatively new and only little damage from excess water has had time to occur. If the damage to the roadway has been significant, it becomes very difficult to prevent water from entering the structural section by the use of thin seals, and thick overlays may be required for effective rehabilitation.

Pavements that show premature signs of distress generally could have their useful life lengthened if there were some way to substantially improve subsurface drainage of the structural section. Even though full width, positive subsurface drainage was not provided in the original construction, it is sometimes possible to improve subsurface drainage by installing transverse or longitudinal drains at selected locations such as sag-vertical curves where water accumulates. Subsurface drains placed along the edges of existing pavements provide some relief for edge pumping, but the typical sand and sandy gravel bases frequently do not have sufficient permeability to convey much water to these drains from interior portions of the roadbeds.

Some highway departments have utilized bases and subbases of so-called "open-graded" types, which may be of some benefit in conveying water to longitudinal drains. If a pavement that is showing distress or weakness has a reasonably permeable base, experimental sections of trial drains can be installed to determine if the pavement structural section will benefit by the installation of longitudinal edge drains. Figure 18 indicates the elements of a longitudinal edge drain system that may assist in the subsurface drainage of existing pavement structural sections.

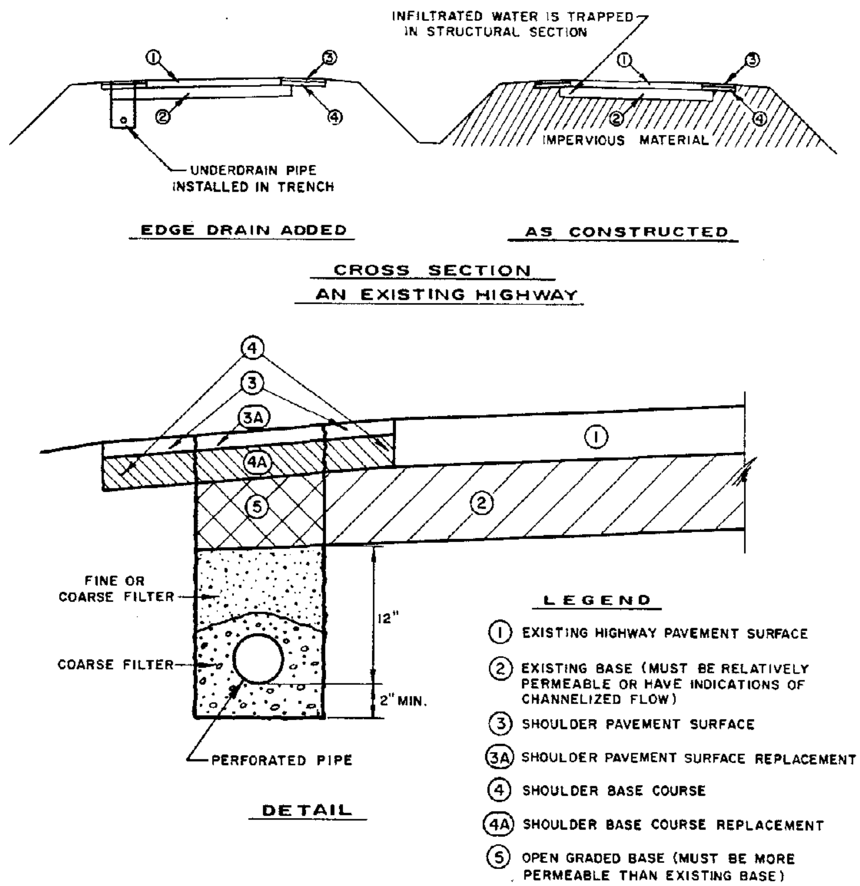


FIGURE NO. 18

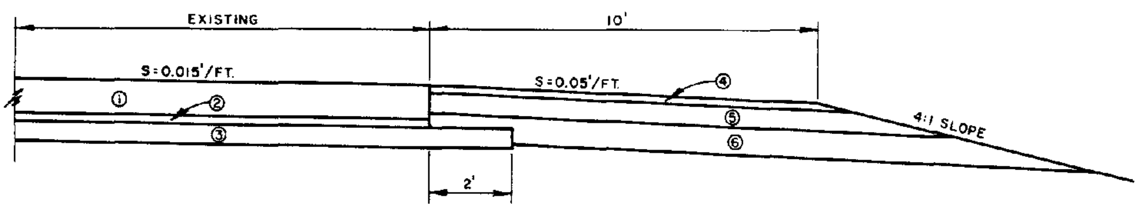
LONGITUDINAL EDGE DRAIN INSTALLATION FOR EXISTING HIGHWAY PAVEMENT SYSTEMS TO IMPROVE SUBSURFACE DRAINAGE

A trench approximately 12 inches wider than the perforated pipe to be installed should be excavated along the lower edge of the pavement to at least 6 inches below the bottom of the most pervious layer in the pavement system, and permanent type perforated or slotted pipes should be installed to provide gravity drainage. Special permeable filter material (usually pea gravel or slightly coarser sized aggregate) should be placed to completely surround the longitudinal pipe. This material should be compacted with care to avoid consolidation under traffic, and to prevent crushing of the pipe under load. Outlet pipes should be provided at frequent intervals (200 to 300 feet apart in finished installations) to ensure unobstructed gravity outflow.

Trial installations to determine if longitudinal edge drain systems installed under maintenance can benefit subsurface drainage should be at least 200 to 300 feet long. They should be located in typical areas where it is thought that side drains may be beneficial. The outlets should be clearly marked and protected with suitable posts set into the ground 18 to 24 inches deep. Each outlet should be observed systematically during and following rainshowers and rainstorms for at least one wet season. Periodic pavement condition surveys should be conducted at the experimental edge drain sections and 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 the trial sections, it is likely that they will be of some benefit.

At locations where little or no improvement can be expected from longitudinal edge drains, it is suggested that normal rehabilitation and maintenance programs be continued. When sections have to be replaced, full-width subsurface drainage systems can be provided, as described in the "Guidelines".

Another type of corrective drainage system is illustrated in Fig. 19, which shows a very pervious blanket drain placed across the full width of a shoulder. The State of Louisiana is planning this type of drain under the shoulder of an existing Portland cement concrete pavement which is showing problems with excess water, and where the shoulders are deteriorated and in need of reconstruction, anyway.



TYPICAL SECTION

LEGEND

1. 10" EXISTING P.C.C.
2. 2" GRANULAR MATERIAL
3. 6" EXISTING SOIL CEMENT
4. 2" TYPE C SURFACING
5. 6" TYPE A DRAINAGE BLANKET
6. 8" TYPE B DRAINAGE BLANKET

SPECIFICATIONS FOR TYPE B DRAINAGE BLANKET

SIEVE SIZE	PERCENT PASSING
3/4"	98—100
3/8"	50—80
NO. 4	10—40
NO. 10	0—5

FIGURE NO. 19

SHOULDER RECONSTRUCTION TO IMPROVE DRAINAGE OF EXISTING ROADBED

8. COST/BENEFIT ANALYSES

8.1 Introduction

The true value of any highway design feature such as subsurface drainage systems for roadbeds depends on determining the total cost of the feature including maintenance costs and all direct or indirect costs to the users. During Phase I - Interviews and Reconnaissance, attempts were made to obtain maintenance cost information from every State Highway Department visited. Accounting procedures utilized by State Highway Departments make it difficult to isolate true maintenance costs. Extensive repairs such as overlays, major grinding, or subsealing or reconstruction are not normally recorded as "maintenance" because this type of work is usually paid from "construction" funds.

Maintenance of important pavements including those of the Interstate System is increasing in major proportions. An article appearing in the Civil Engineering magazine (ASCE) of August 1970, entitled "Interstate Pavements Failing Early" states: "The assumptions on which State and Federal engineers have based designs for the Interstate Highway System have been in error, and the result is increasing cost to the system in terms of repaving and overlayment."

Investigations that were made in developing the "Guidelines for the Design of Subsurface Drainage Systems for Highway Pavement Structural Sections" indicate that the biggest error in the design of pavements is the assumption that pavements can be economically designed as slow-draining systems. The acceleration in maintenance and repair costs is due to a number of causes including the increasing volumes of heavy truck traffic, <u>but in considerable measure it is due to the damaging effects of the heavy loads while roadbeds are in a supersaturated or flooded state</u> (Refer to Phase I - Final Technical Report).

As noted in the Final Technical Report, there is a growing volume of evidence to support the theory that any poorly drained roadbed is inherently inferior to the same road well drained. However, it is difficult to find any major roads that are truly well drained. The Humbolt County, California Case Study has a pavement that was designed and reconstructed by the County Public Works Department in 1967 with an open-graded, two-layer drainage blanket under the entire width of the roadway. Test holes drilled 4 years after reconstruction revealed that the drainage layer had not clogged nor were there any signs of soil intrusion. The base course was remarkably free of water, and the pavement was in excellent condition although heavily loaded logging trucks had destroyed the original, undrained pavement (supposedly properly "designed") within a few years after construction. The Humbolt County Case Study site provides a remarkable example of the benefits of good drainage, and the subsurface drainage system constructed there is the first of its kind under a road in California and possibly in the entire United States.

Studies completed for the preparation of this report indicate that pavements designed as rapidly draining systems (using methods described in the "Guidelines") can be expected to outlast conventionally designed slow-draining pavements by many years.

Actual cost information for highway pavements (construction, operations and maintenance) is very limited, and the following cost/benefit analyses are based on prevailing bid prices for various items as of 1972. These studies compare the costs of constructing pavements that are deteriorating prematurely from excess water to the costs of pavements that incorporate positive drainage systems during original construction. The studies demonstrate that if positive drainage systems effectively reduce maintenance or extend the useful life of pavements only a few years, the added costs will be repaid. These comparisons do not take into account the many other direct or indirect costs of deteriorating and damaged pavements such as the added discomfort to the motoring public, increase of vehicle damage and tire wear, increase of hazards to safety, and time delays to the highway users.

The basic premises of the cost/benefit analysis are outlined below:

(1) The degree of deterioration due to the presence of free water in the highway pavement structural section appears

to be proportional to the number of days with precipitation, the number of precipitation events (distinctly separate rainfalls), the volume of heavy traffic, and the subdrainage and strength characteristics of the different layers in the structural system of the pavement.

(2) The pavement design principles used in comparing the different alternatives are those expressed in the AASHO Interim Guide for the Design of Flexible Pavements and the AASHO Interim Guide for the Design of Rigid Pavements. It is realized that many State Highway Departments utilize other rational, empirical or statistical methods to design pavements; however, the AASHO method appears to be the most suitable basic design method to utilize in the cost/benefit analysis. It is not within the scope of this study to undertake a critical review of pavement design methods.

(3) Commonly accepted values of strength coefficients for the various materials involved have been selected to be used in the cost/benefit analysis. Average unit cost relationships were obtained from 1972 bid prices, in order to calculate relative costs for the different materials used in highway construction. There is a great variation in unit prices throughout the United States and the foregoing approach is the most sensible and indicates the procedure that can be followed if more detailed analyses are desired. Actual unit bid prices and strength coefficients should be used for a

detailed analysis; however, the relative values selected for this study are considered to be realistic for a great portion of the United States.

(4) Lack of detailed information with regard to the breakdown of highway maintenance costs makes it extremely difficult to assign a dollar value to that portion of maintenance work that is directly attributable to deficient subdrainage of pavements. Therefore, and for the purpose of this cost/benefit analysis, the assumption has been made that normal maintenance costs will be constant, regardless of the existence of efficient subdrainage systems. However, it is contended that a substantial savings in maintenance costs should be realized by utilizing efficient highway pavement subsurface drainage systems, as described in the "Guidelines".

8.2 Analysis of Basic Premises

8.2.1 Structural Damage to Pavement

The water actions leading to premature damage to highway pavements have already been discussed in Part 3. An analysis of the findings included in various road test investigations indicates that the damaging process is cyclic in nature and follows the periods of precipitation. Furthermore, the extent of the damaging period appears to correlate with the subsurface drainage properties of the highway pavement structural section materials. A rational analysis of the preceding phenomena was undertaken and the results are presented herein.

During a period of rainfall, some of the water drains off the pavement surface but a certain amount infiltrates the pavement surface, cracks, etc. into the structural section. This process continues for as long as there is a water supply, a period of time approximately equal to the duration of the rainfall. After the precipitation has stopped, the water continues to penetrate further into the pavement section layers until a less pervious layer is encountered, in which case the water moves laterally under a small head. This phenomenon basically follows the laws of fluid flow through porous media.

The quantity of water that is available to filter into the pavement structural section is generally proportional to the length of time the pavement surface has been exposed to water runoff rather than the maximum intensity of precipitation. Thus, a long steady drizzle may be more damaging to a pavement section than a short duration thundershower delivering the same total amount of precipitation.

When the infiltrated water is of sufficient quantity to saturate the most pervious layer in a layered pavement system, it is very likely that the damaging actions of water described in Part 3 will begin. The damaging actions will continue until the water has drained out of the most vulnerable layers and the saturation has reached what is considered to be a noncritical level, generally a function of the physical characteristics of the material. On this basis, it can be said that a given pavement is vulnerable to the damaging actions of free water for a period of time starting with the beginning of precipitation and ending when the level of saturation of any layer in the structural section has become less than the critical saturation. This idea is recognized, although neither identified nor quantitatively described in the AASHO Interim Method for the Design of Flexible Pavements. It is included in the "regional factor" and defined as "an environmental factor to be introduced into the design analysis on the basis of a summation of the seasonal weighting factors used to weight the axle load applications on the Road Test." In addition, the primary determinant of the regional factor is the severity of the moisture condition during spring thaw and the duration of saturation of the roadbed materials. Figure 20 shows the relative load-carrying capacities of highway pavement structural systems when saturated and unsaturated as determined by South Carolina Highway Department and FHWA Research Project No. 522. The slow-moving loads applied in these tests would not necessarily reflect the hydraulic damages caused by fast-moving traffic; nevertheless, they provide another indication that structural sections should be kept dry.

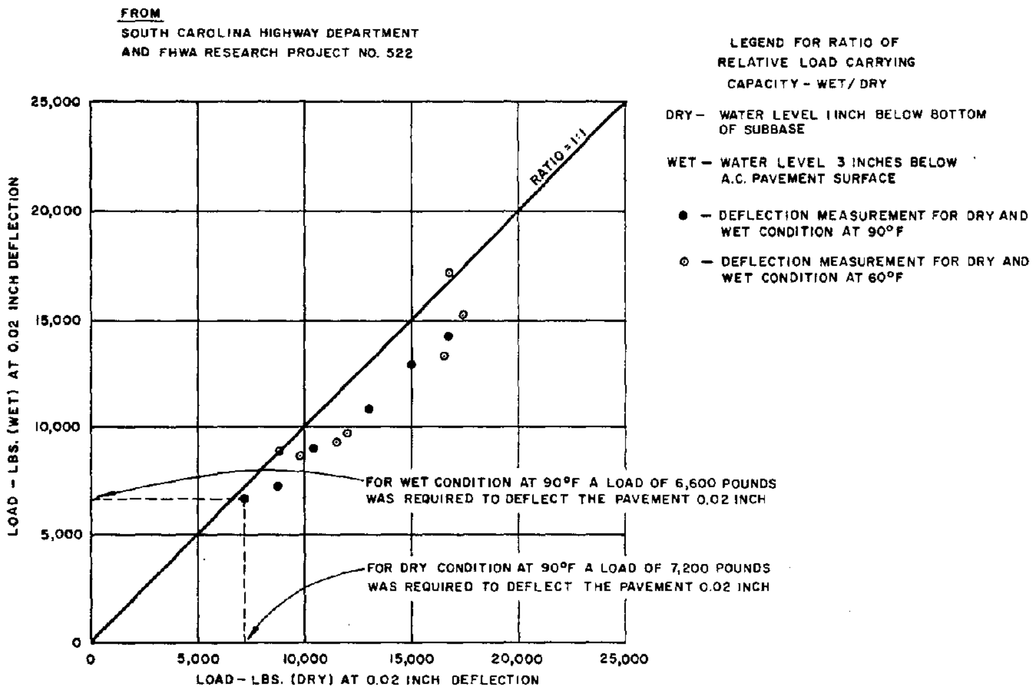


FIGURE NO.20

RELATIVE LOAD CARRYING CAPACITY FOR WET AND DRY CONDITIONS

The concepts expressed in this Final Report are illustrated on Fig. 21 (following page) for two different geographical locations and two different drainage time periods.

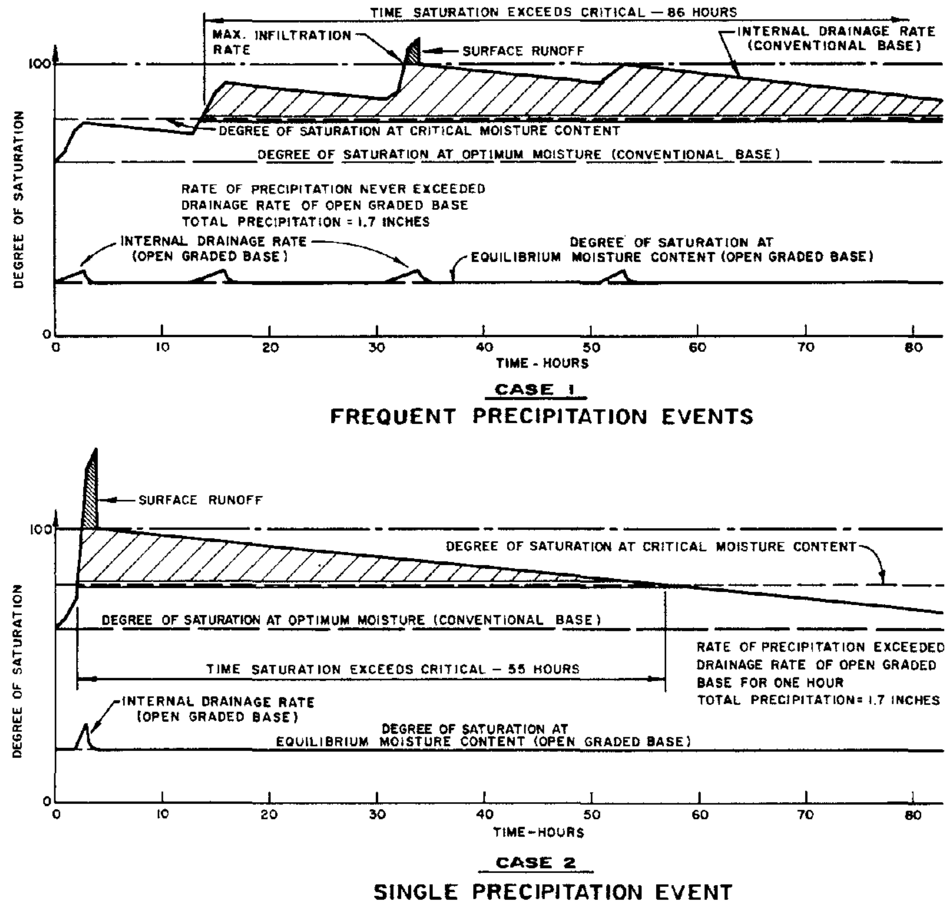


FIGURE NO. 21

SUBSURFACE DRAINAGE CONCEPTS

Case 1 is located in an area of frequent precipitation of moderate intensity where the rate of drainage of the open-graded base is 100 times that of the conventional section and also greater than the infiltration rate. Case 2 is located in an area where the precipitation is considerably less frequent but of higher intensity. The open-graded base drainage rate is 100 times that of the conventional section but less than the infiltration rate. Even though the total amount of precipitation is the same at both locations, the periods of time the base materials are saturated above the critical level are considerably different; the highway structural section is vulnerable for a much longer time in the first case than it is in the second case. Figure 21 indicates that the critical saturation period in a pavement structural section without a subsurface drainage system can be hundreds of hours longer during any one year than the critical saturation period in a pavement structural section that has a subsurface drainage system.

The foregoing situation illustrates isolated events. In the pavement design method, the mean annual precipitation or other representative values describing the environmental factors affecting moisture conditions are generally considered. Assuming those values to include the effect of the number of hours of measurable precipitation per year in Case 1 of Fig. 21, then it can be said that the road has probably been designed to withstand excess water for that number of hours in the average year. Actually, the road must support traffic loads while containing excess water for considerably longer periods. Analyzing Case 1 of Fig. 21, it is evident that the critical saturation level (with a conventional base) is exceeded 86 hours with only 11 hours of precipitation, a factor of almost 8. In Case 2 of Fig. 21, the critical level is exceeded 55 hours with a total of 4 hours of precipitation, a factor of almost 14. In both cases, the total amount of precipitation was the same; however, the period of saturation as a consequence of several small rainstorms is almost 60 percent longer than the period of saturation due to a single rainstorm.

The relationship between actual and assumed duration of unfavorable conditions is defined as the vulnerability factor, V.

$$V = \frac{\text{Actual Number of Hours Critical Value is Exceeded}}{\text{Number of Hours with Measurable Precipitation}}$$

The influence of positive subsurface drainage becomes extremely evident. The vulnerability factors considered were:

Case 1	V = 8
Case 2	V = 14

If the same procedure is repeated when a subsurface drainage system is considered to be operating the values for the vulnerability factors are as follows:

Case 1	V = 0
Case 2	V = 0

The vulnerability factor can only be zero if subsurface drainage occurs almost instantaneously, which obviously demands an extremely efficient subsurface drainage system for the removal of the water.

Data gathered during the performance of the AASHO Road Test, the WASHO Road Test, and the Road Test One-MD were analyzed in an effort to correlate actual field tests with the concepts expressed in the foregoing discussion. It was found that the rates of deterioration, pumping, cracking and other signs of pavement distress during the periods following rainfall or thaw were from 12 to 100 times greater than the rate of deterioration during relatively dry periods. For the AASHO Road Test (asphalt concrete pavement section) it was determined that the deterioration during wet periods was 12 times greater than during dry periods. For the WASHO Road Test (asphalt concrete pavement section), the deterioration was 100 times greater during wet periods than during dry periods. The Road Test One-MD (Portland cement concrete pavement) revealed that during periods of intense precipitation the number of new joints pumping were 20 times greater than during periods of moderate precipitation.

Giving consideration to the fact that all the road tests represent an accelerated process, it is reasonable to assume that under normal traffic conditions the ratio of the rates of deterioration may be in the range of at least 5 to 10. Therefore, the effect of traffic load applications during the vulnerable period is amplified at least 5 to 10 times. This ratio is called the severity factor.

Using the examples set up in Case 1, Fig. 21 and assuming the records represent a 15-day period (360 hours), the pavement system remains vulnerable when no subsurface drainage is provided $\frac{86}{360}$ or 24 percent of the time (pavement system is not vulnerable 76 percent of the time). If actual load applications in that same period are considered to be

100 percent and equally distributed in time, the effect on the pavement system while the saturation level is not critical is 76 percent and the effect on the pavement system while the saturation level is critical is 24 percent times the minimum severity factor (5) or 120 percent. Weighted load applications during the period of record are, therefore, 76 percent + 120 percent = 196 percent.

If adequate subsurface drainage is provided, the pavement is not vulnerable 100 percent of the time. If the actual load applications are represented by 100 percent, then the effect on pavement system (not vulnerable) = 100 percent.

Therefore, in Case 1, the destructive effects of traffic loads on a road with no subsurface drainage system is approximately two times greater than on a road having an effective subsurface drainage system.

If the highway of Case 1 is expected to have a life of 20 years, the effective life may be only one-half, or 10 years, if the pavement is not adequately protected against excessive infiltration. This is a 50-percent reduction. Actual cases have been observed where serious destruction occurred within 4 to 6 years, indicating that this method of evaluation may not be unrealistic.

Even though other assumptions or criteria would be used in making an analysis of the type presented, the same basic conclusion would be reached; namely, that rapid subsurface drainage can provide the vitally needed protection from infiltration of water, and substantially reduce damage to roadbeds everywhere. Although it may often be difficult to greatly improve the drainage of many of the miles of highways that have already been constructed without subsurface drainage systems of the type recommended in this study, major reconstruction, relocations, and new constructions can be given this kind of protection.

8.2.2 Design Principles

In order to demonstrate the cost-effectiveness of subsurface drainage systems it is necessary to briefly discuss pavement design principles for both flexible and rigid types of pavements.

8.2.2.1 Flexible Pavements

There are several different methods of flexible pavement design used in the United States; some of the design methods were developed by State Highway Departments to make the best use of local materials while others were developed by private industry to promote the use of specific products. The methods most used are:

Kansas Method for Structural Design
U. S. Army Corps of Engineers CBR Method
Shell Method of Thickness Design
Texas Highway Department Method
CBR Method
State of California Method of Thickness Design
Canadian Department of Transport Method
  (Good Roads Association)

Asphalt Institute Method of Thickness Design
Michigan Method of Thickness Design
AASHO Interim Guide

Many State Highway Departments have adopted the AASHO Interim Guide with slight modifications to conform to local conditions. The AASHO Interim Guide for the Design of Flexible Pavements provides broad coverage of the design procedures utilized by a majority of the State Highway Departments.

The AASHO Interim Guide was developed from results of the AASHO Road Test by the AASHO Operating Committee on Design and released for study and trial in 1961, and recently updated (AASHO Interim Guide for Pavement Structures - 1972).

The principal design criterion is the adequacy of the structural section as measured by the change in the Present Serviceability Index (PSI) of the pavement. The PSI is defined as the momentary ability of a pavement to serve traffic. The change in PSI is a function of maximum axle load, number of axles, number of load repetitions, seasonal effects, thickness of pavement components and the subgrade soil support.

This design method is based on several assumptions:

The relationships between load repetitions, thicknesses of structural layers, and the foundation soils used in the Road Test are valid for all soil types. Thus, a soil support scale is established.

The effects of axle loads on the pavement performance are those found in the Road Test.

The arbitrary soil support values can be correlated to CBR and "R" value test procedures.

The empirical relationship between the thickness of a component layer in the pavement structural section and the type of material used in constructing the layer is expressed by the Structural Number, SN.

Coefficients for surface course, crushed aggregate base, and sandy gravel subbase were determined from the main experiment at the AASHO Road Test. Coefficients for surface, base and subbase courses, other than those used in the AASHO Road Test, have been established by analyzing their comparative cohesion, stability and bearing values obtained in laboratory tests. For the purposes of the cost-effectiveness analysis given here, the following coefficients were chosen as reasonable values (Ref. 19, 20, and 21).

Asphalt Concrete Surface Course	0.44
Bituminous Open-Graded Base (using crushed aggregate)	0.30
Cement-Treated Base	0.30
Aggregate Base	0.14
Sand Layer	0.12
Aggregate Subbase	0.10

The following example is presented to show the basic procedure utilized in the application of the AASHO Interim Guide design method.

Assume the terminating (lowest acceptable) serviceability index ($\underline{P_t}$) to be 2.5, as suggested for major highways; traffic analysis period is 20 years, regional factor is 1.2, subgrade tests indicate a CBR of 10 at 0.1 inch penetration, and equivalent daily 18 kip single-axle load applications for the most heavily traveled lane is 300.

Determination of the desired structural number, SN, is accomplished by using design nomographs. The SN for this example is 3.4. Assuming that the example location is subject to frost damage, a minimum total pavement section thickness must be determined prior to selecting the thickness of the different layers of the structural section. If the freezing index in degree-days is assumed to be 100, frost penetration according to U. S. Corps of Engineers criteria is 15 inches.

The minimum pavement section thickness required by the various State Highway Departments is variable; therefore, a minimum thickness of 11 inches (approximately 0.75 frost penetration depth) has been adopted for this example.

The two basic parameters for the design of the flexible pavement structural section are now fixed:

$$SN = 3.4 \qquad\qquad T = 11 \text{ inches}$$

The minimum thickness of the pavement surface layer is 3 inches. The design thickness is determined by trial-and-error solutions utilizing the following equations:

$$c_1d_1 + c_2d_2 + c_3d_3 = SN$$

$$d_1 + d_2 + d_3 = T$$

Several combinations of the same structural section components will satisfy the stated requirements; however, there is a unique solution that provides the lowest pavement cost.

Different pavement structural sections can be postulated using the coefficients of strength shown on Page 154.

Trial 1:	3 inches (d_1) asphalt concrete x 0.44(c_1)		= 1.32
	8 inches (d_2) aggregate base x 0.14(c_2)		= 1.12
	10 inches (d_3) aggregate subbase x 0.10(c_3)		= 1.00
	Thickness = 21 inches	SN	= 3.44
Trial 2:	3 inches (d_1) asphalt concrete x 0.44 (c_1)		= 1.32
	8 inches (d_2) bituminous open-graded base x 0.30(c_2)		= 2.40
	Thickness = 11 inches	SN	= 3.72

The foregoing design procedure will be utilized in the cost-effectiveness analysis of subsurface drainage systems presented in 8.3.

8.2.2.2 Rigid Pavements

The best known methods of the design of rigid pavement structural sections are:

Portland Cement Association Procedure
Yield Line Method
Canadian Good Roads Association Method
AASHO Interim Guide
U. S. Corps of Engineers Method

The two design procedures most commonly used in the United States are the PCA Method and the AASHO Interim Guide (as modified by some State Highway Departments to satisfy particular requirements). For the purpose of this study, the AASHO Interim Guide has been selected in order to make cost-effectiveness analyses of various pavement section materials.

The AASHO Interim Guide was developed from results of the AASHO Road Test and released for study and trial use in 1961 (updated in 1972).

The Method is based primarily on the adequacy of the structural section as measured by changes in the Present Serviceability Index (PSI) of the pavement. Definition of the PSI is given on Page 153. The basic assumptions for the rigid pavement design procedure are similar to the flexible pavement method of design except for the following:

> The capacity of the subgrade to support traffic loadings can be measured by the modulus of subgrade reaction (k).
>
> The maximum tensile stress in the concrete can be predicted from the Spangler equation of corner load stresses.

The material parameters required are the modulus of rupture of the concrete and the modulus of subgrade reaction.

The following values were selected as representative for the purposes of establishing comparative pavement structural sections:

Modulus of Rupture	600 psi
Working Stress of Concrete	f_t = 450 psi
Cement-Treated Subbase	k_c = 350 pci
Bituminous Open-Graded Subbase	k_b = 200 pci
Gravel Subbase	k_s = 300 pci

The following example indicates the basic procedures to be utilized in the application of the AASHO Interim Guide. Assuming the terminal (lowest acceptable) serviceability index (P_t) of 2.5, traffic analysis period is 20 years, subgrade modulus (k_g) is 100 pci, and equivalent daily 18 kip single-axle load applications for the most heavily traveled lanes is 1,000. The example location area is frost susceptible and the minimum required structural section thickness, based on experience in that area, has been determined to be 15 inches. Also, the minimum specified Portland cement concrete thickness is assumed to be 8 inches for use on the Interstate System. The total pavement thickness as determined from design charts for two different types of structural section follow:

Conventional Section

Concrete Pavement	9 inches
Cement-Treated Subbase	6 inches
Thickness =	15 inches

Open-Graded Base Section

Concrete Pavement	9 inches
Bituminous-Treated Subbase	6 inches
Thickness =	15 inches

The effect of the various State Highway Departments' policies with regard to minimum pavement section thickness is more significant for rigid pavements than it is for flexible pavements. Although no attempt will be made to compare different pavement designs in the following cost-effectiveness analyses, the final conclusions developed will be valid.

8.3 Economic Analyses

8.3.1 General

The intent of the economic analysis is to demonstrate the economic advantage of using open-graded bases and to establish the parameters to evaluate the boundary conditions for each individual design project.

The economic analysis will undertake to determine the relative construction costs and annual costs of pavements with, and without, subsurface drainage systems. It is recommended that similar type analyses be made by the State Highway Departments, utilizing local estimated unit costs. These analyses will show that if positive subsurface drainage systems effectively reduce maintenance or extend the useful life of pavements only a few years, the added first costs of construction will be repaid in a short time. These comparisons do not take into account the many direct or indirect costs of deteriorating and damaged pavements, such as added discomfort to the motoring public, increased car repairs and tire wear, decrease of safety, and time delays to the users of the roads. The advantages of trouble-free roads are many, in addition to the direct costs considered in this study.

8.3.2 Rigid Pavement Example

In this example, it is assumed that a four-lane, divided highway is to be constructed according to the dimensions shown on Fig. 22, on the following page. Two alternatives are considered on Fig. 22: one alternative provides for positive subsurface drainage; the other alternative does not.

The design data are as follows:

Global permeability of pavement and joints, k_g	0.20 in/hour
Permeability of granular base, k_b	10 ft/day
Permeability of subgrade (AASHO Class A-6), k_s	0.0002 ft/day
PCC pavement thickness	9 inches
Granular base thickness	8 inches
Granular base dry unit weight	130 lbs/cu ft
Granular base moisture content at placement	7 percent
Granular base moisture content at saturation	11 percent

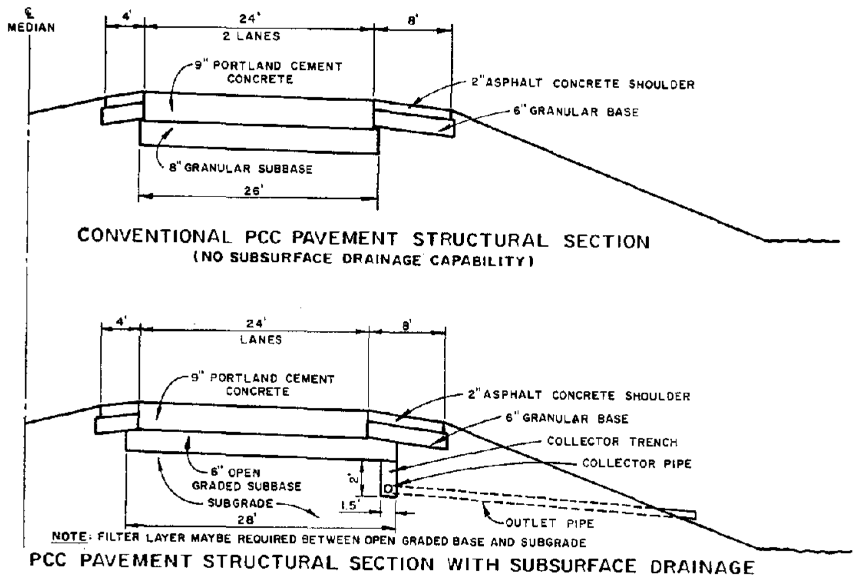


FIGURE NO. 22

RIGID PAVEMENT SECTION EXAMPLES

The moisture content can be expressed in inches of water per square foot of subbase course as follows:

$$\frac{0.07 \times 130}{62.4} \times 8 \text{ inches} = 1.17 \text{ inches at placement}$$

$$\frac{0.11 \times 130}{62.4} \times 8 \text{ inches} = 1.83 \text{ inches at saturation}$$

The difference between moisture content at saturation and the moisture content at placement is the quantity of water that must infiltrate the structural section to saturate the subbase course which creates a condition conducive to pumping:

$$1.83 - 1.17 = 0.66 \text{ inch}$$

Water can inflow through the pavement surface in sufficient quantity to saturate the subbase course, unless the drainage capacity of the structural section is sufficient to prevent accumulation of water therein.

Drainage of the subbase occurs both vertically and laterally, although the relative magnitude of the latter may be negligible (except where highly permeable subbases are daylighted to drain freely). The seepage rate through the subgrade can be obtained by constructing a flow net (see Fig. 23).

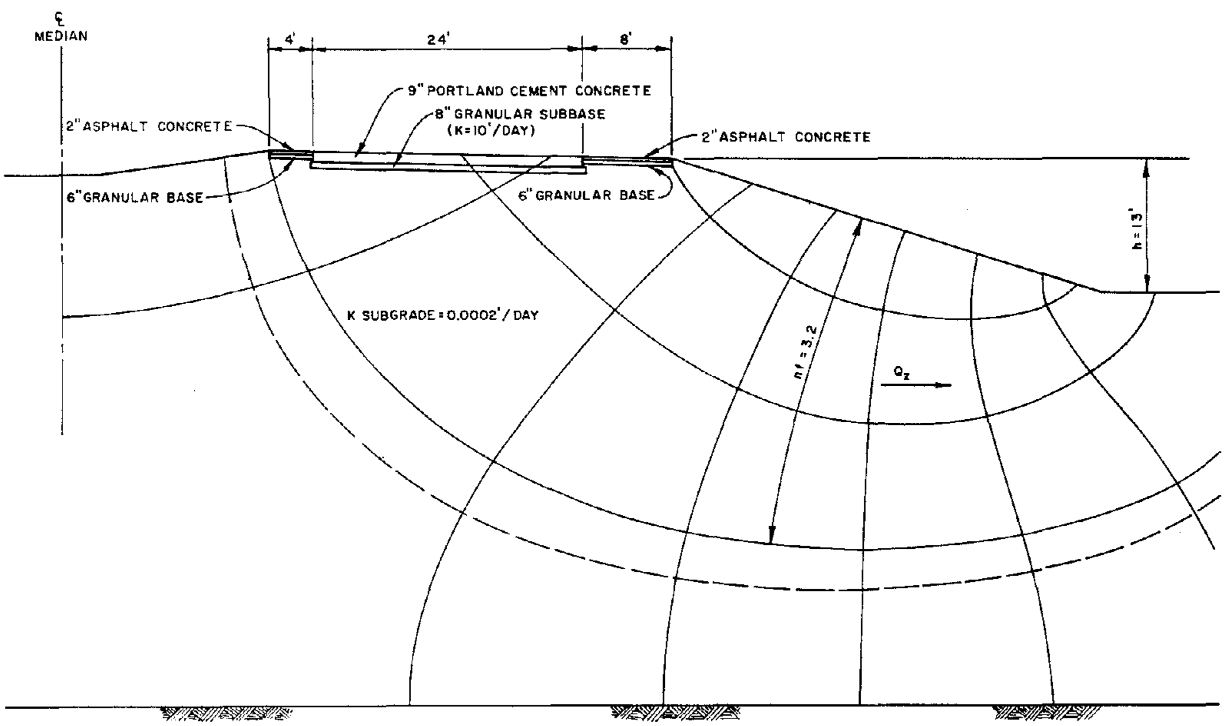


FIGURE NO. 23

FLOW NET TO DETERMINE SEEPAGE RATE THROUGH SUBGRADE

$$q = kh\frac{n_f}{n_d} = 0.0002 \text{ ft/day} \times 13 \text{ ft} \times \frac{3.2}{6.5} =$$

0.0013 cu ft/day for each foot of highway length.

The drainage rate can be converted to inches of water per hour per square foot of subbase course:

$$\frac{0.0013 \text{ cu ft/day} \times 12 \text{ in/ft}}{24 \text{ hr/day} \times 26 \text{ ft}^2} = 0.000025 \text{ in/hr/ft}^2 \text{ (negligible)}$$

The granular subbase will provide some subsurface drainage for the pavement sections located at higher relative elevations. Water will flow downgrade from these higher elevations at a rate determined by the grades in accordance with Darcy's Law ($Q = kiA$). The highway grade at the example location is $g = 0.03$; therefore, the quantity of water that can flow downgrade through the section is:

10 ft/day x 26 ft x 0.67 ft x 0.03 = 5.2 cu ft/day

The net effect of the foregoing is to displace the potential subsurface drainage problem from the higher pavement elevations to the low points of the highway, even though the total inflow through the pavement surface may not be enough to saturate the entire subbase course.

Relief to the subsurface water flow is generally provided by imperfectly sealed joints which permit water to emerge under pressure and flow on the surface of the pavement to the shoulders. (This is a common occurrence that can be observed in many PCC pavements after a rainstorm.)

The quantity of water that infiltrates the structural section depends on the rate of precipitation to a maximum of 0.20 inch per hour (global permeability of pavement). This rate will not be exceeded even if the rate of precipitation increases indefinitely.

When the granular subbase becomes saturated, pumping generally occurs and will continue as long as the subbase contains free water.

By a simple calculation, the maximum theoretical length of highway grade, $\underline{L}$, that can be drained by the granular subbase before it becomes saturated can be determined. Considering $\underline{P}$ to be the precipitation rate (not to exceed $\underline{k_g}$), and the effective width of pavement where infiltration takes place as being 24 feet, then the outflow capacity is equated to the probable inflow:

$$24 \text{ ft} \times L \text{ (ft)} \times P \text{ (in/hr)} \times \frac{1 \text{ ft}}{12 \text{ in}} \times \frac{24 \text{ hr}}{1 \text{ day}} = 5.2 \text{ cu ft/day}$$

$$\text{and,} \quad L \text{ (ft)} = \frac{5.2}{48} \times \frac{1}{P} = 0.108 \frac{1}{P}$$

If the numerical value of $\underline{P}$ is assumed to vary between 0.01 inch/hour and 0.20 inch/hour, the following values for $\underline{L}$ are obtained:

P (in/hr)	L (ft)
0.01	11
0.05	2
0.10	1
0.20	0.5

The foregoing indicates that the capability of the granular subbase to convey a significant amount of precipitation that infiltrates through the pavement surface is extremely limited. Only after the precipitation has stopped will the granular subbase contribute (in a small way) to drain the subsurface water toward low points in the highway section.

The foregoing also indicates that infiltration of water into the structural section will probably slow down as soon as the subbase becomes saturated; that is, after any rainfall totaling 0.66 inch (from Page 161) at precipitation rates not exceeding 0.20 inch/hour.

After the precipitation stops, the free water that has saturated the subbase can drain through the subbase course at the rate of 5.2 cubic feet/day or approximately 0.22 cubic foot/hour. If the subbase course contains 0.66 inch of water per square foot, the total of 0.22 cubic foot that will be drained in 1 hour is contained in a section of highway whose length, L, can be calculated:

$$26 \text{ ft} \times L \text{ (ft)} \times \frac{0.66 \text{ in}}{12 \text{ in/ft}} = 0.22 \text{ cubic foot}$$

$$L = \frac{0.22 \times 12}{26 \times 0.66} = 0.154 \text{ foot (in 1 hour)}$$

Using this method of calculation as a rough criterion of drainability, the granular subbase course would lose its susceptibility to pumping at a rate of approximately 0.16 foot in 1 hour as measured along the centerline of the highway, assuming that edge and transverse joints will permit the water to drain.

If the subbase course does not become saturated because the total amount of precipitation remains less than 0.66 inch, the length of subbase course that can be drained in 1 hour is proportionately longer.

Assuming that every joint in the pavement will permit the escape of water (drainage) and the distance between transverse joints is 40 feet, the length of time required to lower the water content below the critical value in the subbase course between two consecutive joints would be:

$$\frac{40}{0.16} = 250 \text{ hours}$$

If this condition is attained at least six times during any year, the PCC pavement would be exposed to pumping damage for a total of 1,500 hours of the 8,760 total hours per year. While a lesser amount of drainage (possibly around 50 percent) might be sufficient to stop pumping, a value of 100 percent is used in this example to provide a factor of safety to compensate for approximations in the method.

Continuing with this example, if a severity ratio of 10 is used when the granular subbase course is saturated, the effects of traffic loads are estimated as follows:

$$\begin{aligned} \frac{1500}{8760} = 17\% \times 10 &= 170\% \\ 83\% \times 1 &= \underline{\ 83\%} \\ \text{Total} &\quad 253\% \end{aligned}$$

The life factor will be:

$$\frac{100}{253} = 0.40$$

This means that the pavement will deteriorate at a rate 2.5 times faster than it would if it were properly drained, and the predicted life of the pavement is only 40 percent of what could be expected with good drainage.

The cost of constructing the example PCC pavement system with a granular subbase, based on 1972 bid prices, and excluding grading, earthwork, subgrade preparation, and other incidental items which are similar, can be computed utilizing the following unit prices:

Portland Cement Concrete	\$21.00/cubic yard
Granular Aggregate Subbase	\$6.30/cubic yard

The quantities per foot of 24-foot wide highway pavement are:

$$\text{PCC Pavement} = \frac{24 \text{x} 0.75 \text{x} 1}{27} = 0.67 \text{ Cubic yard/foot}$$

$$\text{Granular Aggregate Subbase} = \frac{26 \text{x} 0.67 \text{x} 1}{27} = 0.65 \text{ cubic yard/foot}$$

The cost per foot of 24-foot wide highway pavement is:

0.67 cubic yards @ \$21.00/cubic yard	\$14.00
0.65 cubic yards @ \$6.30/cubic yard	4.10
	\$18.10/foot

The example structural section that incorporates subsurface drainage capability has the following features (see Fig. 22). An open-graded subbase will be utilized to replace the granular aggregate subbase and a system of underdrains will be provided to remove the subsurface water rapidly away from the roadway section.

The open-graded subbase will be designed so that water infiltrating through open transverse and edge joints at a rate equal to the 1 year/1 hour precipitation rate will drain within 1 hour. Enter Fig. 24 for a highway width of two lanes, $\underline{g}$ = 3 percent (0.03) and thickness of subsurface drainage layer tentatively equal to 5 inches. The permeability $\underline{k_b}$ of the drainage layer should not be less than 6,300 feet/day.

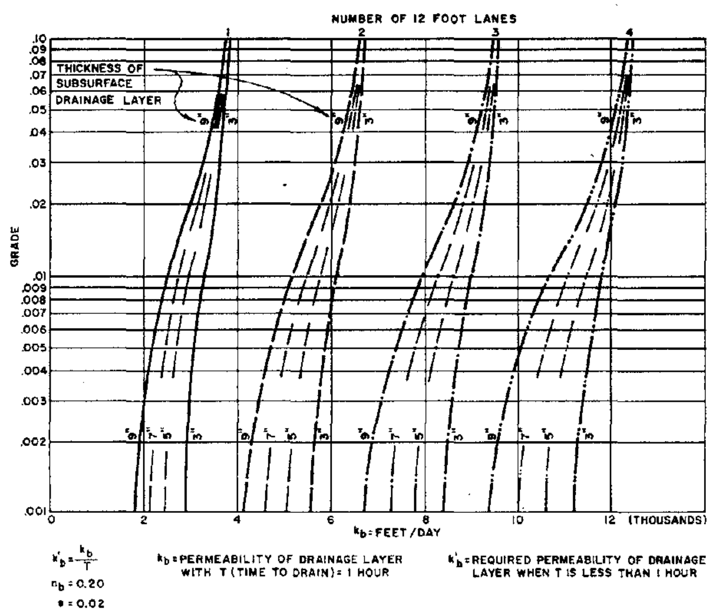


FIGURE NO. 24

PERMEABILITY REQUIRED IN ORDER TO DRAIN SUBSURFACE DRAINAGE LAYER IN 1 HOUR OR LESS

Then, to verify the capacity of the drainage layer to remove the estimated rate of flow, enter Fig. 25 with the values of $\frac{W}{s} = \frac{24}{0.03} = 800$ and the coefficient of transmissibility = 6,300 x 5 inches = 31,500 inch feet/day. In this case, $\underline{I}$ = 1.55 inches/hour, which is greater than the 1 year/1 hour precipitation rate.

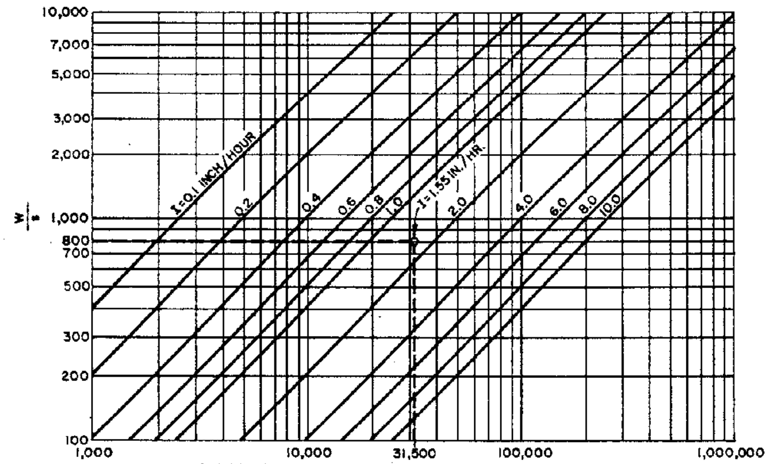


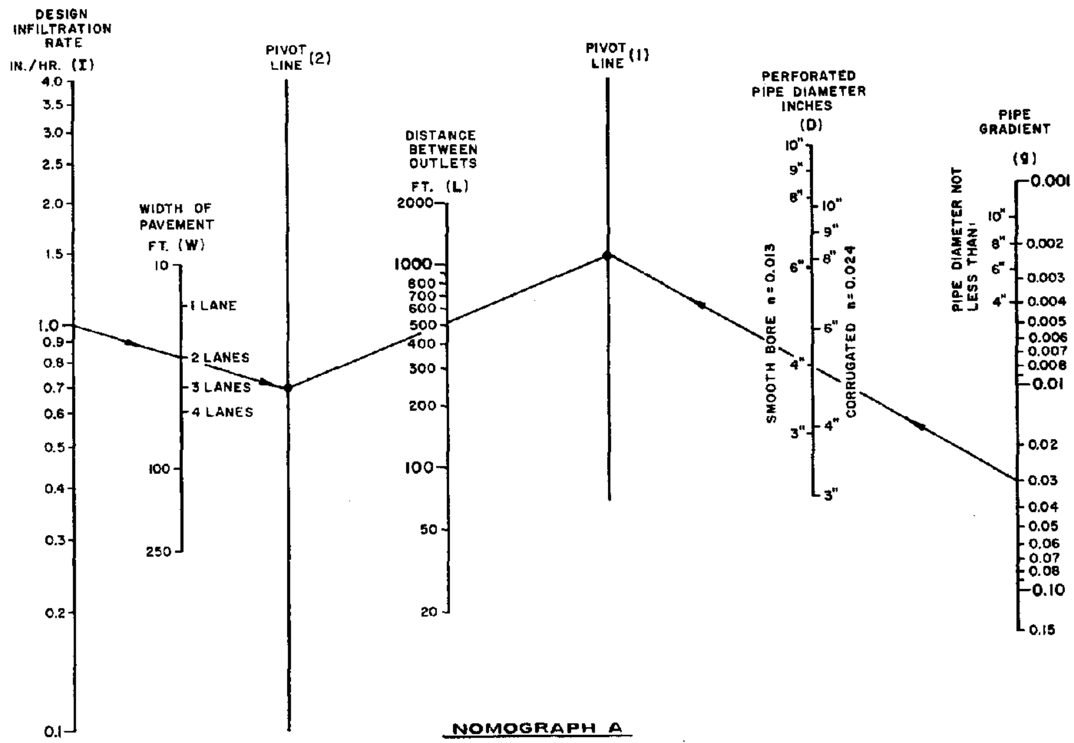
FIGURE NO. 25

TRANSMISSIBILITY VERSUS W/s

By referring to Fig. 25, it can be seen that increasing the magnitude of W/s increases the required coefficient of transmissibility. Also, for a given value of W/s, the required coefficient of transmissibility is directly proportional to the design infiltration rate.

In developing the complete design of an underdrain system, it is necessary to determine suitable collector pipe sizes, and suitable outlet pipe spacings and sizes. To assist with these determinations, Nomograph A was prepared (following page).

To determine the underdrain system required, enter Nomograph A with the value of WI = 24 x 1 = 24 and the pipe gradient, g = 0.03; different combinations of pipe type, diameter, and distance between outlets can be obtained.



NOMOGRAPH A

SELECTION OF PERFORATED PIPE DIAMETERS AND OUTLET SPACINGS

For this example, the following elements were selected for the underdrain system.

Lateral Underdrain - 4-inch (smooth-bore) pipe

Outlet - every 500 feet

The unit prices used to estimate the cost per foot of highway pavement with a subsurface drainage system are as follows:

Portland Cement Concrete	\$21.00/cubic yard
Asphalt Stabilized Open-Graded Subbase	\$10.00/cubic yard
Trench Excavation (lateral underdrain)	\$ 2.65/cubic yard
Pervious Backfill	\$10.50/cubic yard
4-inch, Smooth-Bore Perforated Pipe	\$ 1.60/foot

The quantities per foot of length of highway are:

$$\text{PCC pavement} = \frac{24 \times 0.75 \times 1}{27} = 0.67 \text{ cu yd/ft}$$

Asphalt stabilized open-graded subbase = $\frac{28x0.50x1}{27}$ =

0.52 cu yd

Trench excavation = $\frac{2x1.5x1.10}{27}$ = 0.12 cu yd

Pervious backfill = $\frac{2x1.5x1}{27}$ = 0.11 cu yd

4-inch, smooth-bore perforated pipe = 1.10 ft

The cost per foot of highway pavement is:

0.67 cubic yard @ $21.00/cubic yard	$14.00
0.52 cubic yard @ $10.00/cubic yard	5.20
0.12 cubic yard @ $2.65/cubic yard	.32
0.11 cubic yard @ $10.50/cubic yard	1.16
1.10 feet @ $1.60/foot	1.75
	$22.43

The initial cost of the pavement system with a subsurface drainage system is $4.33/linear foot (or about $20,000/mile) greater than a pavement system with a conventional granular base.

The annual cost of the two pavement systems can be estimated by using the estimated predicted life of both systems. The interest rate on capital investment is assumed to be 5 percent annually, and a design life of 20 years. The predicted life of the pavement system utilizing a conventional base is only 40 percent of 20 years or 8 years; the predicted life of the pavement system incorporating subsurface drainage is 100 percent or 20 years. The annual cost factors are 0.155 and 0.080, respectively; and the annual costs for the two pavement systems are:

0.155 x $18.10 = $2.82/foot for undrained pavement
0.080 x $22.43 = $1.80/foot for well drained pavement

Since the well drained pavement will probably give more than 20 years of good service, its true economic benefits could be much greater than is indicated by these calculations.

8.3.3 Flexible Pavement Example

For this example, the geometric characteristics of the highway pavement system are: six lanes, divided with depressed median, longitudinal grade - 3 percent, cross slope - 2 percent. Dimensions for the structural sections are shown on the following Fig. 26.

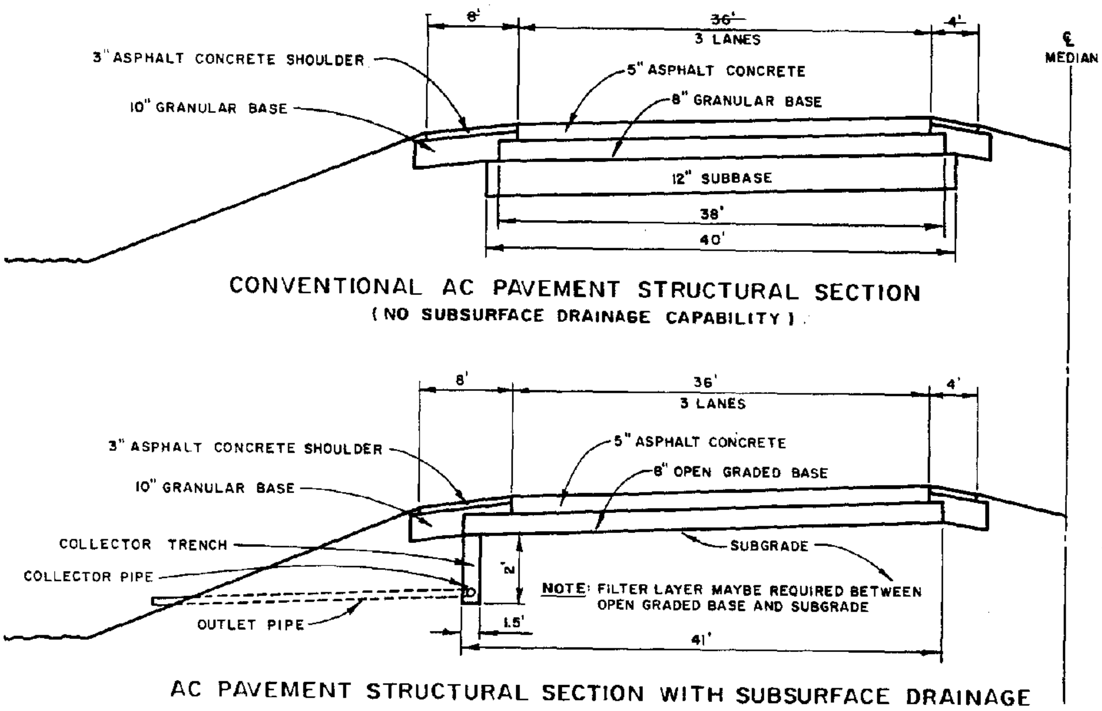


FIGURE NO. 26

FLEXIBLE PAVEMENT SECTION EXAMPLES

Both pavement sections have an identical structural strength number. The following data have been compiled for pavement section design.

	Permeability	Dry Unit Weight	Water Content at Placement	Water Content at Saturation
Aggregate Base	4 ft/day	125 lbs/ft^3	7.3%	13%
Granular Subbase	10 ft/day	114 lbs/ft^3	11.7%	17%
Subgrade	0.04 ft/day	108 lbs/ft^3	15.6%	20%

The global permeability of the flexible pavement, k_g = 0.50 inch per hour. Moisture content can be expressed in inches of water per square foot of pavement. The saturation values (100 percent) for each material at the specified placement relative densities are:

$$\text{Base Course} - 0.13 \times \frac{125\ lbs/ft^3}{62.4\ lbs/ft^3} \times 8\ in = 2.08\ in/sq\ ft$$

$$\text{Subbase Course} - \frac{60\ ft^*}{49\ ft^{**}} \times 0.17 \times \frac{114\ lbs/ft^3}{62.4\ lbs/ft^3} \times 12\ in = 4.55\ in/sq\ ft$$

Values of inches of water per square foot at placement moisture content and relative densities are:

$$\text{Base Course} - 0.073 \times \frac{125\ lbs/ft^3}{62.4\ lbs/ft^3} \times 8\ in = 1.17\ in/sq\ ft$$

$$\text{Subbase Course} - \frac{60\ ft}{49\ ft} \times 0.117 \times \frac{114\ lbs/ft^3}{62.4\ lbs/ft^3} \times 12\ in = 3.14\ in/sq\ ft$$

The infiltrated water required to raise the base and subbase from optimum water content to 100-percent saturation the first time, is as follows:

*width of daylighted subbase
**width of base course

Base:	2.08 - 1.17 = 0.91	inches/sq ft of pavement surface
Subbase:	4.55 - 3.14 = 1.41	inches/sq ft of pavement surface
Totals	6.63 - 4.31 = 2.32	inches/sq ft of pavement surface

Repeated triaxial tests to determine the resilience characteristics of the base, subbase and subgrade materials indicate that the base material is critical. It is assumed that the severity ratios will be proportional to the resilient deformations of the materials at optimum moisture and 100-percent saturation.

The severity ratios at various saturation values can be converted into inches of water per square foot, assuming that both base and subbase courses attain the same degree of saturation simultaneously. This is a simplifying hypothesis. It is assumed that a severity ratio, $\underline{R} = 1$, is exceeded when the 80-percent saturation level in the material is reached. Likewise, $\underline{R} = 2$ is exceeded when the 90-percent saturation level is reached and so successively:

R = 2	6.63 x 0.80 - 4.31 = 1.00 inch
R = 3	6.63 x 0.90 - 4.31 = 1.65 inches
R = 4	6.63 x 0.95 - 4.31 = 2.00 inches
R = 5	6.63 x 0.98 - 4.31 = 2.20 inches
R = 10	6.63 x 1.00 - 4.31 = 2.32 inches

The initial step in the analysis of inflow/outflow balance requires the computation of the outflow characteristics of the highway pavement structural section. In the case presented, outflow occurs both through the daylighted granular subbase and through the subgrade.

Using Darcy's Law, the amount of seepage through the daylighted subbase is:

$$q = kiA, \underline{\text{or}}$$
$$q = 10 \text{ ft/day } (0.02 + \frac{0.50}{60}) \times 1.0 \text{ sq ft}$$
$$q = 0.283 \text{ cu ft/day for each foot of length}$$

Using flow net principles (see Fig. 27), the seepage through the subgrade material is estimated to be:

$$q = kh\frac{n_f}{n_d}, \underline{\text{or}}$$

$$q = 0.04 \text{ ft/day} \times 9 \text{ ft} \times \frac{6}{8} = 0.27 \text{ cu ft/day for each foot of length.}$$

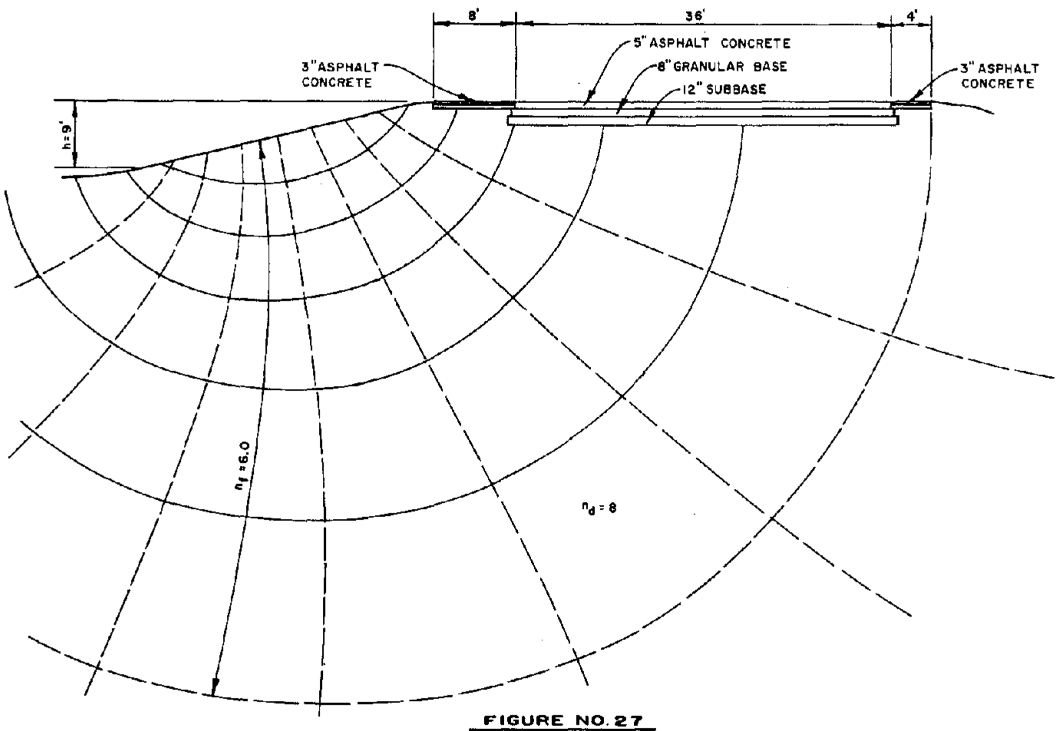


FIGURE NO. 27

SEEPAGE THROUGH SUBGRADE—AC PAVEMENT STRUCTURAL SECTION

The total outflow for average conditions is, therefore:

$$O' = 0.283 + 0.27 = 0.553 \text{ cu ft/day}$$

The total outflow value can be converted into an equivalent pavement infiltration rate expressed in inches per hour:

$$O' = \frac{0.553 \text{ cu ft/day} \times 12 \text{ inches/foot}}{24 \text{ hr/day} \times 48 \text{ sq ft}} = 0.006 \text{ inch/hour}$$

If an evaporation rate of 1 inch per month is considered reasonable for the area, then evaporation losses are:

$$\frac{1 \text{ inch}}{720 \text{ hours}} = 0.0014 \text{ inch/hour}$$

and the total losses (outflow + evaporation) are:

$$O = 0.006 + 0.001 = 0.01 \text{ inch/hour (rounded)}$$

The inflow is derived from application of a 12-month period precipitation model. The inflow/outflow balance analysis is based on the following.

$$S = I - O$$

where, S = water storage in base and subbase courses
I = inflow (infiltration through paved surface)
O = outflow (seepage and evaporation losses)

A detailed analysis is presented in Table 6, following.

TABLE 6

INFLOW—OUTFLOW BALANCE ANALYSIS

L	E	H	P	O+e	I	S	R
	1	1	.03	0.01	.02	0.02	1
		2	.04	0.01	.03	0.05	1
		3	.10	0.01	.09	0.14	1
		4	.04	0.01	.03	0.17	1
		5	.05	0.01	.04	0.21	1
5			-	0.01	-.05	0.16	1
	2	1	.03	0.01	.02	0.17	1
		2	.09	0.01	.08	0.25	1
		3	.18	0.01	.17	0.42	1
		4	.07	0.01	.06	0.48	1
		5	.14	0.01	.13	0.61	1
		6	.04	0.01	.03	0.64	1
		7	.05	0.01	.04	0.68	1
		8	.17	0.01	.16	0.84	1
		9	.15	0.01	.14	0.98	1
		10	.10	0.01	.09	1.07	2
		11	.01	0.01	0	1.07	2
		12	.02	0.01	.01	1.08	2
1			-	0.01	-.01	1.07	2
	3	1	.09	0.01	.08	1.15	2
		2	.05	0.01	.04	1.19	2
		3	.14	0.01	.13	1.32	2
		4	.05	0.01	.04	1.36	2
		5	.02	0.01	.01	1.37	2
		6	.01	0.01	0	1.37	2
7			-	0.01	-.07	1.30	2
	4	1	.04	0.01	.03	1.33	2
		2	.01	0.01	0	1.33	2
2			-	0.01	-.02	1.31	2
	5	1	.01	0.01	0	1.31	2
		2	.17	0.01	.16	1.47	2
		3	.14	0.01	.13	1.60	2
		4	.05	0.01	.04	1.64	2
		5	.03	0.01	.02	1.66	2
		6	.05	0.01	.04	1.70	3
		7	.02	0.01	.01	1.71	3
		8	.01	0.01	0	1.71	3
1			-	0.01	-.01	1.70	3
	6	1	.01	0.01	0	1.70	3
		2	.02	0.01	.01	1.71	3
		3	.03	0.01	.02	1.73	3
		4	.02	0.01	.01	1.74	3
		5	.09	0.01	.08	1.82	3
		6	.05	0.01	.04	1.86	3
		7	.01	0.01	0	1.86	3
		8	.07	0.01	.06	1.92	3
		9	.07	0.01	.06	1.98	3
		10	.05	0.01	.04	2.02	4
		11	.07	0.01	.06	2.08	4
		12	.04	0.01	.03	2.11	4
		13	.02	0.01	.01	2.12	4
		14	.04	0.01	.03	2.15	4
		15	.01	0.01	0	2.15	4
		16	.01	0.01	0	2.15	4
		17	.04	0.01	.03	2.18	4
		18	.10	0.01	.09	2.27	5
		19	.22	0.01	.21	(2.42)	10
		20	.39	0.01	.38	(2.42)	10
		21	.03	0.01	.02	(2.42)	10
		22	.10	0.01	.09	(2.42)	10
		23	.71	0.01	.70	(2.42)	10
		24	.15	0.01	.14	(2.42)	10
		25	.16	0.01	.15	(2.42)	10
7			-	0.01	-.07	2.37	10
	7	1	.01	0.01	0	2.37	10
1			-	0.01	-.01	2.36	10

L	E	H	P	O+e	I	S	R
1			.01	0.01	-.01	2.36	10
	8	1	.17	0.01	.16	(2.42)	10
		2	.07	0.01	.06	(2.42)	10
		3	.04	0.01	.03	(2.42)	10
1			-	0.01	-.01	2.41	10
	9	1	.02	0.01	.01	2.42	10
		2	.07	0.01	.06	(2.42)	10
		3	.01	0.01	0	2.42	10
1			-	0.01	-.01	2.41	10
	10	1	.02	0.01	.01	2.42	10
		2	.03	0.01	.02	(2.42)	10
		3	.12	0.01	.11	(2.42)	10
		4	.01	0.01	0	2.42	10
		5	.05	0.01	.04	(2.42)	10
8			-	0.01	-.08	2.34	10
	11	1	.01	0.01	0	2.34	10
2			-	0.01	-.02	2.32	10
	12	1	.01	0.01	0	2.32	10
		2	.04	0.01	.03	2.35	10
		3	.04	0.01	.03	2.38	10
		4	.04	0.01	.03	2.41	10
		5	.01	0.01	0	2.41	10
1			-	0.01	-.01	2.40	10
	13	1	.01	0.01	0	2.40	10
8			-	0.01	-.08	2.32	5
12			-	0.01	-.12	2.20	4
83 { 20			-	0.01	-.20	2.00	3
32			-	0.01	-.32	1.68	2
11			-	0.01	-.11	1.57	2
	14	1	.05	0.01	.04	1.61	2
		2	.10	0.01	.09	1.70	3
		3	.17	0.01	.16	1.86	3
		4	.20	0.01	.19	2.05	4
		5	.06	0.01	.05	2.10	4
		6	.05	0.01	.04	2.14	4
		7	.08	0.01	.07	2.21	5
		8	.28	0.01	.27	(2.42)	10
		9	.11	0.01	.10	(2.42)	10
		10	.01	0.01	0	2.42	10
1			-	0.01	-.01	2.41	10
	15	1	.01	0.01	0	2.41	10
		2	.01	0.01	0	2.41	10
		3	.01	0.01	0	2.41	10
		4	.01	0.01	0	2.41	10
5			-	0.01	-.01	2.36	10
	16	1	.02	0.01	.01	2.37	10
15			-	0.01	-.05	2.32	5
21 { 12			-	0.01	-.12	2.20	4
4			-	0.01	-.04	2.16	4
	17	1	.01	0.01	0	2.16	4
		2	.03	0.01	.02	2.18	4
		3	.03	0.01	.02	2.20	4
		4	.03	0.01	.02	2.22	5
		5	.25	0.01	.24	(2.42)	10
		6	.08	0.01	.07	(2.42)	10
		7	.14	0.01	.13	(2.42)	10
		8	.03	0.01	.02	(2.42)	10
		9	.01	0.01	0	2.42	10

L	E	H	P	O+e	I	S	R
15 { 10			-	0.01	-.10	2.32	5
5			-	0.01	-.05	2.27	5
	18	1	.01	0.01	0	2.27	5
3			-	0.01	-.03	2.24	5
	19	1	.01	0.01	0	2.24	5
		2	.14	0.01	.13	2.37	10
1			-	0.01	-.01	2.36	10
	20	1	.04	0.01	.03	2.39	10
7			-	0.01	-.07	2.32	5
12			-	0.01	-.12	2.20	4
344 { 20			-	0.01	-.20	2.00	3
32			-	0.01	-.32	1.68	2
68			-	0.01	-.68	1.00	1
205			-	0.01	-2.05	(0.00)	1
	21	1	.01	0.01	0	0	1
		2	.04	0.01	.03	0.03	1
9			-	0.01	-.09	(0.00)	1
	22	1	.01	0.01	0	0	1
		2	.01	0.01	0	0	1
41			-	0.01	-.41	(0.00)	1
	23	1	.12	0.01	.11	0.11	1
		2	.02	0.01	.01	0.12	1
		3	.32	0.01	.31	0.43	1
		4	.01	0.01	0	0.43	1
55			-	0.01	-.55	(0.00)	1
	24	1	.01	0.01	0	0	1
		2	.03	0.01	.02	0.02	1
1			-	0.01	-.01	0.01	1
	25	1	.06	0.01	.05	0.06	1
		2	.14	0.01	.13	0.19	1
341			-	0.01	-3.41	(0.00)	1
	26	1	.05	0.01	.04	0.04	1
		2	.03	0.01	.02	0.06	1
		3	.03	0.01	.02	0.08	1
		4	.08	0.01	.07	0.15	1
		5	.08	0.01	.07	0.22	1
		6	.03	0.01	.02	0.24	1
		7	.06	0.01	.05	0.29	1
		8	.07	0.01	.06	0.35	1
		9	.15	0.01	.14	0.49	1
		10	.11	0.01	.10	0.59	1
		11	.11	0.01	.10	0.69	1
		12	.13	0.01	.12	0.81	1
		13	.35	0.01	.34	1.15	2
1			-	0.01	-.01	1.14	2
	27	1	.20	0.01	.19	1.33	2
		2	.17	0.01	.16	1.49	2
		3	.10	0.01	.09	1.58	2
		4	.03	0.01	.02	1.60	2
		5	.09	0.01	.08	1.68	3
		6	.14	0.01	.13	1.81	3
1			-	0.01	-.01	1.80	3
	28	1	.02	0.01	.01	1.81	3
10			-	0.01	-.10	1.71	3
	29	1	.04	0.01	.03	1.74	3
1			-	0.01	-.01	1.73	3
	30	1	.05	0.01	.04	1.77	3
		2	.01	0.01	0	1.77	3
		3	.05	0.01	.04	1.81	3
13			-	0.01	-.13	-1.68	2
484 { 68			-	0.01	-.68	1.00	1
403			-	0.01	-4.03	(0.00)	1

L	E	H	P	O+e	I	S	R
	31	1	.01	0.01	0	0	1
		2	.04	0.01	.03	0.03	1
250			-	0.01	-2.50	(0.00)	1
	32	1	.20	0.01	.19	0.19	1
		2	.33	0.01	.32	0.51	1
		3	.38	0.01	.37	0.88	1
		4	.69	0.01	.68	1.56	2
		5	.20	0.01	.19	1.75	3
		6	.10	0.01	.09	1.84	3
		7	.01	0.01	0	1.84	3
1			-	0.01	-.01	1.83	3
	33	1	.04	0.01	.03	1.86	3
		2	.10	0.01	.09	1.95	3
56 { 27			-	0.01	-.27	1.68	2
29			-	0.01	-.29	1.39	2
	34	1	.02	0.01	.01	1.40	2
93 { 40			-	0.01	-.40	1.00	1
53			-	0.01	-.53	0.47	1
	35	1	.02	0.01	.01	0.48	1
1			-	0.01	-.01	0.47	1
	36	1	.01	0.01	0	0.47	1
		2	.01	0.01	0	0.47	1
		3	.03	0.01	.02	0.49	1
		4	.01	0.01	0	0.49	1
		5	.01	0.01	0	0.49	1
		6	.04	0.01	.03	0.52	1
		7	.17	0.01	.16	0.67	1
		8	.10	0.01	.09	0.76	1
		9	.18	0.01	.17	0.93	1
		10	.05	0.01	.04	0.97	1
		11	.07	0.01	.06	1.03	2
		12	.03	0.01	.02	1.05	2
		13	.05	0.01	.04	1.09	2
		14	.02	0.01	.01	1.10	2
		15	.04	0.01	.03	1.13	2
		16	.02	0.01	.01	1.14	2
14			-	0.01	-.14	1.00	1
2192			-	0.01	-21.92	(0.00)	1
	37	1	.01	0.01	0	0	1
		2	.03	0.01	.03	0.03	1
3430			-	0.01	-34.30	(0.00)	1
	38	1	.01	0.01	0	0	1
1			-	0.01	-.01	(0.00)	1
	39	1	.02	0.01	.01	0.01	1
		2	.02	0.01	.01	0.01	1
1092			-	0.01	-10.92	(0.00)	1

ABBREVIATIONS

L - Interval between precipitation events (hours)

E - Event number

H - Hour of event

P - Hourly precipitation (inches)

O+e - Hourly outflow and evaporation (inches)

I - Effective inflow (inches)

S - Accumulated inflow = storage in inches of water

R - Severity ratio corresponding to degree of saturation

NOTE: (2.42) indicates 100% saturation

The duration of the critical period can be obtained from Table 6 by totaling the number of hours the pavement structural section has been subjected to damaging saturation levels. Multiplying the severity ratios by the corresponding number of hours, the total effect of traffic loads on the pavement can be evaluated as follows:

Severity Ratio (R)	Number of Hours (T)	R x T
1	8,329	8,329
2	185	370
3	80	240
4	54	216
5	43	215
10	69	690
Total	8,760	10,060

That is, for the average environmental conditions prevailing at the example location, the action of traffic loads on the pavement during a typical 12-month period is equivalent to 10,060 hours of traffic loads.

The evaluation of the life factor for the example pavement section is:

$$L = \frac{8,760}{RxT}$$

or

$$L = \frac{8,760}{10,060} = 0.87$$

The estimate of construction cost for a conventional pavement section (without subsurface drainage) is as follows.

Asphalt Conc. -	$\frac{(5x36+3x12)12.5}{2000}$	= 1.35 tons @ \$10.50 =	\$14.20
Base Course -	$\frac{8x50x10.4}{2000}$	= 2.08 tons @ \$6.30 =	13.10
Subbase Course -	$\frac{10x60x9.5}{2000}$	= 2.85 tons @ \$4.75 =	13.50
		Total Cost per Foot of Length	\$40.80

An analysis of the flexible pavement structural section with subsurface drainage features that has identical strength characteristics of the conventional section follows. This structural section differs from the conventional section because it incorporates an open-graded base, the subdrainage element.

The following data have been compiled for design:

Longitudinal grade	-	3 percent
Time to drain structural section	-	30 minutes

Figure 24 indicates the minimum required asphalt stabilized open-graded base thickness. A 3-inch open-graded base drainage layer with a permeability $\underline{k_b}$ of at least 19,000 feet per day is required. However, the selected structural section is:

5 inches of asphalt concrete pavement
8 inches of open-graded base ($\underline{k}$ = 18,000 feet/day)

In addition, a penetration treatment will be applied to the top of the subgrade to stabilize the material and prevent migration of fines into the open-graded base. From Nomograph A, the size of the lateral perforated underdrain pipe and the distance between outlets can be determined.

Enter Nomograph A for 3 lanes, $\underline{I}$ = 1 inch/hour and $\underline{g}$ = 0.03, If a 4-inch diameter, smooth-bore perforated pipe is selected for the lateral underdrain, the outlet spacing will be 350 feet. The minimum trench width is determined by:

$B = \frac{12WI}{k_t}$, where k_t is the permeability of the trench backfill.

Using k_t = 150 feet/day, $B = \frac{12x22}{150} = 1.75$ feet

The cost per unit length of highway for the pavement section with subsurface drainage is as follows:

Asphalt Concrete -	$\frac{(5x36+3x12)12.5}{2000}$	= 1.35 tons	@	$10.50 =	$14.20
Open-Graded Base -	$\frac{8x40x10.4}{2000}$	= 1.66 tons	@	$10.00 =	16.60
Penetration Treatment -	$\frac{40}{9}$ x 0.30	= 1.33 gals	@	$0.32 =	0.43
Aggregate Base -	$\frac{6x10x10}{2000}$	= 0.30 ton	@	$6.30 =	1.89
Trench Excavation -	$\frac{2.5x1.75x1.1}{27}$	= 0.18 cu yd	@	$2.65 =	0.47
Pervious Backfill		= 0.18 cu yd	@	$10.50 =	1.90
4-Inch Perforated Pipe		= 1.10 feet	@	$1.60 =	1.75

Total Cost of Pavement Section per Foot of Length = $37.24

In this example, the initial cost of the structural section incorporating the drainage layer is less than for the conventional pavement section using aggregate base and granular subbase. The open-graded asphalt stabilized base contributes to the total strength of the pavement structural section.

8.3.4 Relative Costs of Open-Graded Bituminous Base and Granular Subbase Blankets

Some State Highway Departments have been utilizing granular blankets to overcome the problems caused in the structural section by high ground water and rainfall infiltration through the pavement surface. In order to demonstrate the multiple advantages of the open-graded base course, a simple analysis of the cost of installing layers of granular blankets versus the cost of constructing open-graded bituminous bases is given in the following paragraphs.

Relative strength values of aggregate base, sand layers and open-graded base are on Page 154. The permeabilities of some of these materials are indicated on Fig. 4. Unit bid prices for 1972 have been used together with the aforementioned strength values and permeabilities to evaluate the efficiency of the open-graded base course as compared to a granular blanket. The average unit prices utilized are representative of three highway projects in FHWA Regions 1 and 2 and are:

Open-Graded Bituminous Base	-	\$21.00/cubic yard
Granular Blanket	-	\$7.35/cubic yard

Assuming that a structural number of 1.0 is desired, the strength coefficients for the two materials are 0.30 and 0.12, respectively. The required thickness of each layer will be:

$$\frac{1}{0.3} = 3.33 \text{ inches} \quad - \quad \text{open-graded bituminous base}$$

$$\frac{1}{0.12} = 8.33 \text{ inches} \quad - \quad \text{granular blanket}$$

If the pavement lane is 12 feet wide, the relative costs per lane foot of length will be:

$$\frac{1x12x0.274}{27} \times \$21.00 = \$2.56 \quad - \quad \text{open-graded bituminous base}$$

$$\frac{1x12x0.695}{27} \times \$7.35 = \$2.28 \quad - \quad \text{granular blanket}$$

The conveyance capability of each layer is calculated using Darcy's Law. Thus, assuming a cross slope of 0.02 and coefficients of permeability of 10,000 feet per day for the open-graded base and 10 feet per day for the granular blanket, the maximum quantity of water that can be drained by each of the 1-foot-wide layers is:

Open-graded base - 10,000 x 0.02 x 0.274 = 55 cu ft/day
Granular blanket - 10 x 0.02 x 0.695 = 0.14 cu ft/day

The relative costs to accomplish the drainage function are:

Open-graded base - \$2.56/55 = \$0.046/cu ft/day
Granular blanket - \$2.28/0.14 = \$16.20 cu ft/day

To summarize, an open-graded bituminous base course layer performing both structural and drainage functions is approximately 350 times more cost-effective in draining a highway pavement structural section than a layer of granular material of equivalent strength.

8.3.5 Summary

The cost/benefit calculations that have been presented here illustrate types of calculations and types of comparisons that can be made. In presenting these calculations, it is not expected that studies in this amount of detail will necessarily become routine procedures. The primary purpose for giving them is to illustrate possible methods of analysis, demonstrate the profound influence of free water in shortening pavement life, and point up the substantial economic advantages of well drained roadbeds over conventional slow-draining roadbeds when annual costs are compared.

The slight additional construction costs that may sometimes be incurred in building well drained roads will usually be repaid many times over in lengthened service life and improved performance.

9. CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

This study has shown that surface water can infiltrate through highway pavement surfaces and immediately adjacent areas in sufficient quantities to pose a real potential for damage to many of the highways in the United States. Observations made during performance of the Case Studies and subsequent analyses of the data obtained from the Case Study sites and from laboratory tests provide indications that pavement distress, in the majority of instances, is associated with poor subsurface drainage of highway pavement structural sections. Also, in many cases, these unfavorable conditions are inherent to the design and construction of the road, and are practically independent of the local topographic characteristics.

The degree of severity of damage to pavements due to lack of subsurface drainage depends on natural and man-made environmental conditions; particularly the precipitation characteristics of the area, depth of annual frost penetration, and the volume and weight of traffic loads.

Water creates problems for all types of pavements, primarily because excess water in pavement structural sections (1) reduces frictional strength of materials because of the buoyance of supersaturated layers, (2) creates excess pore pressures by wheel impacts, and (3) provides a medium for erosion and ejection of material out of cracks, joints, etc. These are the major mechanisms of failure.

The nature of the problems created in flexible pavements by excess water is somewhat different from those created in rigid pavements. It appears that excessive deformations in base, subbase and subgrade layers beneath asphalt concrete pavements are the primary causes of damage to flexible pavements, whereas the erosion and physical ejection of base materials from beneath PCC pavements are the primary causes of damage to PCC pavements. Excess water is a common factor regardless of the type of pavement.

There appears to be a definite correlation between flexible pavement deformations, moisture content of structural section materials and resilient properties of structural section materials. Further investigations are needed to quantitatively relate these factors to flexible pavement distress.

Rigid pavements spread the wheel loads imposed and therefore have the ability to bridge over soft areas that may develop in bases or subgrades. However, this load spreading ability is greatly reduced at rigid pavement edges and joints where the problems are magnified when excess water is present.

An indicator of potential excess water problems in a rigid pavement system is pumping. By the time visual evidence of pumping has been detected, damage generally has been inflicted to the pavement structural system by the dynamic water actions. With flexible pavements, cracking or rutting often becomes apparent at early stages in the development of structural problems.

Studies made under this project indicate that the provision of subsurface drainage systems of the kind described in the "Guidelines" can greatly reduce, if not virtually eliminate, damages from excess water in structural sections.

Cost studies indicate that effective subsurface drainage systems usually are economically and technically feasible under the prevailing environmental conditions within continental United States. However, there may be exceptions to the foregoing statement. Therefore, economic analyses and evaluations should be performed for each particular case to determine the cost-effectiveness of fully integrated subsurface drainage systems with respect to other alternatives. If the type of subsurface drainage system advocated in the "Guidelines" (dual-layer, full-width drains with pipes) had been in widespread usage during the past few decades, it is highly probable that pumping and other serious water-caused damage would not have occurred or would have been greatly reduced, and potentially millions of dollars in maintenance and replacement costs might have been saved.

Subsurface drainage systems should be designed for the requirements of each specific drainage problem, rather than relying on a "standard" design that has been previously developed or has been adopted on some arbitrary basis. In the past, use of "standard" types of drainage materials and designs without the analysis of water-removing requirements has provided only very limited roadbed drainage because the most widely used "standard" types of bases, subbases, and even drainage layers, had very low permeabilities and very low water-removing capabilities.

Design of subsurface drainage systems is straightforward when basic principles of seepage and hydrology are applied, and when these systems are designed to remove the necessary quantities of water. Relatively simple calculations of inflow-outflow quantities indicate, for example, that effective subsurface drainage systems for roadbeds must contain a layer of material of much greater permeability than is currently being used in structural sections.

Generally, an open-graded, hot-mixed bituminous base is a very satisfactory type of drainage layer for pavement structural sections. Untreated open-graded aggregate mixtures of high durability and frictional strength may also be utilized as drainage layers in certain instances. The principal advantages of an asphalt stabilized base are good strength characteristics, excellent hydraulic conductivity, and good stability during construction.

Several State Highway Departments contacted in this study have indicated that the performance of open-graded bases has been satisfactory. Open-graded bases have proved durable and have provided good supporting characteristics under traffic even where only thin wearing courses of dense-graded AC have been constructed over these bases. On one major State highway, such a layer was in excellent condition after 10 years of heavy truck traffic although it was covered with less than an inch of dense-graded AC.

This Final Report and the "Guidelines" present very detailed analyses of the entry of water into roadbeds and its discharge through subsurface drainage systems. The principles of subsurface drainage applications are relatively simple. It is very important, however, that <u>an effort be made to consider all probable important sources of water inflow into structural sections</u> and to make reasonable estimates of the probable maximum inflow rates. The optimum thickness and permeability of the drainage layer and appurtenances can be easily determined by Darcy's Law or by the use of flow nets. Crude estimates or even educated "guesses" of inflow rates, if tempered with experience and judgment, will almost always indicate the need for drainage systems that contain a layer of one-sized stone of pea gravel or larger size. Even a very minimal full-width dual-layer subdrainage system containing a few inches of highly permeable stone can remove hundreds, if not thousands, of times as much water as thicker layers of most of the so-called "pervious" bases in use today.

To ensure that the intrinsic water-removing capabilities of properly designed subsurface drainage systems will remain effective for the life of a road, careful attention should be given to important details such as the following:

(1) Preparation of clear and concise plans and specifications.

(2) Construction in accordance with the plans and specifications, with quality control procedures designed to avoid contamination of the drainage layers and any blocking of the drainage system.

(3) Proper maintenance programs emphasizing adequate protection of subsurface drainage systems.

(4) Coordination of landscaping, sprinkling, and related programs with subsurface drainage system operation.

(5) Performance of numerous other related activities or practices that can have an important influence on the long-time efficiency of subsurface drainage systems, such as the proper sealing of cracks and joints in pavements.

All of the foregoing factors have been discussed in detail in this report.

9.2 Recommendations

Many basic recommendations and suggestions for analyzing subsurface drainage needs of highway pavement systems are indicated throughout this Final Report. Some of the broad aspects of subsurface drainage of roadbeds follow:

(1) Subsurface drainage systems should be designed to meet the needs at specific locations, taking into account both climatic and geometric conditions. Some situations requiring special attention are: long sustained slopes, horizontal curves, and sag-vertical curves.

(2) The subsurface drainage needs of roadbeds should be estimated in rates of flow per foot of roadway, using recognized principles of hydrology and soil mechanics.

(3) Cost-effectiveness/trade-off studies should be made of alternate designs with and without subsurface drainage systems, taking into account all known direct and indirect costs over a reasonable life for a given road. These studies should include all direct construction costs, maintenance and replacement costs, and when possible should make reasonable allowances for costs to the users for delays caused by pavement repair work.

(4) Educational training programs should be established to acquaint highway department personnel with the fundamentals of subsurface drainage system design. Those in interrelated fields (maintenance, landscaping, etc.) should be made aware of the importance of subsurface drainage systems, and the need to avoid practices that could be detrimental to the long-time functioning of these systems.

(5) Research and special investigations should be

conducted to obtain factual data on such items as (a) the global permeabilities of both asphaltic and PCC types of pavements, penetration types of shoulders, etc.; (b) the relative damaging effects of wheel loads on sections under various conditions of moisture, excess water, height of free water level in the structural section, etc.; (c) maintenance costs for pavements that are being damaged by excess water in their structural sections; (d) the mechanisms of failure of both AC and PCC types of pavements with particular attention to water-induced problems; and (e) improved methods for sealing cracks in pavements or otherwise sealing or waterproofing pavement surfaces.

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