National Cooperative Highway Research Program

NCHRP Synthesis 239

Pavement Subsurface Drainage Systems

A Synthesis of Highway Practice

Transportation Research Board
National Research Council

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Synthesis of Highway Practice 239

Pavement Subsurface Drainage Systems

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PREFACE

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

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

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of interest to geologists; hydrologists; geotechnical, pavement, construction, and maintenance engineers; and researchers. State DOT program managers and administrators will also find it of interest. The synthesis describes the current state of the practice for the design, construction, and maintenance of pavement subsurface drainage systems. It provides information on the positive effects of good subsurface drainage and the negative effects of poor subsurface drainage on pavement surfaces.

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

This report of the Transportation Research Board presents data obtained from a review of the literature and a survey of the state DOTs. It is a supplemental update to *Synthesis of Highway Practice 96: Pavement Subsurface Drainage Systems* (1982). The synthesis provides a supplement to design issues not found in Synthesis 96, but faced by current designers, e.g., type and quality of aggregate, compaction requirements for open-graded aggregates, asphalt and cement binders, and use of geosynthetics. In addition, it describes the effects of design, construction, and maintenance decisions on the performance of pavement subsurface drainage systems.

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

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

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This study was managed by Stephen F. Maher, P.E., Senior Program Officer, who worked with the consultants, the topic panel, and the 20-5 project committee in the development and review of the report. Assistance in topic panel selection and project scope development was provided by Sally D. Liff, Senior Program Officer. Linda S. Mason was responsible for editing and production, with assistance from Beth Rosenfeld. Cheryl Keith assisted in meeting logistics and distribution of the questionnaire and draft reports.

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PAVEMENT SUBSURFACE DRAINAGE SYSTEM

SUMMARY

Many premature pavement failures (occurring at less than 50 percent of expected life) have been traced to inadequate subsurface drainage. Although most state agencies recognize that water in pavement is not desirable, different philosophies exist on how to reduce the effects of this problem. Attempts range from completely sealing the pavement (including incorporating low permeable base with no drainage) to incorporating a fully drainable pavement section with permeable base and edgedrains. Numerous approaches fall somewhere in between (e.g., using edgedrains with dense-graded bases). This synthesis reviews practices in pavement subsurface drainage.

The differences in pavement drainage practices apparently relate to inconsistencies in the reported performance of pavements with drainage systems. However, inadequate performance of pavements with drainage systems appears to be related more to inconsistencies in design, construction, and maintenance than in the philosophy of positive pavement drainage. This synthesis focuses on the development of consistent practices in the drainage component of pavement design and discusses the effects of good and poor subsurface drainage. Also reviewed is the impact of decisions in planning, budgeting, procurement, construction, and maintenance on drainage performance.

Results of a survey of state transportation agencies on current pavement drainage strategies are interjected throughout the discussion to emphasize the important issues that influence design decisions. The drainage strategies currently used by state transportation agencies are presented, along with methods for evaluating performance. A team approach to decision making is proposed. This approach involves all functional groups during the design process, with feedback provided to the team throughout the life cycle of the pavement section.

This synthesis reviews design factors and appropriate design methods for pavement subsurface drainage systems, which should be considered as an update to *NCHRP Synthesis of Highway Practice 96: Pavement Subsurface Drainage Systems*. There has been significant activity in subsurface drainage in the areas of design, construction, and maintenance since Synthesis 96 was printed in 1982. Much of the design information in the present synthesis was obtained from the design methods proposed in the participant's notebook provided by Federal Highway Administration (FHWA) Demonstration Project 87: Drainable Pavement Systems. The proper use of and design details for edgedrains in both new and retrofit construction are included in the present synthesis, and existing standards and specifications are reviewed.

Poor construction techniques can destroy the best-designed subsurface drainage system. As a result, construction decisions and actions can have a significant impact on the design performance of a pavement section. This synthesis addresses how pavement design and construction affect each other and, more important, how they affect the long-term performance of the roadway system. Construction difficulties in the placement of permeable base and edgedrains do exist; but, as confirmed by the routine and successful installation experiences of many state departments of transportation (DOTs), all can be overcome with good training of and inspection by construction personnel.

Maintenance practices among state agencies vary as widely as their design philosophies. These practices range from no maintenance unless there are problems to full preventive maintenance with initial inspection starting at the time of construction. Unfortunately, maintenance-free

pavement systems do not exist. Maintenance of subsurface drainage systems is essential to the long-term success of the drain system and, subsequently, the pavement. Support in both design and construction is necessary for an effective maintenance program. The requirements for a good maintenance program are reviewed. In fact, a major concern of many state agencies is consistency in the support of maintenance programs over the design life of the pavement system.

Difficulties were found to exist in the establishment of performance indicators, which stem from the elimination of factors that mask the effects of subsurface drainage (such as construction damage, poor materials, and lack of maintenance). The status of these performance indicators, along with the results of long-term performance studies, are examined. The opinions of state DOTs on the importance of pavement drainage are reviewed. Current research completed or under way in this area is identified, along with available performance information on drainage systems and their impact on pavement life. A preponderance of evidence was found supporting the philosophy that a combination of good sealing and good drainage, with a commitment to long-term maintenance, will lead to the optimum performance of a pavement system.

CHAPTER ONE

INTRODUCTION

BACKGROUND

Subsurface drainage is a key element in the design of pavement systems. Indiscriminate exclusion of this element will assuredly lead to the premature failure of pavement systems, thereby resulting in high life-cycle costs. Faulting and associated pumping in rigid pavement systems, extensive cracking from loss of subgrade support in flexible pavement systems, and distress from significant frost heave are clear signs of inadequate drainage. After years of unsuccessful sealing attempts, we have learned that we cannot prevent water from entering a pavement and that the removal of that water is essential for the pavement elements to perform as predicted.

Most free water will enter the pavement through joints, cracks, and pores in the surface of the pavement. Water also will enter from backup in ditches and groundwater sources. Drainage prevents the buildup of free water in the pavement section, thereby reducing the damaging effects of load and environment. The gains in design life are significant.

Based on documented case studies, Cedergren (*1*) projects that pavement life can be extended up to three times if adequate subsurface drainage systems are installed and maintained. Forsyth et al. (*2*) report a ratio of 2.4 to 1 for reduction of new crack formation in Portland cement concrete (PCC) pavements with drainage, compared with pavements without drainage. Forsyth et al. also report at least a 33 percent increase in service life for asphalt pavements and a 50 percent increase for PCC pavements. Ray and Christory (*3*) observed premature pavement distress in undrained pavement sections in France, inferring a reduction in service life of nearly 70 percent, compared with drained sections. The evidence is clear: the optimum performance of a pavement system is achieved by preventing water from entering the pavement and removing any water that does enter by means of a well-designed subsurface drainage system.

SCOPE

This synthesis focuses on the drainage component of pavement design. Included are discussions on (1) the positive effects of good and negative effects of poor subsurface drainage; (2) the effects of design, construction, and maintenance decisions; and (3) the present state of the practice as identified by a nationwide survey and literature reviews. This synthesis is provided as an update to *NCHRP Synthesis of Highway Practice 96: Pavement Subsurface Drainage Systems,* by Hallis H. Ridgeway (*4*). Synthesis 96 is still a contemporary design reference because it focuses on the basic hydraulic considerations of design, based on classic works such as those by Moulton (*5*) and Cedergren (*6*). This document provides a supplement to design, based on current issues concerning designers such as type and quality of aggregate, compaction requirements for open-graded aggregates, asphalt and cement binders, and use of geosynthetics, which are not covered in Synthesis 96. Other significant activities that have taken place since Synthesis 96 are reviewed, including the performance of different drainage strategies and their effect on pavement life.

The experiences of many state departments of transportation (DOTs) were collected through a nationwide survey and are summarized. Perspectives on various subsurface drainage strategies such as the use of permeable base, underdrains, edgedrains, filters, outlets, and prefabricated geocomposite edgedrains are included in the summaries. The best practices (as reported) are highlighted in cases in which there is consensus, and areas in which major controversies were exposed are identified.

DEFINITION OF TERMS

An important element of this synthesis is the definition of terms used. A review of these terms is recommended to avoid confusion and misinterpretation of information. Definitions are based on existing standards from the American Association of State Highway and Transportation Officials (AASHTO), American Society for Testing and Materials (ASTM), and FHWA.

A drainable pavement contains the integral components shown in Figure 1. The primary components include the asphalt or concrete surface pavement, a permeable base, a separator/filter layer, the subgrade, and edgedrains. Table 1 shows the optional elements that can be selected for the design of each component. If any of these system components do not function properly, the system will not perform (e.g., a drainable pavement that does not drain will be a liability to the pavement system).

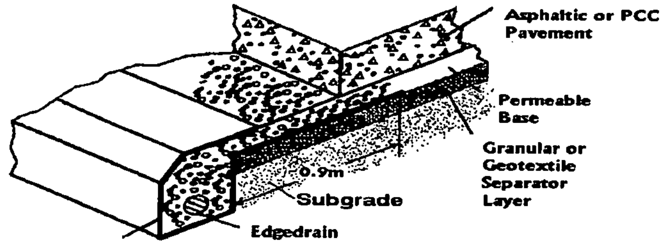

FIGURE 1 Components of a pavement drainage system (after *7*).

Terms associated with the pavement section as well as other terms used in this synthesis are defined as follows:

TABLE 1

COMPONENTS OF A PAVEMENT DRAINAGE SYSTEM

Basic Components	Variable Design Elements
Surface Pavement	Rigid: Portland Cement Concrete Flexible: Asphaltic Concrete
Permeable Base	Unstabilized Granular Asphalt Stabilized Granular Cement Stabilized Granular
Separator/Filter Layer	Dense-Graded Granular (Subbase) Geotextile
Subgrade	Strength of Subgrade Soil Location of Water Table Final Grade
Edgedrains (including outlets with headwalls)	Aggregate Trench Drain w/Geotextile Filter and Pipe Prefabricated Geocomposite Edgedrain (PGED)

- Base (base course): A layer or layers of specified or selected granular material of designed thickness, constructed on the subgrade or subbase for the purpose of supporting the pavement by distributing load, providing drainage, and/or minimizing frost action.
- Base crossdrain: A subsurface drain, generally perpendicular to the roadway alignment, designed to drain infiltration water. Often needed at bridge abutments, toll plazas, and across the road on long downgrades.
- Dense-graded aggregate base (DGA): Mixture of primarily sand and gravel, well-graded from coarse to fine (usually unstabilized, but sometimes asphalt or cement stabilized).
- Drainage aggregate: Open-graded aggregate with high permeability.
- Drainage pipe: Rigid or flexible pipe conduit designed to collect and/or transport water out of the pavement section (usually perforated).
- Edgedrain: A subsurface drain usually located at the edge of the pavement (between pavement and shoulder) at an appropriate depth to intercept expected pavement section infiltration water.
- Groundwater: Free water in the subgrade soils. Often controlled by deep ditches or deep underdrains.
- Headwall: A protective structure at an edgedrain outlet.
- Infiltration: Free water in the pavement structural elements entering through cracks, joints, or permeable paving.
- Outlet: The point of discharge of an edgedrain. It may be the pipe or a headwall.
- Outlet pipe: The lateral connection from the edgedrain to the outlet. Usually a solid pipe and usually strong to prevent damage.
- Pavement: All elements from the wearing surface of a roadway to the subgrade. Includes the surface pavement (asphalt or PCC), the base (may include permeable base), and the subbase.
- Permeable base: A free draining layer in the pavement designed to rapidly remove free water from most elements of the pavement. Usually placed between the surface pavement and a separator/filter layer. It may be aggregate or aggregate stabilized with either PCC or asphalt. Usually with a permeability of more than 300 m/day.
- Prefabricated geocomposite edgedrain (PGED): An edgedrain consisting of a drainage core covered with a geotextile. Usually 1 to 2 in. thick by 1 to 3 ft high, placed in a narrow trench. It may include drainage aggregate or sand as part of the installation.
- Separator/filter layer (aggregate or geotextile): A geotextile or aggregate (subbase) layer separating a permeable base layer from an adjacent soil (or aggregate) containing fines to prevent the fines from contaminating the drainage aggregate. Must meet the filter criteria for drainage filters.
- Stabilized aggregate: Aggregate that contains an asphaltic or cement binder.
- Subbase: The layer or layers of specified or selected material of designed thickness, placed on a subgrade to support a base course.
- Subgrade: The native soil that supports the pavement.
- Underdrain: A deep subsurface drain located at a sufficient depth to intercept and lower the groundwater to a required design level.

RECENT DEVELOPMENTS

This synthesis was prepared in recognition of the changes in design philosophy and substantial developments that have taken place in the 14 years since publication of Synthesis 96. FHWA has defined the current design philosophy for rigid PCC pavements and provided guidance through Demonstration Project 87, Drainable Pavement Systems. Although the project is complete, the participant notebook (*7*) is still available. The notebook, which is one of the primary sources of information on PCC pavements, provides guidance on design, installation, and maintenance of drainable pavement systems.

AASHTO and FHWA are currently emphasizing longer life pavement designs. This emphasis is increasing the importance of subsurface drainage. FHWA has distributed Technical Paper 90-01 (*8*) to inform the transportation community of its position on the importance of subsurface pavement drainage. The report on FHWA Experimental Project No. 12 (*9*) shows how extensively water can infiltrate what appear to be good, well-sealed pavement systems.

Much experience has been gained with materials and techniques that were new or unavailable when Synthesis 96 was prepared. The national survey conducted for the present synthesis and published records (*2,10,11*) demonstrate that drained and maintained pavements last up to twice as long as undrained pavements. Local transportation agencies have found that maintenance and overlays do not greatly improve the life of pavements that do not have good subsurface drainage (*12–16*). As a result, many agencies are now willing to spend the extra money needed for subsurface drainage than they were in the past. Information supporting the good performance of subsurface drainage led to the use of more than 4 million linear m of edgedrains, crossdrains, and underdrains in new or reconstructed pavements at the time the national survey was conducted.

The recognition that good subsurface drainage can extend the life of a pavement also has led to a greater use of permeable

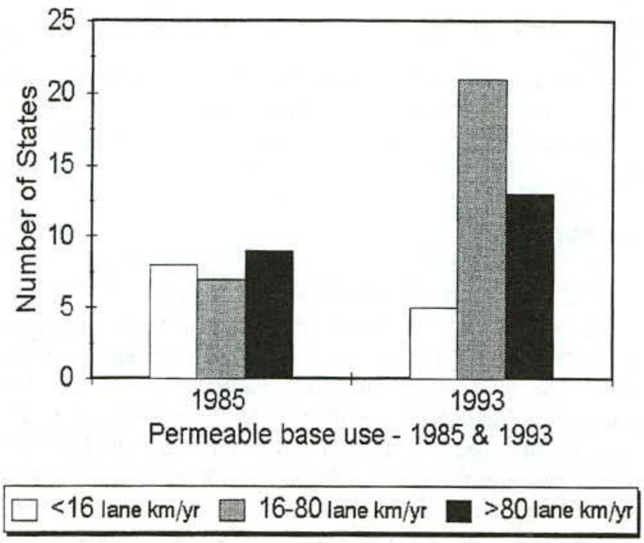

FIGURE 2 Use of permeable base in the United States (based on the national survey, with 42 states responding).

base by DOTs. More than 6,000 lane km of permeable base were installed in 1993, with 34 states installing more than 16 lane km that year, compared with only 16 states that did this in 1985 (see general trend in Figure 2). Many states have made the use of permeable base under PCC pavements their standard. As indicated by the survey, several states (e.g., Florida, Oregon, and Virginia) use permeable base under all high-traffic roads.

The increased use of permeable base has helped to solve some problems previously associated with it and to identify applications in which permeable base should not be used. Many states have concentrated on using stabilized permeable base to avoid the constructibility and trafficability problems of unstabilized permeable base. Studies by New Jersey (*17*) have led to the development of new gradations of materials for permeable bases that overcome construction stability problems and still provide adequate permeability. Pavements with subsurface drainage that have not been maintained have been found to perform as poorly as pavements without subsurface drainage (*18*). As a result, FHWA has recommended that permeable base not be installed unless there is a commitment to maintain the subsurface drainage system.

Some states (e.g., Minnesota) have reported success in improving the drainage of their less permeable, denser graded base by installing edgedrains during construction (*19,20*). In this case, the primary purpose of the edgedrain is to drain the infiltration that enters through the joints. Minnesota also has experimented with special crossdrains placed beneath the horizontal joints (*20*).

Postconstruction, retrofit edgedrains have been installed along most interstates in recent years in an attempt to decrease the rate of pavement deterioration. The survey indicates that more than 2 million linear m of retrofit drains were installed in 1993. These attempts have been reasonably successful, with several states (e.g., Kentucky, Minnesota, and Virginia) reporting a significant increase in the performance and design life of the roadway. Many unsuccessful attempts occurred in poorly draining bases, emphasizing the importance of using free draining base and incorporating subsurface drainage into the initial design.

Corresponding with increased edgedrain use is an increase in the use of newer types of drains, such as PGEDs. The performance of PGEDs has been established through field and laboratory evaluation, as reported in *NCHRP Report 367: Long-Term Performance of Geosynthetics in Drainage Applications* (*19*). An important finding is that failures evaluated as part of the study were predictable and related to either the absence of design, misapplication, or improper construction of PGEDs. New installation equipment and procedures have reduced the unit cost of PGED installation, which makes its use very attractive. The national survey indicates that about 600,00 linear m of PGED was used on new or reconstructed pavements in 1993, and an additional 600,000 linear m of PGED was used for retrofit applications for existing pavements.

One agency, Minnesota DOT, has reduced the cost of its standard drain installation by using narrow trench drains (*21*). MinnDOT's drain installation cost is now equal to or less than that of a PGED.

Inspection also has improved. Small-diameter optical tube video cameras with closed circuit video systems placed inside subsurface drainage facilities have exposed weaknesses in construction and inspection procedures (see Figure 3). Iowa *(22)*

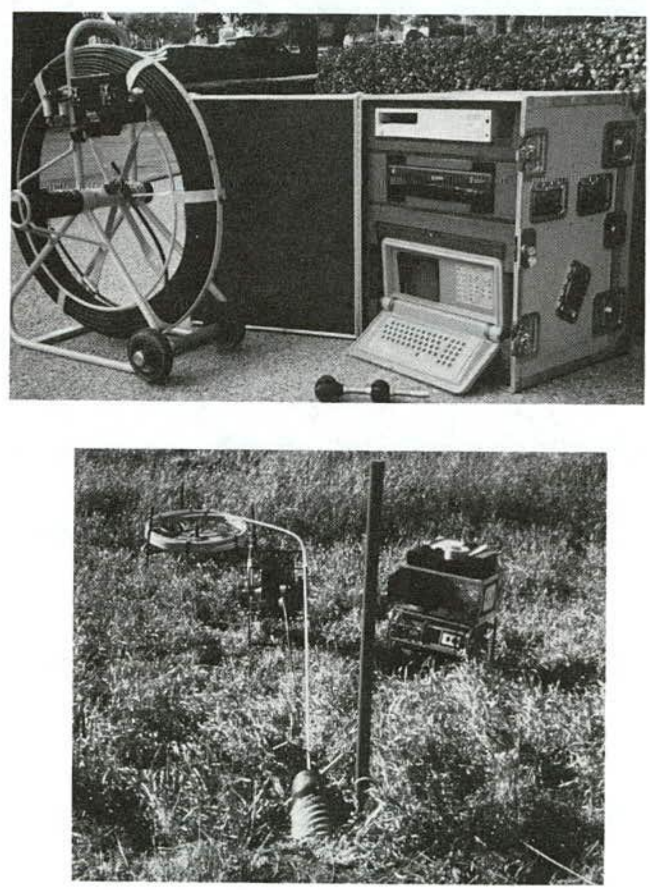

FIGURE 3 Video camera equipment used for inspecting edgedrains and outlets: *(a)* camera, cable, and recorder; *(b)* video inspection in the field.

and Kentucky (from survey) found many instances of damage and improper construction and now make subdrain inspection by video camera a standard practice. Other states (e.g., Indiana) are considering requiring video camera inspections before acceptance of construction projects. Numerous other states have discovered flaws in their subsurface drains by using various types of video inspection cameras pushed into drain outlets. Minnesota indicated that most of its subsurface drainage problems were found between the edgedrain and the outlet. Maintenance activities usually can repair outlet pipe damage. The survey indicates that most maintenance departments do not have a routine inspection policy and therefore may not identify problem areas until damage is done and early pavement distress becomes visible on the surface.

Systematic inspection using appropriate performance indicators appears to ensure the performance of drains. As a result, longer life pavements can be expected. The survey indicates that few agencies (approximately 7 percent of the respondents) have set up systems of performance measures and only 20 percent have routine inspection procedures for pavement subsurface drainage. More than half of the respondents indicated that these are needed, and they are planning to emphasize subsurface drainage maintenance within their agencies. Comments from the survey indicate that more effort is needed in training maintenance staff on performance indicators and maintenance strategies. Survey results indicate that a more systematic approach is needed in many maintenance groups.

The results of the survey conducted for this synthesis may help agencies develop a more unified approach to pavement subsurface drainage design, construction, and maintenance.

APPROACH

This synthesis is oriented around the tools and practices for design, construction, and maintenance of pavement subsurface drainage systems. The design approach is an extension of the procedures in Synthesis 96, which continues to be a valuable reference. In the present synthesis, the team approach to design is introduced in Chapter 2. The details for design are presented in Chapters 3, 4, and 5. Issues of performance measurement and the importance of performance data for planning and budget are included in Chapter 6. The findings and conclusions resulting from the survey conducted for this synthesis appear in Chapter 7.

As indicated previously, this synthesis is supported by a national survey, the results of which are discussed throughout the document. The survey questionnaire, along with a summary of the responses, appear in Appendix A. The survey was sent to the 50 DOTs in the spring of 1994. Forty-two agencies responded.

CHAPTER TWO

THE TEAM APPROACH TO PAVEMENT DRAINAGE SYSTEMS

INTRODUCTION

The performance of pavement drainage system components can be impaired by incorrect design decisions. However, decisions made in planning, budgeting, procurement, construction, and maintenance have impacts on performance that are often overlooked. The design of each component needs to be made with due consideration of events that may affect each component throughout the design life of the pavement.

The life-cycle effects of construction and maintenance decisions are less understood than those of design. Planning and budgeting decisions affecting construction and maintenance also must be made with respect to the life-cycle performance of the pavement drainage system. More effort may be needed by designers to obtain sufficient data from these other groups to produce the most effective design strategies.

There also is a need for an approach that allows for strategic changes as conditions change with time. The functional groups, therefore, must work together as a team to select the appropriate subsurface drainage strategy. This team approach provides a forum for communication throughout the design, construction, and maintenance process, which is needed to successfully implement pavement drainage strategies that have an optimum chance for success.

In this chapter, the potential influence of decisions made by each functional group on the pavement drainage system's performance are reviewed. The drainage strategies currently used by state transportation agencies are presented, along with methods of performance evaluation. Finally, the decision-making process required to implement the team approach is discussed with respect to the results of the national survey.

CURRENT PRACTICE

Table 2 summarizes the use of different drainage strategies as identified by the survey. The table shows that permeable base is widely used (77 percent of respondents indicated at least occasional use) under both asphaltic concrete and PCC pavements. A majority of permeable base is constructed with unstabilized aggregate, whereas significantly more asphalt stabilized base is being used than cement stabilized base. Edgedrains apparently are used fairly extensively by some states for new construction, even when permeable base is not used. Although the use of edgedrains for new construction is spread throughout the states, a majority of retrofit edgedrain usage is concentrated in several states. Separator/filter layers are not always used with permeable base. However, when they are used, geotextiles appear to be used almost as often as aggregate.

The results of the survey indicate that designs that are not appropriate for site conditions still exist, construction practices often result in poor performance, and maintenance practices often are not performed. The survey also indicates that there needs to be a better method of informing the maintenance staff of the particulars of the design and construction of pavement subsurface drainage systems so that the proper maintenance actions can be taken.

DESIGN

The two basic design strategies promoted to obtain full pavement life are to (1) prevent water from entering in the first place and (2) quickly remove any water that does infiltrate. Both approaches could be used together to obtain maximum effectiveness. Joint sealing, surface treatments, and slurry seals are used to prevent water from entering. Generally, this sealing strategy has been left to maintenance because it often is not considered during design. The national survey indicates that sealing usually has not been effective at eliminating water infiltration (also see Hagen and Cochran, *20*). However, sealing can reduce the infiltration rate as well as prevent particulates from entering and clogging the drainage system. In addition, sealing in the fall may be beneficial in reducing frost heave. For these reasons, sealing may still be an essential element in the drainage strategy, if it is given due consideration at the design stage.

Suitable drainage media (permeable base and edgedrains) are installed to remove water quickly. Although drainage strategies are increasingly being used in design, improper installation and inadequate maintenance of drainage components have often led to poor performance. The poor performance record of pavement systems documented in the national survey is strong evidence that the subsurface drainage strategy selected by the design group must be developed with full input from all other groups.

The type of aggregate and edgedrain components selected have cost, as well as construction and maintenance, implications. Other decisions that require a thorough review with the construction group include those on adequate drainage grades, headwall construction, outlet markers, ability to construct the design, construction sequencing, alternate construction procedures, installation, care, construction equipment used, construction traffic, and procedures. If maintenance personnel cannot find the outlets, no maintenance can be performed (*7*). The design, therefore, should incorporate concrete headwalls and reference markers or painted arrows to facilitate locating the outlet so that maintenance can be performed. Maintenance requirements anticipated for successful performance of the drainage system should be reviewed with the maintenance group, along with the maintenance inspection program and training of maintenance staff.

TABLE 2

USE OF PAVEMENT DRAINAGE SYSTEM FEATURES (in lane km per year)

Transportation Agency	Permeable Base						Edgedrain		Separator/Filter Layer	
	Unstabilized		AC Stabilized		PC Stabilized					
	Pvt. Type	Use	Pvt. Type	Use	Pvt. Type	Use	New	Retrofit	Agg.	Geotextile
Alabama	–	0	AC	20	–	0	28	–	–	–
Alaska	–	0	AC	16	–	0	2	0	0	0
Arkansas	–	–	PCC	12	PCC	7.4	91	–	–	–
California	–	0	AC&PCC	610	PCC	64	157	39	0	148
Colorado	PCC	25	–	0	–	0	–	–	24	–
Connecticut	–	–	–	–	–	–	24	2	–	–
District of Columbia	–	0	–	0	–	0	2	0	0	–
Georgia	–	0	–	0	–	0	34	–	0	0
Hawaii	AC&PCC	–	–	–	–	–	–	–	–	–
Idaho	PCC	65	PCC	48	–	–	3	–	–	91
Illinois	–	0	PCC	23	PCC	103	373	–	–	–
Iowa	–	80	–	0	–	0	91	216	34	0
Kansas	AC	16	–	–	PCC	32	23	15	–	–
Kentucky	AC	1730	AC	464	–	–	315	–	–	118
Louisiana	–	0	–	0	–	0	77	–	0	0
Maine	–	–	–	0	–	0	–	10	–	–
Maryland	–	0	AC&PCC	23	–	0	122	0	23	0
Massachusetts	AC	80	AC	266	AC	1.6	28	–	–	–
Michigan	PCC	37	PCC	18	PCC	6	40	22	189	545
Minnesota	PCC	105	AC&PCC	64	PCC	1	457	610	222	0
Missouri	–	0	AC&PCC	16	AC&PCC	16	11	46	0	–
Nebraska	PCC	105	–	–	–	–	9	–	6	–
New Hampshire	–	0	–	0	–	0	18	–	–	–
New Jersey	PCC	32	AC	32	–	0	16	16	64	–
New Mexico	–	–	PCC	16	–	0	1	0	–	–
New York	AC	6	AC&PCC	26	PCC	5	579	–	–	–
North Carolina	–	0	PCC	64	–	–	184	37	–	–
North Dakota	–	0	–	0	PCC	40	91	3	147	0
Ohio	AC&PCC	112	AC&PCC	145	AC&PCC	16	335	305	273	0
Oregon	AC	80	AC&PCC	32	–	0	30	–	57	57
Pennsylvania	PCC	800	–	0	–	0	–	615	0	114
South Carolina	–	0	PCC	48	–	0	46	6	0	0
South Dakota	–	–	–	–	PCC	6	5	24	–	–
Tennessee	–	–	PCC	360	PCC	–	169	–	–	–
Texas	–	–	PCC	26	–	–	40	0	–	–
Virginia	–	0	AC&PCC	64	AC&PCC	32	30	40	136	–
Vermont	–	0	–	0	–	0	–	–	–	–
Washington	PCC	–	PCC	–	–	–	–	–	–	–
Wisconsin	PCC	160	–	0	–	0	433	0	43	–
Total Usage	AC PCC	1970 1463	AC PCC	1293 1100	AC PCC	32 298	3864	2006	1216	1073

ACC = Asphaltic Concrete, PCC = Portland Cement Concrete, AGG. = Aggregate, – = Information not provided.

The designer also is responsible for evaluating the capabilities and limitations of the construction and maintenance groups in maintaining the pavement. Recognition of local factors that may influence pavement performance (e.g., experience level of staff) must be included in design decisions. It is important to remember that design is not about numbers, it is about getting the pavement structure to drain.

The design group often coordinates with the planning and budgeting groups, which bear the responsibility of communicating their needs and the results of their decisions throughout the agency. The philosophy expressed in FHWA Demonstration Project 87 (*7*) still appears to be appropriate. The designer should not design permeable base into a pavement if there is no commitment (i.e., budget and adequate training) to maintain the subsurface drains.

To facilitate communication, routine feedback is needed so that the designer can collect enough information to make the best decisions. There also must be a process available to correct design deficiencies identified from any source.

CONSTRUCTION

The choices made in construction often control pavement subsurface drainage performance; therefore, they must be made by trained staff who have adequate information. New, detailed inspection techniques are showing how construction decisions and actions may damage subsurface drains and thereby shorten pavement life. Problems identified include the following:

- Poor control of grades, which leaves water pooled in the pipes;
- Guide and guardrail posts driven through drains and outlet pipes;
- Pipes and other parts of the facility crushed and collapsed by construction traffic;
- Altered drainage outlet spacings;
- Headwalls that tilt backward;
- Bad or poor headwall connections;
- Improper use of connectors (e.g., T-connectors used on grades);
- High ditch lines that do not allow proper drainage from outlets; and
- Outlets that have been left out altogether.

These problems have led agencies to look for better ways of evaluating the quality of pavement subsurface drainage facilities.

The survey conducted for this synthesis indicates that most problems with subsurface drainage facilities originate in the construction phase (because this is the only phase in which problems can be corrected effectively). The survey also identifies training for the construction staff as the need with the highest priority (inferring that both contractors and inspectors need training).

MAINTENANCE

Maintenance groups are well aware of the performance problems that result from water infiltration. As indicated in the design section, attempts to reduce the quantity of infiltrated water include the use of joint sealing, membranes, and surface treatments. Attempts to remove water include maintenance of edgedrains installed during pavement construction or retrofit edgedrains installed after problems are observed. Maintaining these systems often includes cleaning outlets, replacing rodent screens, flushing or replacing outlet pipes, repairing damage, and deepening ditches. Neither the sealing nor drainage approach has proven successful without the other, and both approaches would greatly benefit from appropriate consideration during design.

The contribution of subsurface drainage system maintenance (or lack of maintenance) on pavement life has only recently been identified and understood (*6,10,19,22*). Kentucky DOT (*23,24*) found numerous locations where subsurface drainage outlets were missing, damaged, plugged, under water, or otherwise not functioning as intended. In France, a major highway section that received no subsurface drainage maintenance started deteriorating after only 7 years, and after 14 years, the section was performing worse than sections in which no subsurface drainage was installed (*3,18*).

Survey results strongly support the position taken by FHWA Demonstration Project 87 (*7*), which states: "If a state highway agency is unwilling to make a maintenance commitment, permeable bases should not be used since the pavement section will become flooded. This increases the rate of pavement damage." In other words, if you can't maintain it, don't drain it. The undrained pavement section will most likely fail prematurely, but failure will not be as rapid as on nonmaintained permeable base.

The concept of preventive maintenance generally has not been accepted for pavement subsurface drainage facilities. California is an exception and has implemented a preventive maintenance policy that includes a complete inventory, positive identification systems for outlets and cleanouts, and scheduled periodic drain flushing. It is now evident that maintenance strategies are as important to pavement life as design strategies. It is important, therefore, to evaluate the present and future capabilities of maintenance (the staff, their training, and expected funding) before making design or construction decisions.

PERFORMANCE EVALUATION

One of the difficulties in evaluating the performance of a pavement subsurface drainage system is that deficiencies often can be identified only after the pavement shows signs of distress. By the time pavement distress is identified, the subgrade and subbase usually already have failed and the problem cannot be corrected without removing the pavement. Recent investigations indicate that there are better ways to identify subsurface drainage inadequacies before the damage is irreversible. Early identification requires better clues, tools, and training.

Survey respondents indicated that there is a need for more thorough training of maintenance staff on specific procedures of subsurface drainage inspection. Scheduled periodic inspections are becoming more common, and some agencies have started to develop standard inspection procedures. Inspections immediately after rain events often uncover signs of subsurface drainage deficiencies. Water pumping up through construction in dry pavement (Figure 4) indicates inadequate drainage. Lack of water flowing from a subsurface drain outlet often means that the integrity of the drain has been compromised (e.g., through improper installation or a crushed or plugged drain or outlet). As indicated in Chapter 1, video inspection has been found to be a very effective inspection tool (*9,22*).

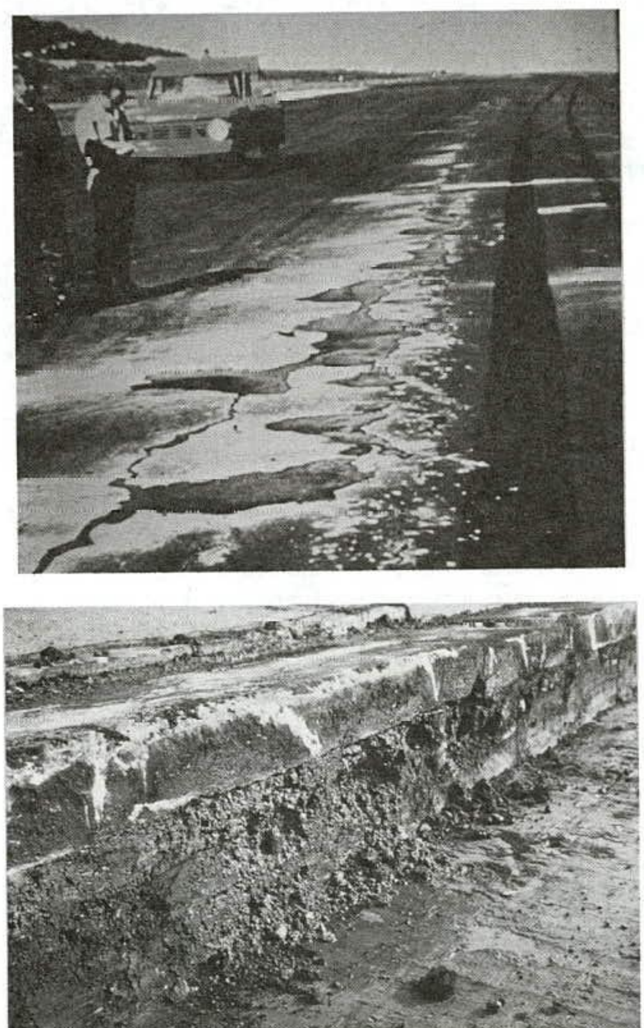

FIGURE 4 Examples of inadequate drainage: *(a)* water bleeding up through cracks in pavement; *(b)* base failure caused by contamination of aggregate with fines.

Preliminary studies with nondestructive pavement test methods, such as ground penetrating radar and falling weight deflectometers, indicate that these methods are able to quantify the level of damage to the pavement. In addition, the methods can help agencies decide which methods are best for correcting deficiencies identified by surface inspections (*10,20*). More investigations into the application of new technology to evaluate the adequacy of an installation are needed.

DECISION-MAKING PROCESS

To implement the team approach, an agency needs continuous feedback to provide appropriate input for decision making. Figure 5 illustrates the relationship between the performance of subsurface drainage systems in pavement and the decisions made by policy makers, standards groups, design, construction, and maintenance. Agency planning and budgeting groups need to be educated about the need for consistent, continuous funding for maintenance activities so that all decisions can be implemented.

One suggestion has been to formalize some communication lines to try to get necessary information to the decision maker before the decision is made. This approach works if changes are continuously fed back into the system. It is difficult for the decision maker to delay a project if the importance of the change is not evident.

A quality steering committee (QSC) also could be established to facilitate the communication process. The QSC continuously reviews information from all phases of the project and feeds it to decision makers. The QSC oversees all work and establishes teams to resolve problems between functional groups. The QSC consists of representatives from the design, construction, and maintenance groups who are in positions of authority, knowledgeable about drainable pavements, and directly involved with implementation. The contractor also could be represented on the QSC. The QSC could meet before and during design to review plans and specifications and identify construction and maintenance issues and potential problems.

It is suggested that the QSC do the following:

- Review quality control/quality assurance (QC/QA) plan for construction and modify to include complex areas that need special attention;
- Review supplier QC/QA program;
- Review project when construction is completed to note any deficiencies and evaluate potential solutions for future projects; and
- Periodically review project performance with the maintenance group.

The QSC approach may be most appropriate when design, field monitoring, or maintenance are subcontracted. Members of the QSC are agency and subcontracted groups under partnering agreements. Partnering programs have been established by several states (e.g., Washington).

Standards are another way of communicating effectively with all interested groups. Standards are a major element in system design, but few are in place. Federal and local standard-setting groups are attempting to communicate successful practices to user groups. One agency's approach to the

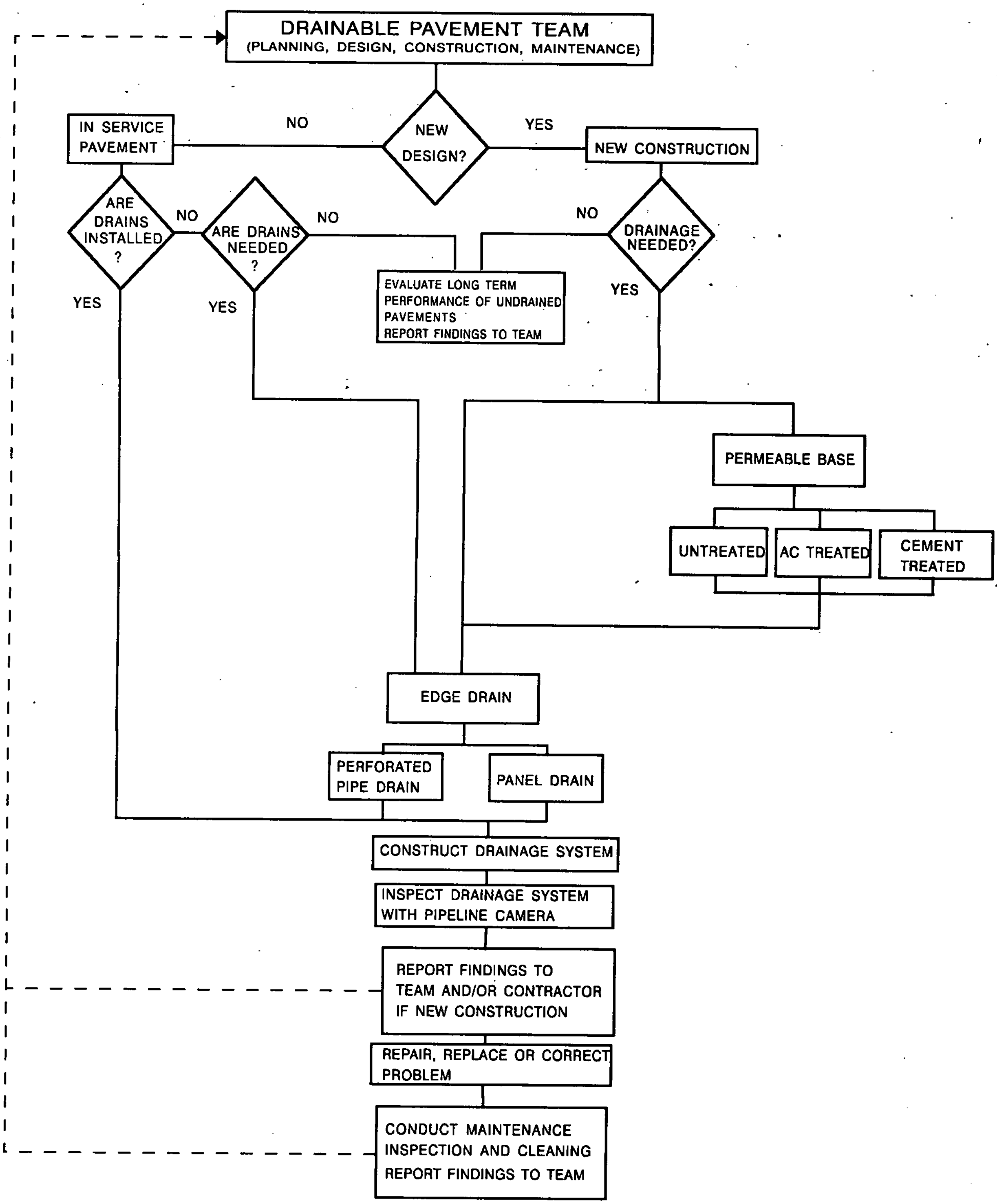

FIGURE 5 The team approach to the decision-making process.

decision process and standard and guideline setting is presented in Appendix B.

Decisions without adequate feedback cannot be completely eliminated. Survey respondents indicated that the new awareness of the importance of each group's contribution to a pavement's lifetime performance will lead to improved communications and that better systems will evolve to reduce weaknesses. The information obtained in Iowa (*22*) by video inspection of subsurface drainage has led to changes in processes that will improve a pavement's lifetime performance. Kentucky (*23*) also improved its processes by uncovering weaknesses in design, construction, and maintenance practices that led to poor pavement performance. Both states have implemented efforts to correct weaknesses.

Some questions on practices that need improvement in group cooperation follow:

- How do you build a subsurface drainage system with adequate grades in flat terrain and high water table conditions?
- Can the drainage system be installed within the constraints of the construction and roadway traffic that must be accommodated?
- Can the maintenance group find the drainage system and perform maintenance functions within the right-of-way and grades?
- What is considered adequate information to pass on to the contractor? The inspector? The maintenance foreman?
- What is the method for accomplishing the information transfer?

These and other questions are now being addressed by many agencies to improve overall pavement performance. Most agencies surveyed believe that there is a need for more and better training of maintenance and construction staff on the important features of subsurface drainage.

A poor design can be corrected during construction if a deficiency is recognized, but maintenance seldom can correct a poor design. A good design can be made ineffective by poor construction practices. A well-designed and constructed drainage system will not perform properly without adequate maintenance. Most systems will not perform properly if a design flaw was introduced in the planning stage, unless adequate knowledge and funds to correct the error in design are available.

CHAPTER THREE

DESIGN ISSUES AND SUGGESTED DESIGN APPROACHES

INTRODUCTION

The principles of subsurface drainage design are well known, but there appears to be little consistency in decision processes on whether to include drainage in the pavement. It is general knowledge that the structural support of the pavement system is the most important aspect of the design, but what many designers fail to realize is that drainage, in many cases, is absolutely necessary to maintain structural support over the life of the road. This chapter reviews design factors and appropriate design methods for subsurface pavement drainage systems. Results of the survey are interjected throughout the discussion to emphasize the important issues that may influence design decisions. The proper use and design details for edgedrains in both new and retrofit construction are included. Finally, existing standards and specifications are reviewed.

DESIGN IN THE TEAM PERSPECTIVE

Although design groups historically have been aware of the need for a complete system design that takes into consideration technical and administrative concerns for pavement subsurface drainage, the results of the survey indicate that improvements are needed. Issues that need to be addressed in the system concept include the following:

- Constructibility,
- Local weather,
- Alternate materials,
- Alternate installation equipment and procedures,
- Bidding alternates,
- "Value engineering" changes,
- Knowledge of local contractors,
- Changing administrative rules (e.g., EPA rules),
- Local traffic conditions,
- Local events,
- Knowledge of maintenance staff,
- Funding for local maintenance, and
- Local maintenance policies.

The design group bears the responsibility for organizing the information gathered from construction and maintenance groups so that important issues are addressed and rational design decision processes are developed. As discussed in Chapter 2, involvement of the construction group is critical for addressing constructibility issues in selecting the most appropriate system. Maintenance can be an invaluable source of information on the influence of drainage (or the absence thereof) and for determining the best drainage approach for specific site conditions. It only recently has started to become evident how important maintenance functions are to the life expectancy of pavements.

Improvements in communication with other functional groups become even more critical when considering current environmental issues, new materials being used for design, recent developments in construction equipment and procedures, and the current move toward longer design life. For example, local environmental regulators may not allow construction of certain design features (e.g., drainage into a potable water source or environmentally sensitive wetland).

Designers should recognize the current effort by FHWA and AASHTO to increase design life requirements for roadway systems (*8*). FHWA and AASHTO recognize that our society is maturing and transportation facilities for most urban areas need to have an expected life far exceeding the 20 to 35 years presently expected. These organizations also have noted the European practice in which major arteries are designed for a minimum 50-year life, with some European countries contemplating a 75- to 100-year life for all road components but the surfacing (*25*). The move toward increasing design life places a greater emphasis on drainage and puts greater demand on the subsurface drainage systems and other buried elements of the highway. It also puts a greater emphasis on basic maintenance functions to obtain the expected long-term performance. Recognition of these issues must be included in the decision processes established in the design phase.

DESIGN FACTORS INFLUENCING SUBSURFACE DRAINAGE DECISIONS

The benefit of a functional subsurface pavement drainage system will vary depending on climate, subgrade soils, and the design of the overall pavement system. Considering the variability of these factors and their influence on other factors that influence design decisions, a decision matrix could be prepared to guide an agency in making decisions on individual projects. Items that could be included in the design decision matrix include the following:

- Pavement classification (service level);
- Expected design life;
- Type and width of pavement and shoulder;
- Hydraulic considerations (infiltration and time to drain);
- Grades (longitudinal and transverse, surface and subsurface);
- Environmental influences (rain, temperature, frost, chemicals);
- Subgrade soils (natural or disturbed by construction);
- Structural contributions of subsurface drainage elements;
- Constructibility of each element;

- Maintenance capabilities and requirements;
- Joint sealing program;
- Maintenance funding;
- Coordination of agency groups;
- Local, regional, and federal standards;
- Initial costs; and
- Life-cycle cost evaluations of alternatives.

The guide also could include key decision points in the overall project selection process that influence other points. For example, the selection of grade line should not be made until the need for subsurface drainage has been assessed, because drainage in a high water table location might cost more than the highway itself, unless the grade is raised. Some agencies have developed standard procedures for addressing these and other factors in the decision process and placed them in design guides (e.g., Maryland, Minnesota, New Jersey, and Wisconsin).

The national survey and review of literature uncovered a number of issues that may influence the selection of a paving project's overall design strategy. Following is a list of some of the more important, or otherwise least remembered, issues:

- Pavement type
  - Because it leaks, jointed concrete pavement must have a suitable subsurface drainage system (*11*).
  - For asphalt pavements, subsurface drainage systems may not be as critical (*7*).
- Environment
  - For less than 0.4 m of rain per year, pavement subsurface drainage systems are usually not critical (*26*).
  - Agencies in freeze/thaw areas need to pay special attention to subsurface drainage systems (*27*).
  - Subgrades with more than 3 m per day permeability generally do not need subsurface drainage systems (*11,28*).
- Type of construction
  - For widening, the use of permeable base and drain system should be considered.
  - For rubbelizing and breaking and seating, large amounts of calcium carbonate can be released; therefore, edgedrains open to the rubble (crushed stone backfill around pipe) should be installed.
  - Retrofit edgedrains, to be effective, must have an open flow path from area of free water (usually the interface of the pavement and the dense base/subbase) to the drain core (*19,29*).
  - Drainage will not fix a failed pavement.
  - Focus should be on keeping water out (e.g., consideration should be given to increasing cross slopes).
- Maintenance policies
  - Consideration should be given to the need for permeable base under PCC pavement if joints are not routinely maintained (*3*).
  - Concrete headwalls should be used and maintained (*23*).
  - Coarse aggregate (e.g., AASHTO No. 2 stone) placed around headwalls reduces vegetation buildup in the outlet (*23*).
  - Subsurface drain outlets should be marked (*23*).
  - Joint sealing is required to prevent particulates from infiltrating and clogging the permeable base (*3,18,29*).
- Cost considerations
  - The additional costs associated with the drainage system should be related to the equivalent thickness of pavement materials or the extension of pavement life (*2*).
  - The expected life and performance of equivalent designs should be estimated, and cost cuts should be reflected in the evaluation.
  - The cost, quantified if possible, of traffic disruptions for each equivalent should be considered.
  - Alternate maintenance strategies should be considered and added to costs.
  - Local public/agency decision costs should not be added into the study (such as the need for curbs).

These issues do not include those related to routine subgrade drainage, such as springs, subgrade permeability, slope, and grade, which must be addressed for groundwater instead of pavement infiltration water control. Groundwater must be controlled before water leakage problems can be solved. Sometimes it is possible to combine the two water control systems effectively. However, the compromises needed to combine them may lead to poorer performance of both.

Different agencies are developing standards for primary decision factors, based on their local conditions. Some agencies relate the decision to type of pavement (e.g., California supports the use of permeable base under all new concrete pavements); some to load, such as equivalent single axle load (ESAL) (e.g., Wisconsin requires all pavements with daily ESALs greater than 500 to have permeable base); and some to traffic importance (e.g., Wisconsin and FHWA Demonstration Project 87 indicate that all pavements on critical traffic sections should have a permeable base). Minnesota combines traffic volume and load, subgrade soil type, pavement type, and functional classification in its decision process (see Appendix B). Table 3 contains guidelines for use of permeable pavement systems suggested by select agencies.

TABLE 3

CONSIDERATION OF SELECT AGENCIES FOR USE OF PAVEMENT DRAINAGE SYSTEMS

Agency	FHWA (*8*)	PIARC (*18*)	USA-COE (*28*)
Consider permeable base	Interstate All PCC Pvt.	All PCC Pvt.	All Pvt. over 200 mm thick. Optional under 200 mm thick.
Comments	Needs edgedrain system		Needs edgedrain system

The table presents examples of key criteria being used as part of the decision process. Once the primary decision has been made to include a permeable base layer in the pavement section, design makers need to address the specifics of the design, based on appropriate design methods.

DESIGN METHODS

Design of subsurface pavement drainage systems consists of balancing permeability and stability and removing collected water rapidly (*30*). Important design components, thus, consist of the base material, a separating filter layer to prevent infiltration of subgrade into the base, and a collection and removal system, as shown in Figure 1. As indicated in Chapter 1, the design of these components for PCC pavements is well covered in the FHWA Demonstration Project 87 participant notebook (*7*). The principles and procedures appear to be applicable to asphalt concrete (AC) pavements as well. Synthesis 96 (*4*) provides additional supporting information on hydraulic evaluation. The following summarizes the design approaches from these two publications for each component addressed in them, along with supporting information on practices obtained from this study.

Permeable Base

The primary purpose of the permeable base is to remove infiltration water; therefore, the optimum location is directly beneath the AC or PCC surface pavement. The permeable base should consist of durable, crushed, angular aggregate with the best porosity (i.e., essentially no minus No. 200 sieve material) so that it will release the maximum amount of water. The base can be stabilized or unstabilized. The following sections address typical structural, hydraulic, material durability and quality, constructibility, and maintenance requirements necessary for developing an effective permeable base design.

Structural Requirements

As noted in the FHWA Demonstration Project 87 notebook (*7*), pavement drainage is not a substitute for pavement thickness, positive load transfer, or a strong subgrade. The structural requirements of the overall pavement section must be met using AASHTO or other accepted design procedures. For angular, crushed aggregate permeable base with a percentage of two-face crushing, an equivalent structural capacity of an equal thickness of dense-graded base is usually accepted. Although stabilizing the base with a cement or asphalt binder will initially offer greater structural support than dense-graded base, the primary purpose of the stabilizer is to provide stability to the permeable base during the construction phase. It is generally assumed that the binder will either break down or be removed by stripping over time. Thus, an increase in structural support generally is not assumed for stabilized aggregate.

Hydraulic Requirements

Hydraulic requirements must be addressed for specific project conditions; however, in any case, the minimum coefficient of permeability for the base is on the order of 300 m per day. A coefficient of permeability of 600 to 900 m per day is preferable. To maintain positive flow though the base, the road section should be sloped as much as possible, with a recommended minimum cross slope of 0.02 m/m (*7*).

Procedures for meeting hydraulic design requirements are given in the FHWA Demonstration Project 87 notebook as well as in other sources (*5*). The procedures address material permeability, cross slope, longitudinal slope, width of pavement, and an assumed infiltration rate based on expectations of leakage often related to expected maintenance levels. Evaluation should include both longitudinal and transverse sections. Estimates of the likely range of infiltration can be made from the information presented in Minnesota's recent work (*20*), Moulton's manual (*5*), or Chapter 5 of the FHWA notebook. FHWA Experimental Project No. 12, conducted on mature pavements (*31*), discovered drain discharge rates of up to 50 percent of the rainfall reaching the pavement surface. Also, discharge rates for long-term slow rain (*31*) and frost melt (*20*) may be greater than those for heavy rain.

FHWA recently developed a pavement subsurface drainage microcomputer program called DRIP (Drainage Requirements in Pavements). This program will perform necessary drainage calculations. Permeability estimates for different material gradations can be obtained from equations or charts (*7*), laboratory tests on materials similar to those expected to be used for the project (AASHTO T-215) (*32*), or field tests on similar materials from prior projects (*33*).

Alternative materials often need to be considered to accommodate local conditions. The highest permeability materials often are unstable under construction traffic; therefore, it is often desirable to use a more stable material with a lower permeability. New Jersey uses a reasonably stable gradation that facilitates construction without causing damage (*17*) (see Table 4 in the following section). A higher permeability material can be stabilized for construction by using an asphalt or cement binder. Stabilized permeable base provides a stable work area with only a slight decrease in permeability (less than 10 percent of the initial material permeability).

Laboratory testing is the current method for estimating the permeability of stabilized materials. In regard to the required thickness of the permeable material, experience has shown that there is a practical minimum limit of 100 mm that can be installed successfully (*7*).

The geometry of the pavement section often is complex and sometimes changes during construction. It is difficult, therefore, to accurately estimate the drainage paths for all sections of the roadway, and conservative assumptions must be made. The current FHWA philosophy is to make the permeable base 100 mm thick and calculate the time to drain. It may be appropriate to change the thickness at locations where needs change (such as at toll plazas). If this is done, proper consideration of all features associated with a change in thickness must be modified at the transition (shoulders, edgedrain location/elevation, outlets, slopes, ditch/catch basin, constructibility, and so on).

The amount of fines in an open permeable base may create a problem for the drainage system if the fines segregate and collect at the transition zone between different materials (such as a geosynthetic wrapped edgedrain). Therefore, the design should minimize or eliminate both the transition zones between drainage components and the fines that could be introduced to the system during or following construction. For wrapped trench drains, the geotextile filter could be wrapped around a portion of the trench, but not over the interface between the permeable base and drainage aggregate. Joint seals could be included in the design to minimize fines from the road surface, as well as the amount of water entering the pavement section (*29*). The permeable base should not be daylighted at the edge of the road for two reasons: (1) to prevent silty material or stormwater in ditches from entering the pavement structure and (2) because it most likely will be blinded by topsoil and vegetation.

Projects using recycled concrete, rubbleizing, or crack-and-seat techniques may be susceptible to clogging of subsurface drain facilities by precipitate formation (*34*). Geotextiles are especially susceptible to clogging by precipitate and should not be indiscriminately used to separate the permeable base from the drain or wrap-around pipes. If used, geotextile filters should be carefully selected and evaluated for clogging resistance following FHWA geosynthetic design guidelines (*35*). Use of very open permeable base type material, from the recycled material to the drain, appears to be reasonably effective in preventing clogging. Geotextiles could be placed beneath and on the outside of the drain to prevent infiltration of the subgrade, as shown in Figure 1.

The hydraulic requirements of edgedrains and outlets will be discussed later in this chapter. In addition to regularly spaced drainage outlet requirements, the designer should be aware of the possibility that outlets may need to be supported by crossdrains at special locations. Long downgrades may require closely spaced outlets at periodic intervals that need to be designed using the guidelines in the FHWA Demonstration Project 87 notebook (*7*). Outlet spacing design is based on the discharge from the permeable base and the pipe's capacity, with due consideration of maintenance requirements. An increased slope, thicker base section, or crossdrains may be required at low points in vertical curves to prevent a backup of water from the high side of the pavement at its low point.

Crossdrains are a discontinuity in an otherwise uniform pavement section and therefore need to be addressed as such. In addition, transition sections may need to be designed. Crossdrains also may be needed to support outlets at discontinuities in the roadway, such as bridges, culverts, and utilities.

Material Durability and Quality Requirements

The FHWA Demonstration Project 87 notebook (*7*) states that quality of crushed aggregates is the single most important factor for the stability of a permeable base. Breakdown of the aggregate could cause both loss of support and a decrease in permeability. L.A. Abrasion Wear should not exceed 45 percent, and aggregate soundness loss should not exceed the requirements for a Class B aggregate as specified in AASHTO M283-83 (*32*) (i.e., 12 percent for sodium sulfate test or 18 percent for magnesium sulfate test). Other agency quality specifications may be applicable.

Constructibility Requirements

After structural and hydraulic requirements have been met, the designer has to consider the ability of the construction staff to build the designed facility economically, without damaging the facility. Some guidelines that have been used by different groups follow.

Minimum Dimensions—Unstabilized materials generally are used in thicknesses of 100 mm or more. Asphalt and cement stabilized materials can be built as thin as 50 mm, but most use 100 mm as a standard.

Material Gradation—AASHTO No. 67 stone (see Table 4) provides a gradation with high permeability, but requires asphalt or cement stabilization (see Table 5) to ensure stability under construction traffic. New Jersey (*17*) and others (*15*) have addressed the stability issues of unstabilized permeable base by requiring a well-graded material with greater stability, as shown in Table 4, but with less permeability (still greater than 300 m/day). Where heavy construction traffic is anticipated or where tighter control is needed, asphalt or cement stabilized permeable bases often are justified.

TABLE 4

PERMEABLE BASE GRADATION

Sieve Size	New Jersey % Passing	AASHTO #67 (e.g. Wisconsin and New York) % Passing
38 mm (1.5 in.)	100	
25 mm (1 in.)	95–100	100
19 mm (3/4 in.)		90–100
9.5 mm (3/8 in.)		20–55
13 mm (1/2 in.)	60–80	
4.8 mm (No. 4)	40–55	0–10
2.4 mm (No. 8)	5–25	0–5
1.2 mm (No. 16)	0–8	
300 μm (No. 50)	0–5	

Segregation—Permeable base materials are very susceptible to segregation during placement. Special care sometimes is needed to prevent migrating fines from collecting and blocking drainage from the base. The addition of water (2 to 3 percent by weight) before hauling and placement will reduce the likelihood of segregation. Limiting the fine grader passes also will help.

Compaction—Excessive compaction with heavy vibratory compactors is not recommended on permeable base because of the potential for damage and reduced permeability. Adequate

TABLE 5

COMMON GUIDELINES FOR STABILIZED MIXES (after 7)

Stabilized Method	Item	Requirement
Asphalt Stabilized	Gradation of material	AASHTO No. 67 stone, preheat at 135°C to 160°C.
	Amount of asphalt	2 to 2.5 percent by weight using a harder asphalt, such as AC 40 or AR 8000.
	Temperature of mix	Lay at 90°C to 120°C and seal with one to three passes of a 7.2–10.9 metric ton (8–12 ton) smooth wheel roller. Start compaction rolling after the temperature reaches 65°C, but before it drops to 38°C.
Cement stabilized	Gradation of material	AASHTO No. 67 stone (gradation table 4).
	Amount of cement	Use 110 to 150 kg of cement per cubic meter. (135 to 150 kg for high traffic loads). (From the survey, a minimum compressive strength of 4.1 MPa (600 psi) is suggested in cold regions to resist frost deterioration.)
	Curing requirements	Not clearly understood and may require local testing (consider a 150-m-long test strip). It is suggested that the mix be covered with plastic for 5 days after laydown or that light misting be done starting the second day after laydown.

compaction may be achievable with lightweight vibratory compactors or smooth drum rollers because of the relatively narrow gradation range of the permeable base. Method specifications based on the number of passes of specified compaction equipment could be used to control the compaction effort.

Damage to the Subgrade and Separator/Filter Layer—Care should be exercised to prevent damage to the unseen subgrade and separator/filter layer when placing the permeable base and performing subsequent work. Permeable base allows the rain to immediately go through to the underlying separator/filter layer. Because the top looks dry, there is a tendency to allow traffic over the surface before the rain has drained out of the underlying layers. Construction placement equipment may cause ruts in the subgrade or separator/filter, creating locations for ponding of water and later failures.

Integration of Edgedrain—The permeable base design must include an appropriate collector drain system integrated with the permeable base layer. The drain needs to be located where it will do its job, but it also has to survive construction of the roadway above it. Consideration of likely construction procedures during design may cause a design change, such as moving the pipe from under construction wheel paths. It is sometimes advisable to carry the permeable base to the edge of the shoulder or beyond to ensure that the pipe is not underneath the construction traffic and work area; however, as previously indicated, the permeable base should not be daylighted.

Temporary Rainfall Control—Rain falling on permeable base before it is covered infiltrates 100 percent; therefore, the outlet system temporarily must be able to handle at least twice the design flow rate. Alternatively, the permeable base may be temporarily daylighted, if the edgedrain is to be installed after the surface pavement is in place. All surface runoff should be directed away from areas of permeable base, because the runoff may carry fines that would clog the permeable base.

Temporary Traffic—Stabilized and unstabilized bases can carry light traffic for a short time at low speeds. Care should be taken to prevent damage from vehicles turning and carrying in fines, overly heavy loads, traffic too soon after rain, and so on. The design should reflect these and other concerns, and appropriate changes should be made to the design if damage is likely to occur.

Maintenance Requirements

The permeable base must drain, or it will become flooded and increase the rate of pavement damage. The designer, therefore, should ensure that the design of the drainable pavement section meets requirements to maintain drainage. Maintenance can do little other than flush the edgedrains to reduce the effects of fines entering the pavement system. Maintenance personnel, therefore, should be consulted on the types of joint seals to use in the design to limit fines infiltration. These personnel also should be consulted on the spacing and location of edgedrain outlets and cleanouts, as discussed later in this chapter.

Separator/Filter Layers

There is usually a need for a separator/filter layer between the permeable base and natural soils. Dense-graded subbase is often placed below the permeable base, which usually provides adequate separation. The designer, however, needs to check the filter criteria (*28*) for subbase materials that will be adjacent to the permeable base. Filtration compatibility of the subbase must be evaluated with respect to both the subgrade (to prevent infiltration of fines into the subbase) and the permeable base (to prevent migration of the subbase into the permeable base). Although a dense-graded subbase adds to the structural support of the pavement section, it may also create a zone of saturated material, reducing the time to drain and requiring reduced subbase and subgrade structural support values.

Geotextiles are also commonly used as separator/filters, using the criteria in the FHWA geosynthetics manual (*35*). Design methods are also shown in FHWA Demonstration Project 87 and Synthesis 96 (*4*). In this case, full-depth permeable base is used, and improved subgrade support can be anticipated (*34*).

Construction Requirements

For dense-graded subbase separator/filter layers, about 200 mm minimum is needed to provide adequate support after placement. It is difficult to place a thinner layer without segregation or damage. Thicker layers are required to accommodate construction over weak subgrade conditions.

Geotextile thickness is not a significant item in the separator/filter application. The thickness of the material covering the geotextile, however, is a consideration because of the potential for damage during aggregate placement. Normally, 150 mm is considered a minimum thickness when earthmoving equipment is used for placement. If the cover material is placed with care using a spreader box, 100 mm may be used. The geotextile also may be used to stabilize soft subgrade conditions. In any case, geotextiles should meet or exceed the strength requirements in AASHTO M288 (*32*).

Maintenance Requirements

Maintenance is an issue only if the design of the separator/filter layer is inadequate or a separator/filter layer is not used and fines are allowed into the permeable base.

Edgedrains: New Construction

Edgedrains for new construction generally consist of pipe in a trench filled with geotextile wrapped aggregate. Typical installation sections are shown in Figure 6. Design of edgedrains for new construction and major reconstruction projects is usually straightforward when using existing guidelines from the FHWA Demonstration Project 87 notebook (*7*) or other design procedures (*5*). The notebook has simplified procedures for edgedrain design so that they are easy to follow. The design consists of ensuring that the trench backfill and edgedrain pipe have the capacity to handle the design flow from the permeable base.

Trench backfill aggregate could be the same as the permeable base or a material with a greater permeability. The geotextile used to wrap the edgedrain trench must be designed as a filter, considering both the subbase and subgrade soils when using the criteria in the FHWA geosynthetics manual (*34*). The geotextile should not be extended between the

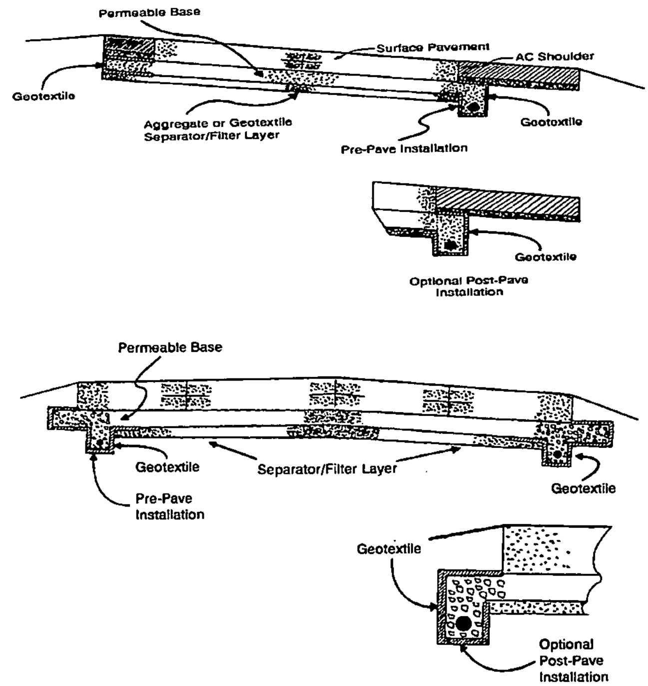

FIGURE 6 Typical edgedrain installations: *(a)* installation for PCC or AC surface pavement with aspahlt shoulders (after *4*, *7*); *(b)* installation for PCC surface pavement with tied concrete shoulders (*7*).

interface of the permeable base and trench backfill aggregate because it may form a barrier. Also, a geotextile should not be wrapped around the perforated pipe.

The size of pipe set often is based on maintenance requirements for cleaning capabilities and reasonable distance between outlets. As previously indicated, maintenance personnel should be consulted before finalizing these dimensions. The smallest diameter suitable for cleaning is 75 mm. Use of outlet spacing of 75 m is recommended for maintenance. Surface caps for cleanouts should be located in areas with minimum damage potential and with sufficient strength to withstand traffic and environmental influences (e.g., ice, salt, contaminant chemicals, and vandals).

One of the most critical items for edgedrains is the grade of the invert. Construction control of very flat grades usually is not possible, leaving ponding areas that result in subgrade weakening and premature failures. It may be more economical, therefore, to raise the pavement grade to develop adequate drain slopes for the subsurface drainage facilities. To achieve a desirable drainage capacity, a minimum slope that is greater than the slope of the road may be required for the edgedrain. However, this requirement may not be practical, and the pipe mostly will be sloped the same as the roadway. It is suggested that rigorous maintenance be anticipated, especially when adequate slopes cannot be achieved (*7*).

The ditch or storm drain pipe must be low and large enough to accept the inflow from the edgedrain without backing up. FHWA recommends that the outlet be at least 150 mm above the 10-year storm flow line of the ditch or structure (Figure 7). The outlet also should be at a location

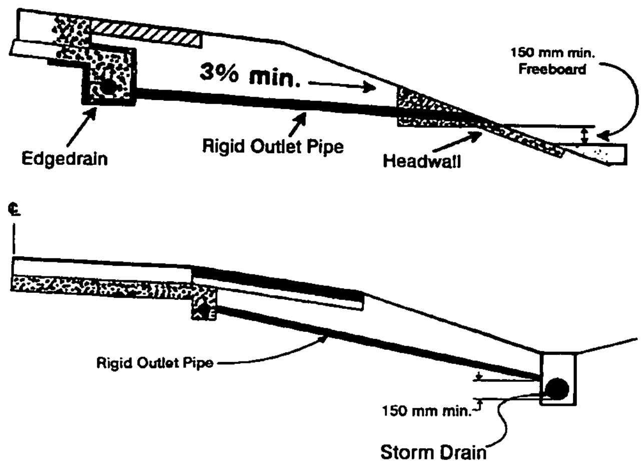

FIGURE 7 Location of outlet pipe (after *7*): *(a)* flowing into drainage ditch; *(b)* connected to storm drain.

and elevation that will allow access for maintenance activities (both cleaning and repair). Outlets and shallow pipes should be located well away from areas of expected future surface maintenance activities such as sign replacement and catch basin cleanout or repair. Locations of guardrail, sign, signal, and light posts need to be adjusted to prevent damage to the subsurface drainage facilities.

Construction Requirements

The designed drain trench and backfill must be constructible with normal construction equipment so that they will perform at their design level. Construction problems, of course, are time-consuming and expensive. For example, if the edgedrain has a different slope than the roadway, it will be difficult to daylight the outlet pipe, and placing a tapered geotextile to fit the trench will be almost impossible, very time-consuming, and expensive. However, the designed shape and dimensions usually are not as important to performance as the construction methods and subsequent construction problems. Some agencies (e.g., those in Louisiana, Minnesota, New York, and Pennsylvania) require that the edgedrain not be installed until the construction work is completed up to and, in some cases, after placement of the surface pavement. This apparently is an attempt to reduce the probability of construction damage to drain systems that cannot be seen. Others indicated that the drain should be installed as the subbase and permeable base are being installed to achieve uniformity of materials (e.g., agencies in Massachusetts, New Hampshire, New Mexico, and Vermont). The consensus is that either method should perform satisfactorily if the construction inspection is adequate and timely. Failures of both have been observed because of poor construction practices and unreported accidents.

Feedback on performance of the different methods for local circumstances is needed to develop a firm policy. The performance of each method can be expected to change with the education of contractors and inspectors. The designer, therefore, should work closely with the construction and maintenance groups to establish policies for installation.

Maintenance Requirements

The location and elevation of the outlet is an important issue for long-term performance and maintainability. It is recommended that concrete headwalls be installed at the outlet to prevent damage from maintenance activities such as mowing and ditch cleaning.

Precast headwalls, as shown in Figures 8a and 9, are used by many states (e.g., Kentucky, Minnesota, and New York). Some states have used cast-in-place headwalls using both conventionally formed (e.g., Alabama) and fabric formed concrete headwall (e.g., Oklahoma, see Figure 8b). A rodent screen usually is required (see Figure 9) and needs to be removable for cleaning and replacement. The outlet pipe from the edgedrain to the outlet should be solid and stronger than the standard edgedrain because it is shallower and more susceptible to damage. The use of a broad radius curve from the edgedrain to the outlet pipe (see Figure 10) also is recommended to facilitate insertion of inspection and cleaning tools.

Permanent markers should be included for locating key subsurface drainage elements (i.e., headwall, cleanouts, and buried junctions) for future maintenance inspection and repair. The most common marker is a delineator post, as shown in Figure 8c, but a number of agencies install markers on the pavement. To prevent traffic and maintenance damage, delineator posts should be located on the backslope rather than the inslope. Marking systems, especially those on pavements, require maintenance to ensure that they are clearly visible.

On long runs, periodic cleanouts to provide maintenance with a way of inspecting, cleaning, and flushing the drain may be considered. One state, California, recommends cleanouts at 90-m spacing if outlets are not provided at closer spacing. Cleanouts are difficult to build and maintain; therefore, it is advisable to install outlets more frequently or use the dual outlet scheme suggested in FHWA Demonstration Project 87 (*7*) (see Figure 10b).

Other structures, such as curbs, catch basins, and guardrail, sign, signal, and light posts should be designed to accommodate future subsurface drain maintenance.

Retrofit Edgedrains

A majority of pavement distress problems are related to excess moisture in the pavement section. Retrofit edgedrains (Figure 11) can be used in rehabilitation projects to remove water; however, their design is substantially different from new and reconstruction projects, which use permeable base designs. Edgedrains are just one method to consider to correct water problems. The designer is referred to the *Federal Highway Administration Pavement Rehabilitation Manual* (*36*) for alternate methods. Much of the guidance in this section is from that document.

For retrofit edgedrains to be effective, a thorough evaluation of the existing pavement layers and nature of pavement distress must be performed. Detailed requirements for the project survey are included in the FHWA manual (*36*). When excessive moisture is the cause of distress, little can be done to improve drainage of in-place layers; however, edgedrains can

FIGURE 8 Typical outlet headwalls and location marker *(7)*: *(a)* precast concrete headwall; *(b)* fabric formed concrete headwall; and *(c)* delineator post used for marking outlets.

shorten the drainage path and intercept almost all inflow through longitudinal shoulder joints.

Water from center line and transverse joints and cracks in the pavement system and water from the subsurface must still get to the edgedrain through the base or subbase. This creates

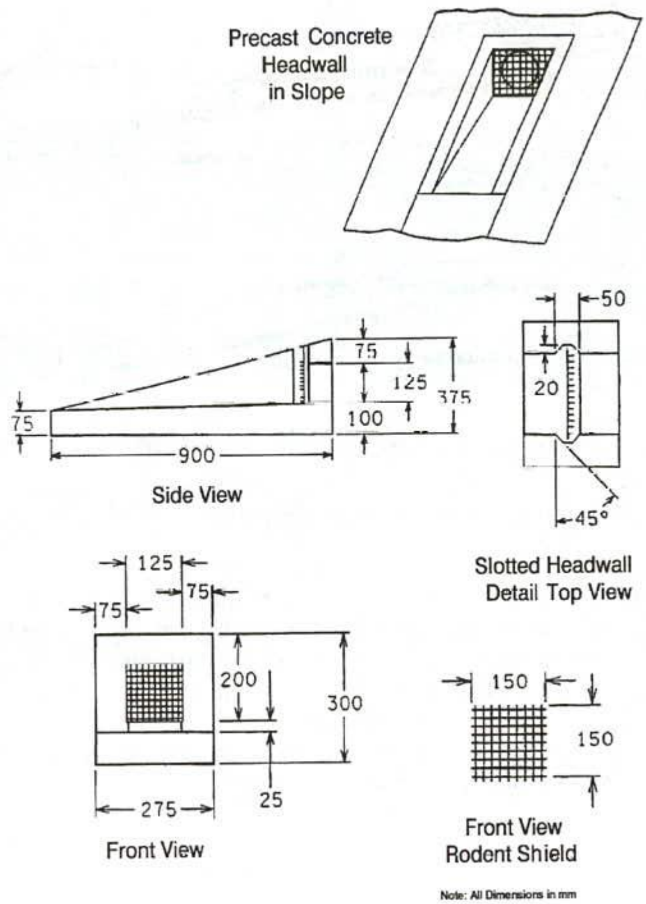

FIGURE 9 Typical precast headwall detail (after 7).

two somewhat related design problems. First, the rate of flow through the base to the edgedrain may be too slow for the edgedrain to be effective in reducing the saturation period. Second, if pumping of the pavement continues because of high saturation levels, erosion of fines from the base will most likely either clog the edgedrain (by clogging the filter or the pipe) or wash through the system, creating a continual faulting condition. As a result, an edgedrain, by itself, may not solve the problem and may even make it worse. However, not using edgedrains, as some states have chosen to do, does not solve the problem either. Instead, reducing water infiltration potential, along with a carefully designed edgedrain system and maintenance program to address any anticipated clogging and piping problems, has been found to be the most effective solution.

The combined approach requires good joint sealing and maintenance programs to maintain the seals, monitor edgedrain performance, and perform periodic cleaning of the edgedrain. Good practice dictates that the filter for the edgedrain be designed to limit movement of fines. Even if the filter clogs at the base-edgedrain interface, the design should still allow for drainage of the longitudinal joint (i.e., the condition is still an improvement over the condition with no edgedrain). Center line drains and drain laterals in transverse joints and heavily cracked sections also should be considered.

Specific design requirements for the edgedrain in terms of dimensioning, slope, and outlet spacing typically follow those

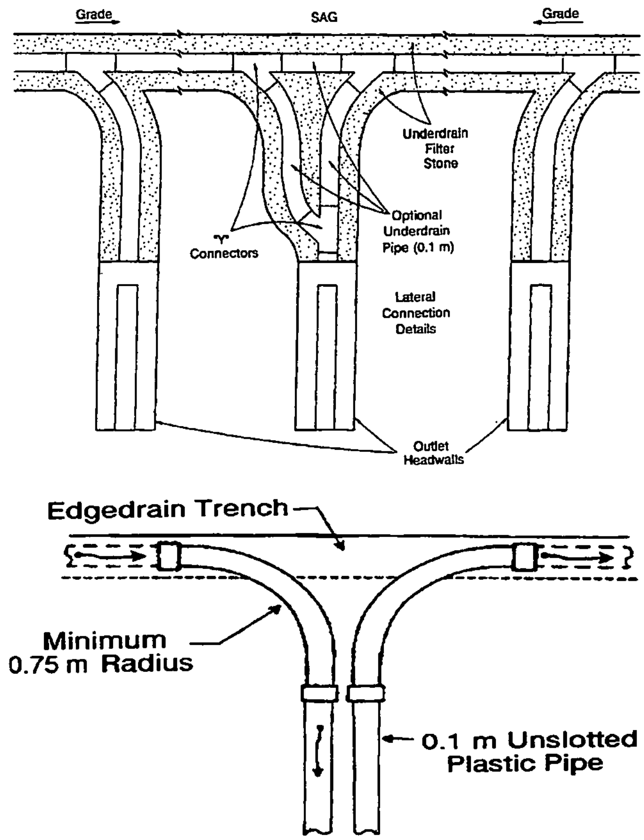

FIGURE 10 Broad radius curves required for edgedrain outlets to facilitate inspection and cleaning *(7, 15)*: *(a)* example of broad radius curve detail *(15)*; *(b)* smooth, long radius bends with dual outlet *(7)*.

recommended for new construction. Infiltration of water can be evaluated using the procedures outlined in Synthesis 96 (*4*). For pipe drains, 75- to 100-mm diameter pipe generally is sufficient to handle the free water. Special design considerations are required for using geocomposite edgedrains, as reviewed in the following section. A test section is recommended for evaluating the effectiveness and potential improvements of the solution.

This combined approach has been verified by significant experience with retrofit edgedrains on most of the original interstate highway system in an attempt to extend pavement life. It has been found that installation of edgedrains sometimes increases the rate of joint faulting and deterioration (*37*). PCC with failed joint supports have been observed to continue to deteriorate after edgedrains have been installed (*37*). Both geotextile wrapped trench edgedrains and prefabricated geocomposite edgedrains (see next section) placed next to pavements with pumping problems have, in some cases, become clogged from fines that either blind the geosynthetic filter (*19,24, 37*) or are pumped through the filter into the core (*19, 38–40*).

Because of these earlier erratic performances, it appears from the survey that several states have developed successful programs by following the combined approach (e.g., Kentucky, Tennessee, Virginia, Minnesota, and New York). The choice of location, type, and detail of retrofit edgedrain needs to be standardized for the local agency and geological area. Based on the results of the survey in states with successful programs, the following observations are provided:

- For severe cracking, drainage will help extend the life of the overlay.
- For moderate cracking and pumping, drainage may help with sealing and joint repair.
- For light pumping or staining, drainage will extend the life of the pavement, but joint sealing also should be used.
- Edgedrains most likely will be effective if the base is moderately to highly permeable or if the water is at the primary interface, the pavement/shoulder.
- For AC overlay of PCC, retrofit edgedrains may be effective in draining joints and cracks, thus extending the life of the overlay, even if the underlying base and subgrade are not drainable.

Construction Requirements

The construction requirements reviewed in the new construction section also apply to retrofit edgedrains. An additional primary concern is the loss of pavement support resulting from possible undermining during installation of the drain.

Maintenance Requirements

Because of the low permeability of most bases and subbases, ease of maintenance, cost, and availability usually determine the type and size of edgedrain pipe or geocomposite, outlet spacing, and cleanout requirements to be used.

Geocomposite Edgedrains

Prefabricated geocomposite edgedrains (PGEDs), in many cases, have been found to be very effective in removing water, with a draining rate equal to or faster than that of pipe drains. In many states, installation of PGEDs has been found to be more cost-effective than installation of pipe drains for retrofit applications. However, problems related to clogging caused by the intrusion of fines and buckling during or following construction have been noted (*19,24,37,38,40,41*).

Special design considerations for using PGEDs are suggested and detailed in NCHRP Report 367 (*19*). Because it is nearly impossible to clean a geocomposite once it becomes plugged, the presence of erodible fines and the potential for migration should be investigated before a geocomposite (or any other) edgedrain system is selected. The geotextile filter must be selected carefully to ensure that it is compatible with these conditions. Generally, the presence of fines requires the use of a geotextile with openings smaller than those that are standard on most current geocomposite drains.

Another problem related to geocomposite clogging and buckling is the potential for a void to exist between the

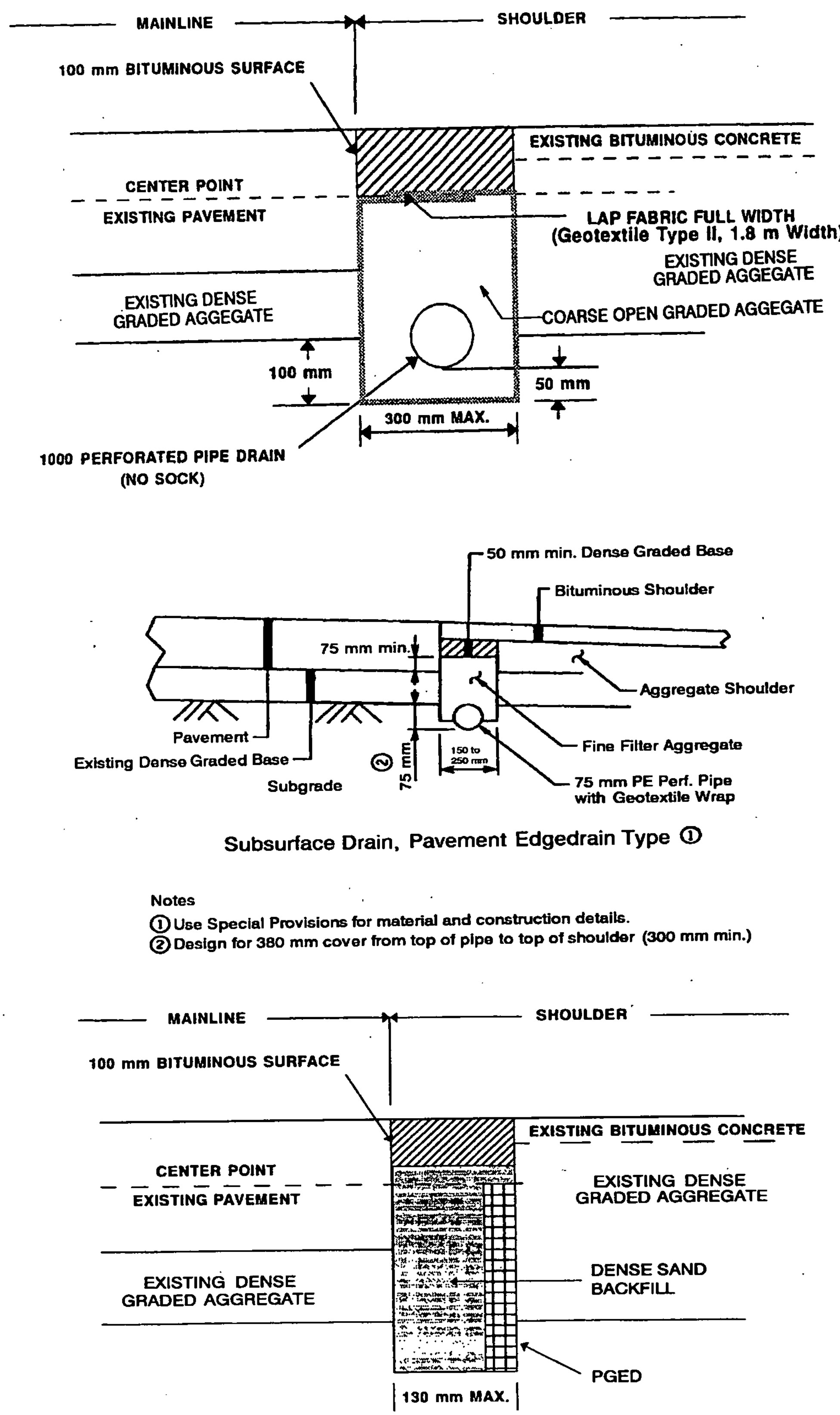

FIGURE 11 Typical retrofit edgedrain installations: *(a)* pipe with wrapped aggregate trench *(24)*; *(b)* sand filter retrofit edgedrain *(21)*: *(c)* prefabricated geocomposite edgedrain (PGED) *(24)*.

geocomposite and inside wall (pavement side) of the trench. Adequate compaction of the soil in the trench without damaging the drain also is a key performance factor (*19,42*). Modifications in geocomposite installation by installing sand between the pavement and the PGED, as shown in Figure 11c, appears to eliminate or at least substantially reduce the clogging and buckling problem (*24,27*). This approach is detailed and supported by research in NCHRP Report 367 (*19*) and by the Kentucky Transportation Center (*24*).

STANDARDS AND GUIDANCE FOR DESIGN

American Standards

As shown in Table 3, many of the larger agencies have established standards for incorporating permeable base drainage into pavement design. The U.S. Army Corps of Engineers recommends the use of a drainage layer under all pavements with a structural thickness of more than 200 mm, with optional use allowed for pavements that are less than 200-mm thick (*28*). Edgedrains are required with all permeable base installations and do not require permeable base when the permeability of the subgrade material in a nonfrost area is greater than 6 m/day (*28*).

AASHTO provides guidance for evaluating the influence of drainage on pavement design in the *AASHTO Guide for Design of Pavement Structures* (*43*). The influence of drainage is evaluated using a drainage coefficient to determine AC and PCC pavement thickness. The reduction in thickness with good drainage versus poor drainage is substantial; however, increasing pavement thickness most likely will not compensate for poor drainage.

European Standards

Based on their experience during the past several decades, nine participating countries in the Concrete Roads Technical Committee of the former Permanent International Association of Road Congress (PIARC), now the World Road Association, have identified three major factors that affect the long-term performance of concrete pavements (*18,44*):

- Drainage of infiltration water at the slab-base shoulder interface (water was noted as an essential element of the aging process);
- Use of low-erodible materials at interfaces; and
- Optimization between drainage of interfaces by using low-erodible or nonerodible materials and waterproofing pavements.

Christory (*18*) notes that in designs for very heavy traffic and severe climates, the tendency is to use doweled slabs with sealed joints or continuously reinforced concrete over a highly erosion-resistant base, with either longitudinal draining of the base or a complete shoulder in cement concrete. The option to use a fully free-draining base is gaining in application. For pavements with little truck traffic, the use of erodible materials and no drainage may be considered.

Periodic resealing of joints is essential and should be carefully executed at least every 5 years. Drainage systems must be maintainable and maintained. Drain diameters of 150 mm are recommended, with a radius of curvature that will allow passage of "hydrocuring" tools. Outlets should be marked and maintained in good condition.

Designs should consider the integration of drainage systems during the construction phase, with preference given to full-width drainage layers instead of drainage trenches. Interface geotextiles are noted for offering advantages for construction of separator/filter layers. The use of more porous pavements with void ratios of 20 percent to 25 percent also were cited as a design improvement for urban pavements. The combination of these strategies is anticipated to generate gains of 400 percent to 500 percent in pavement service life.

COMMON PRACTICES FROM SURVEY

In addition to the common guidelines for stabilized mixes given in Table 5, users appear to be in agreement on the following design concepts for permeable bases:

- A soil subbase or geotextile separator/filter layer is required.
- 150 mm of separator/filter material is appropriate for soil subbase.
- 100 to 150 mm of permeable base is needed (the majority suggest permeable base treated with 2 to 3 percent asphalt).
- 100 mm perforated plastic pipe edgedrain should be installed in backfill that is at least as permeable as the permeable base.
- Installation of edgedrain on both sides of the pavement section or at the low edge of super-elevated pavement sections is recommended.
- Most states space edgedrain outlets at 75 m, although some states are using up to 150 m for spacing.
- Most agencies do not routinely mark the location of outlets for future maintenance inspection and repair even though most recognize the need.

DESIGN INNOVATIONS AND DEVELOPMENTS

Research is ongoing in the use of geogrids to provide lateral restraint and stabilize permeable base layers (*45*). In Europe, the use of special high-flow geotextiles and geosynthetic drainage net composites as a drainage layer between the pavement and dense-graded aggregate is being evaluated (*46*). Minnesota has evaluated the use of special PGED crossdrains placed directly below lateral pavement joints (*20*). The outflow values of these crossdrains were found to be similar to those of edgedrains along the same section of roadway.

A new design course is under development by FHWA and the National Highway Institute. NHI Course 13126, Pavement Subsurface Drainage Design, will cover both flexible and rigid pavements.

CHAPTER FOUR

CONSTRUCTION ISSUES

INTRODUCTION

As indicated in Chapter 3, design can have a significant influence on the constructibility of a pavement subsurface drainage system. Likewise, construction decisions and actions can have a significant impact on the design performance of the pavement section. The design and construction groups must consider (1) each phase of construction, including subgrade preparation, placement of separation/filtration layer, construction of edgedrains, placement of permeable base, and construction of pavement surface and shoulder section, and (2) how the actions of one group will affect the actions of the other. Just as important, both groups must consider how such actions or inactions will affect the long-term performance of the roadway system. The following sections provide a review of these issues, supported by comments from the survey with respect to current practice.

CONSTRUCTION-RELATED DESIGN ASSUMPTIONS

In addition to the construction-related considerations for each design element reviewed in Chapter 3, decisions concerning construction details, sequencing, site accessibility, and protection of drainage components will influence both the methods and equipment that can be used for pavement construction. Design decisions such as location of collector pipes and outlets, temporary and permanent surface drainage, and aesthetic treatments will influence how construction can be conducted. Such decisions also will affect the right-of-way required for implementing construction of drainage system features.

In cases in which there is no impact, sequencing may be best left to the contractor, with the expected outcome or method clearly specified in the contract. Another important construction-related design consideration is pipe access at the upstream end of a segment so that inspection and maintenance flushing activities can take place (e.g., using dual outlets, as shown in Figure 10).

IMPORTANCE OF CONSTRUCTION CARE

One of the primary reasons for bringing construction personnel in at the design phase is to acquaint them with the impact of construction on design. Care exercised during construction of the designed section without compromising the effectiveness of the design is essential to the pavement's long-term performance. Key performance elements for construction personnel include the following:

- Good pavement starts with a good foundation. A stable platform is required for construction of the permeable base.
- Quality of aggregate and its ability to meet gradation requirements is essential for meeting expected design performance levels.
- An awareness is needed concerning the fact that the introduction of fines into the permeable base during construction could result in premature failure of the pavement.
- Unstabilized base tends to displace under traffic.
- Too much compaction or fine grading can significantly reduce the expected permeability of the base.

In addition to these key elements, construction personnel (contractor and inspector) should be aware of how each construction activity can affect the performance of the pavement system.

Subgrade Preparation

As with all road sections, the foundation surfaces are required to be level, somewhat smooth, and constructed to required grades. On drainable pavement sections, constructing and maintaining required subsurface grades until pavement construction takes place is essential for maintaining positive pavement drainage. Local depressions resulting from soft areas or depressions from equipment trafficking can lead to ponding of water below the pavement structure and subsequent loss of foundation support.

Separator/Filter Layers

For granular subbase separator/filter layers, the gradation of materials needs to be checked carefully against design specifications. Material that is more open than specification requirements may allow migration of fines through or from the subbase, which could contaminate the permeable base. Good compaction of the separator/filter layer is essential for placement of the permeable base. The subbase should be observed for rutting during compaction and subsequent trafficking. Subbase surface rutting may be an indication of subgrade rutting, which requires immediate attention (e.g., by reducing equipment loads or increasing the lift thickness). As stated in the participant notebook provided with FHWA Demonstration Project 87, "A separator is not a substitute for proper subgrade preparation" (*7*).

For construction of geotextile separation/filter layers, material and certification should be checked against design specification requirements to make sure the proper materials have been received and used. A smooth subgrade surface is desirable. It is recommended that sharp rock protrusion and loose rocks (usually larger than 19 mm) be removed to avoid damage to the geotextile, unless such conditions have been anticipated and heavier geotextiles (greater than 250 g/m^2) have been specified (*35*).

Edgedrains

Proper pipe grade control is essential for edgedrains to be effective. Undulating drain lines are not acceptable because water will accumulate in depressed areas. Good practice dictates that drains be properly connected to the permeable base and outlets. Outlets are required to be set at the proper grades, and ditch lines are required to be graded according to drainage requirements.

Drain lines are to be carefully marked and care is to be maintained throughout construction to avoid crushing the pipe with construction equipment (e.g., concrete trucks and other heavy vehicles or equipment are not allowed to travel over drain lines). Drains sometimes are constructed after pavement construction to avoid this problem. In this case, temporary drainage (either through temporary drain lines or daylighting) is required for the permeable base to prevent a bathtub effect from water trapped in the porous base.

The drain trench filter (geotextile or aggregate) has to be placed carefully at the design location around all sides of the backfill, except for the section in contact with the permeable base (*7*).

The edgedrain is required to be backfilled with material at least as permeable as the permeable base. Most states use a graded gravel or crushed rock. For retrofit installation through existing dense-graded aggregate, some states use free-draining sand with PGED systems, as shown in Figure 11c (e.g., Kentucky); some states use trench systems, as shown in Figure 11b (e.g., Minnesota), and some states use both. In any case, the drainage backfill should be placed below the invert of the pipe and compacted to better support the pipe, reduce the risk of crushing the pipe, and prevent subsequent subsidence that could affect the road. As with the trench line, the pipe should be placed at the proper grade on a smooth surface.

Additional drainage backfill is placed to the final elevation and protected from fouling until the pavement section is complete. Maintaining an open drainage aggregate is critical during the remaining construction period. A shovelfull of fines could clog the drain. In addition, construction traffic should not be allowed to traverse over the drain line. The drain line could be covered with a geotextile to help prevent fouling during construction. Outlets must properly drain during this phase to provide temporary drainage during construction. Ditch lines should be checked and maintained continuously because erosion sediments could back up and foul essential features. Headwalls for outlets should be installed, and outlets should be marked so that they will not be disturbed by subsequent construction.

The edgedrain system should be inspected and tested for proper operation toward the end of construction, before final acceptance. An acceptance criteria based on performance parameters must be established, otherwise signs of poor construction practices most likely will not be identified until major structural damage occurs and the pavement life has been shortened.

Inspection techniques can consist of simply pouring water on the drainage layer or in an upstream section of the drain, measuring the outflow, and comparing the outflow with the anticipated rate. A simple "go, no-go" gauge on the end of a long fiberglass rod can be pushed from the outlet into the edgedrain to verify continuity. Video equipment (e.g., the borescope used in Iowa and other minicameras) also provides an effective tool for postconstruction evaluation (see Figures 2 and 12). The findings of several state DOTs when using such techniques are reviewed in the Current Practice section. As indicated previously, pipe access could be provided at the upstream end of the drain line to facilitate effective testing and video camera inspection and subsequent maintenance flushing activities.

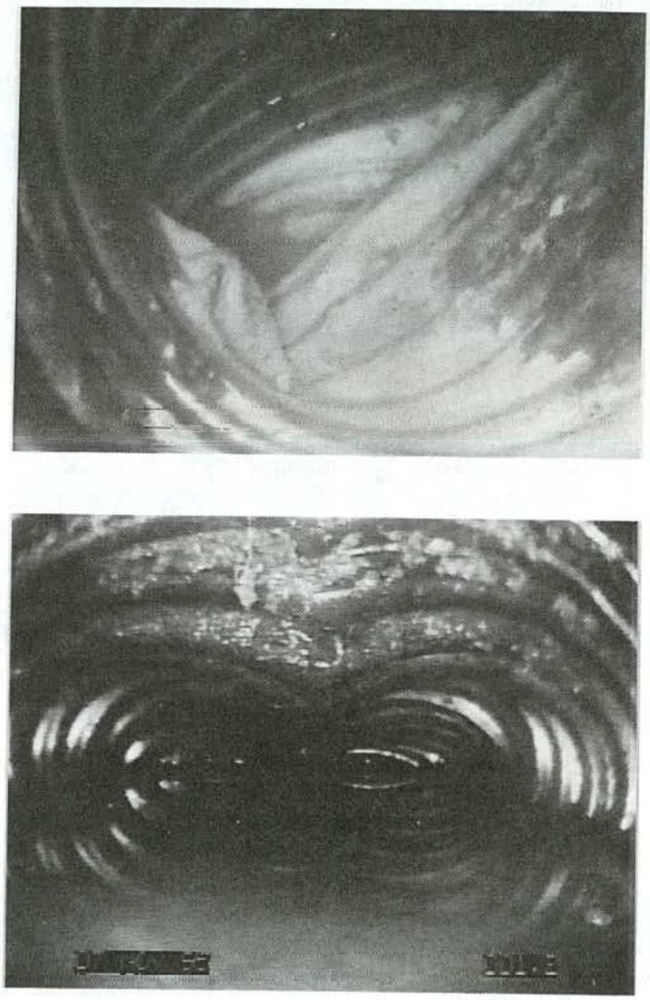

FIGURE 12 Video camera images of edgedrains damaged during construction: *(a)* crushed edgedrain; *(b)* crushed and sagging edgedrain holding water.

Permeable Base Materials

Unstabilized permeable base requires close control of material gradation and attention to activities that might cause segregation (*28,47*). An asphalt spreader box usually is required to reduce segregation (Figure 13). As previously indicated, unstabilized base tends to move around and rut under traffic.

Asphalt stabilized permeable base (see Figure 13) usually contains AASHTO No. 67 or No. 57 crushed aggregate plus 2 to 2.5 percent asphalt by weight. Higher asphalt cement percentages may be required when a less open gradation is used (*28*). Some states prohibit the use of bank run gravel aggregate because of the rounded faces. As previously indicated in Table 5, stabilized aggregate should be placed at 90° to 120° C, but not rolled until it is below 65° C (*7,28*). Vibratory rollers usually are not allowed, and the number of roller passes usually is between one and three (*7,28*).

Cement stabilized permeable base usually contains 2 to 3 bags of No. 67 and No. 57 crushed aggregate (*7,28,47*). As with asphalt stabilized base, higher amounts may be required for less open-graded aggregate (*28*). Cement stabilized base could be cured similar to the way pavement is cured. Test strips are recommended to determine appropriate curing and compaction methods (*7*).

Care is required to protect the permeable base from fine contamination (e.g., from dirty construction equipment, adjacent backfilling operations, or erosion sediment). Even though the permeable base generally can support light construction loads, it should not be used for a haul road. Good practice dictates that traffic be minimized and restricted to low speeds and minimal turning. No equipment should be allowed until complete drainage of the base and subbase has been confirmed.

Equipment that could cause rutting (e.g., loaded dump trucks), dirty equipment, and equipment transporting fines should not be allowed to traverse over the permeable base. If only concrete trucks are to be allowed on the base, asphalt or cement stabilized base should be used (*7*). Otherwise, side delivery of concrete should be required.

CURRENT CONSTRUCTION PRACTICE

Based on the results of the survey, good construction of pavement subsurface drainage systems appears to depend on a number of factors:

- The contractor and inspector should be knowledgeable about drain installation principles and practices.
- Someone with knowledge of drainable pavements must be on site at startup.
- Water needs a continuous, unobstructed path to drain, both during and after construction.
- A positive slope is required.
- Any discontinuity in flow path can destroy the system's effectiveness.
- The surface pavement (or shoulder) is supported by the base and drainage system; therefore, compaction is essential.
- Construction activities for other work in the area can destroy good drainage installations.

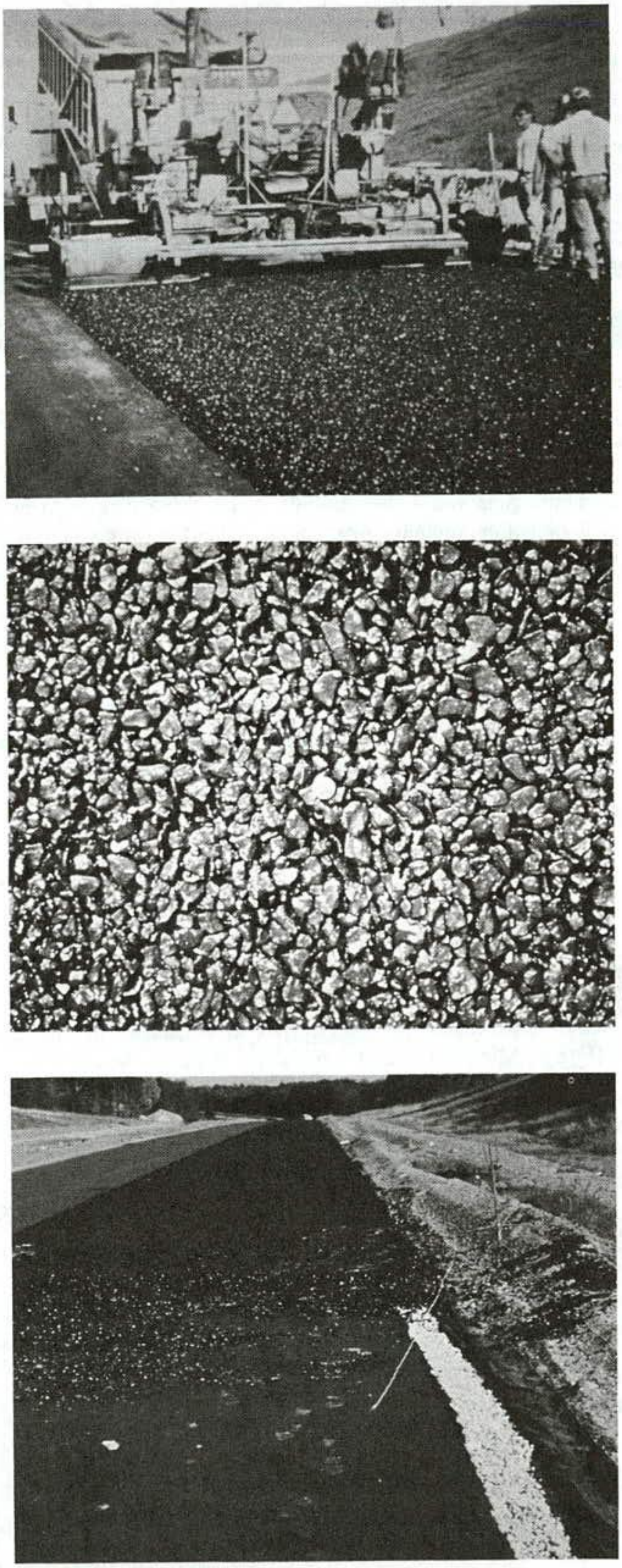

FIGURE 13 Permeable base construction; *(a)* placement using an asphalt spreader box; *(b)* closeup of in-place permeable base; *(c)* asphalt stabilized permeable base placed over a geotextile separator and the edgedrain.

Most respondents believe that the long-term performance of pavement subsurface drainage systems depends on good construction control. Iowa (*22*), Kentucky (*23*), and Pennsylvania (*37*) found many examples of poor construction control. Some examples of unacceptable construction include the following:

- Drains not connected to outlets,
- Drains crushed by equipment,
- Drains punctured by guardrail or delineator posts,
- Drains going uphill,
- No compaction,
- Backfill not meeting specifications,
- No outlets,
- Outlets not placed in sags,
- Backward tilting of headwalls, and
- Use of outlet "T's" on slopes.

Few respondents (less than 22 percent) reported using acceptance testing. According to a paper in *Transportation Research Record 1329* (*22*) and survey results, some occasionally use video cameras in the pipe systems and often are surprised by poor grades, crushing, and obstructions before acceptance. Iowa changed its policies on maintenance, design, and construction inspection as a result of its use of video inspection of existing drainage systems (*22*).

Respondents reported good pavement subsurface drainage system performance with systems installed both during subbase placement (before permeable base placement) and after surface pavement installation. Many leave the choice to the contractor. From the responses it appears that improper installation procedures may affect system performance more than the timing of its installation. Some of the reported construction damage (such as crushing) might have been reduced if the drainage systems had been installed after pavement construction.

There are reports, however, of drainage systems installed after surface pavement construction that did not intersect the drainable material under the pavement or that had low permeability backfill (excavated shoulder material) placed next to the drain, thereby making it inoperative (*9,19,38*). To achieve success, there is a strong need for a knowledgeable inspector on site at critical times during drainage system installation. To assist in construction monitoring, Kentucky uses the inspection form shown in Appendix C.

A number of respondents believe that there is need for additional research into better construction techniques. Most believe that there is a need for more training of construction staff and inspectors. To be effective, the inspector must be knowledgeable, trained, on site during critical stages, and willing to enforce replacement of improperly constructed systems. A drainage system can be made inoperative by a few shovels full of fine material placed in the flow path; therefore, the inspector must be aware of critical details to expect good performance.

The fact that careless construction can destroy the best designed pavement subsurface drainage system generally has been accepted, but few respondents have any established construction acceptance testing or criteria. A few states are planning video camera inspections for edgedrain pipe acceptance. Because the outlet pipe is the only accessible segment of the system, it is the only part to be checked directly. It is imperative, therefore, that knowledgeable inspectors be on site when any work that might damage the outlet pipe (through spills, rutting, or excavation) is being conducted.

CHAPTER FIVE

MAINTENANCE

INTRODUCTION

Maintenance of pavement subsurface drainage systems has been identified as essential to the long-term success of drainage systems and, subsequently, pavements (*3,18,23,24*). There do not appear to be any maintenance-free drainage or pavement systems. As discussed in Chapters 3 and 4, support from both design and construction is necessary for an effective maintenance program. This chapter highlights the essential requirements of such a program.

MAINTENANCE PROGRAM

The most effective maintenance programs use a five-phase approach:

- Routine inspection and monitoring
- Routine preventive maintenance
- Spot detection of problems (occurrences)
- Repair
- Continued monitoring and feedback.

Unfortunately, because of budget constraints and shortsighted economics, most state DOT maintenance programs use only two phases: spot detection and repair.

Inspection, in conjunction with preventive maintenance, has proven to be many times more cost-effective (a \$3 to \$4 return on each \$1 invested) than detection and repair programs (*4,48*). Several respondents noted that program managers may not be aware that the lack of subsurface drainage maintenance has a delayed effect on pavement performance and, therefore, on future system costs. Thus, "worst to first" funding strategies, in which pavements are repaired only after they fail, generally propagate future system failures.

Program managers often do not have adequate information with which to plan overall allocation of funds within their transportation facilities. A strong commitment from the central office to fund standard subsurface drainage maintenance is needed to prevent loss of drainage and subsequent premature failure of a costly pavement (*7,44*).

Informing management of required commitments to the planned subsurface drainage inspection and maintenance strategy is a fundamental part of the design phase. Policies could be established to provide assurance that the strategies will be implemented. For example, a standard inspection/maintenance form similar to that used by Kentucky (see Appendix C) could be required, with summaries provided for key design, maintenance, and other management personnel on a periodic basis.

Inspection and Monitoring

The inspection phase of maintenance provides important data on the effectiveness of drainage elements and the need for further maintenance. Inspection practices include visual inspection and effectiveness testing. Visual inspection consists of inventorying outflow following storm events and assessing outlet condition. Outflow inventories generally are qualitative (e.g., high, moderate, low, and no flow).

Visual inspection can be significantly enhanced though the use of video cameras (see Figure 14). These cameras have proven to be effective tools for identifying fine buildup and other potential blockages in drainage pipes (*22,49*). Ahmed and White (*50*) have proposed a system of inspection for transportation agencies that includes visual and video camera inspection techniques. Training in the use of video equipment for inspecting and maintaining highway edgedrain systems has been part of FHWA Demonstration Project 87. Demonstrations have been performed in 27 states (*49*).

Effectiveness testing can provide a more quantitative assessment of performance. Effectiveness testing can consist of post–storm event monitoring with bucket sampling, in which tip buckets are set up at strategic locations and which may even incorporate remote sensing, or direct upstream inflow and downstream outflow measurements. Design should facilitate inspection and effectiveness testing by incorporating pipe access at the upstream end of all drain lines.

Preventive Maintenance

The following preventive maintenance actions that help ensure good subsurface drainage system performance were identified (*8*):

- Clean and seal joints and cracks.
- Clean and verify grade of outlet ditches.
- Clean catch basins and other discharge points.
- Clean outlet screen and area around headwalls.

Experience indicates that for optimal performance, a joint sealing policy should be implemented in conjunction with pavement drainage system design. Although the effectiveness of joint seals in preventing the ingress of surface water has proven to be short-lived, over the long-term, the seals are still effective in preventing the wash-in of particulates that can clog the drainage system (*4,29*). Guidelines for joint sealing are reviewed in *NCHRP Synthesis 211* (*29*) and detailed by FHWA (*51*), the American Concrete Pavement Association

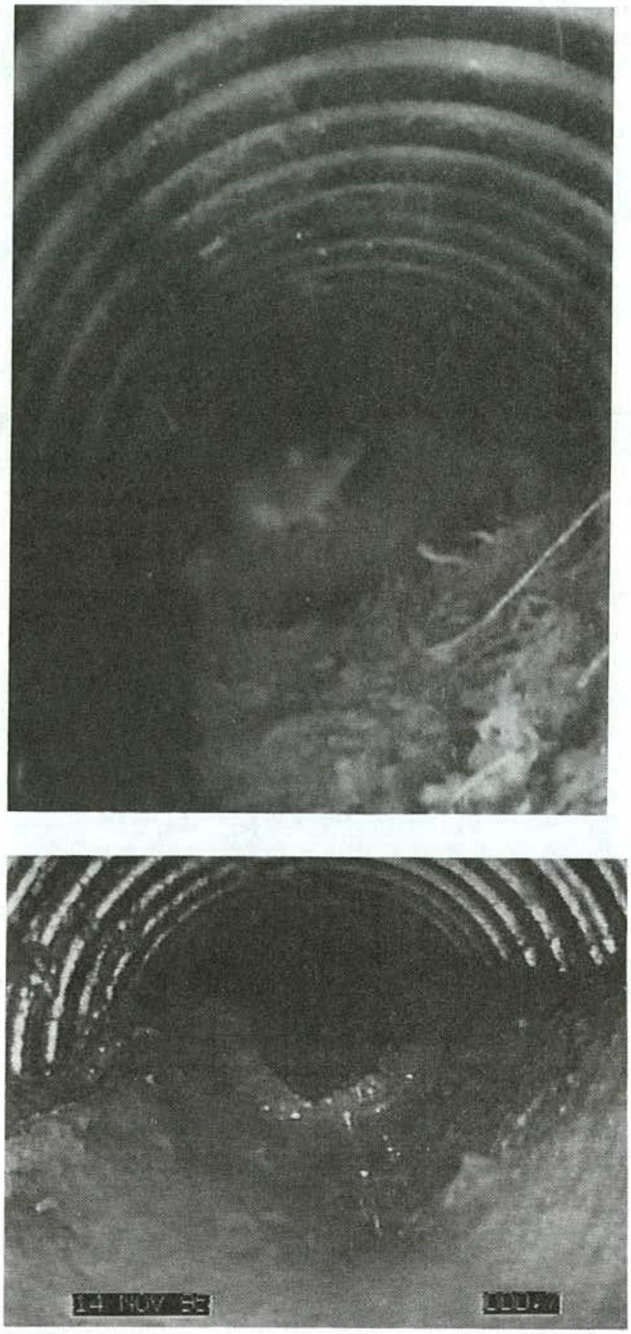

FIGURE 14 Problems identified by video camera inspection of edgedrains *(49)*: *(a)* rodents' nest; *(b)* heavily silted drains.

(ACPA) (*52*), and Strategic Highway Research Program (SHRP) (*53*).

California is one of the few states that believes that pipe flushing is an effective maintenance strategy and does it routinely. According to *Transportation Research Record 1425* (*26*) and survey results, some states have installed cleanouts to aid in flushing of subsurface drainage systems. Some states require a minimum pipe size of 75 mm to allow for flushing (*26*). Most require wide curves for outlet connections to facilitate insertion of a flushing unit (Figure 9).

Based on results of the outlet inspection program, a routine outlet cleaning program also should be implemented. One of the detriments to an effective strategy for maintaining pavement subsurface drainage systems is the inability to locate outlets for visual inspection and maintenance. One way to avoid this is to install permanent concrete headwalls and delineator posts, as shown in Figures 8 and 9. More than 30,000 prefabricated headwall outlets were reported to have been installed in 1993 by the 20 states responding.

Repair

It is generally accepted that once pavement damage from blocked subsurface drainage is visible, the damage is irreversible and the pavement life has been shortened (*3*). For this reason, any problems observed, no matter how minor in appearance, should be addressed immediately to confine them to a localized area.

The pipe and outlet are accessible for maintenance, but aggregate and filters can be maintained only by removing costly surface materials. Damaged or nonfunctional outlets, clogged outlets, buried outlets, deposits at outlets, and water above outlets need prompt attention, because distress in the pavement is imminent. When blockage is apparent in the drain line, flushing may be performed. If flushing is not successful, the drain line may require replacement.

Distress in the surface of the pavement or shoulder, seepage from cracks and joints, pumping, and frost heaves are signs that blockage of the drainage system already has occurred. When distress is visible, it is often too late for maintenance to help, and replacement of the pavement section usually is the only viable option.

Continuous Monitoring and Feedback

Monitoring is a continuous improvement process, especially for pavement sections that did not perform as intended. But improvements are achieved only through providing feedback to the design and construction groups. Maintenance should provide inspection results along with performance indicators to both design and construction for review. In addition, information on the performance of treatments and costs to apply them should be fed into the DOT's pavement management, maintenance management, and cost accounting systems.

Pavement management methodologies and maintenance strategies are reviewed in Syntheses 222 and 223 (*48,54*), respectively. FHWA is currently considering video inspection as a potential pavement management systems tool. A training program for maintenance staff on subsurface drainage strategies and their importance to long-term pavement performance also should be a part of the feedback process.

CURRENT PRACTICE

The survey indicates that many respondents have little information on the maintenance activities of their agencies and that many agencies have more than one policy, depending on the responsible individuals in each maintenance jurisdiction (district or region). Most respondents agreed that maintenance of the outlet is the single most important maintenance task that contributes to long-term performance of pavement subsurface drainage systems. However, locating the outlets was noted as a problem. Of 33 agencies that reported using edgedrains, 39 percent use posts to locate outlets, 9 percent use markers on the pavement, 9 percent stake the location or use the headwall, and 21 percent reported having no marker system. (The remaining 22 percent did not provide a response.) Outlets that are crushed, plugged, or under water, poor grades on the outlet pipe, and plugged rodent screens have been cited as problems leading to system failures.

Only nine states indicated that they have a program for periodic subsurface drainage maintenance inspection. Most states require a yearly inspection of the outlet condition. Some have follow-up actions, depending on findings of the inspection. Ditch cleaning, pipe flushing, and total replacement are actions states take based on inspections. Many respondents indicated that many maintenance groups select their own maintenance strategies with little central control (i.e., with little uniformity of application of technology).

One concern expressed by the designers is that there is insufficient control over the flow of money into maintenance activities and, therefore, the designers cannot predict whether any maintenance will get done. For this reason, design decisions may not be the most appropriate for actual maintenance capabilities.

All designers surveyed expressed the importance of maintenance to pavement subsurface drainage systems. However, there appears to be a lack of confidence that maintenance support will be consistent and can be relied on when design decisions are made. Most designers expressed a desire for training of maintenance staff, and some also expressed a desire for more basic research in the maintenance area.

CHAPTER SIX

PERFORMANCE EVALUATION

INTRODUCTION

Through research projects and monitored case studies, proper pavement drainage (with good maintenance) has been found to extend pavement life from several years to more than several times that of a conventional "undrained" pavement (*1,2,18*). Although this experience has demonstrated the effective performance of pavement subsurface drainage systems, there still remains a need to establish performance indicators for input into pavement management systems and to support decisions on the appropriate use of "drained" pavements.

One of the difficulties in establishing performance indicators is the recognition and elimination of factors that mask the effects of subsurface drainage (such as construction damage, poor materials, and lack of maintenance). In this chapter, the status of performance indicator establishment and the results of long-term performance studies are examined. The opinions of state DOTs regarding the importance of pavement drainage also are reviewed.

ESTABLISHMENT OF PERFORMANCE INDICATORS

Obtaining performance information begins with a visual inspection immediately following construction and periodically thereafter, as reviewed in Chapter 5. Again, forms similar to those in Appendix C provide a good inspection tool. Other tools that could be used on a periodic basis to achieve good performance monitoring include statewide surveys, measurements of faulting (i.e., vertical displacement between joints), falling weight deflectometers (FWD), ride quality indexes, flush testing, and video cameras.

For comparative monitoring programs and test sections, it is essential that drained test sections include a control section whose construction is based on the undrained standard of practice. Site conditions, including subgrade, grades, and structural support, need to be consistent between sections. Materials, as well as edgedrain components, used in construction need to be well documented, especially the initial permeability of the base and separator/filter layers.

Initial baseline measurements need to be obtained immediately following construction. This may include excavation of sections to document as-built conditions and provide initial assessment of materials that may be sensitive to construction (e.g., drainage layers, PGEDs, and geotextiles). Field permeability tests also could be performed. Tipping buckets are excellent tools for assessing changes in drainage outflow and for comparing drainage alternatives. Weather in the test area also should be monitored on a routine basis.

CURRENT PRACTICE

Based on the results of the survey, there does not appear to be a consistent, routine method of relating pavement subsurface drainage to pavement performance. Only two states (Iowa and Kentucky) indicated that they regularly perform statewide surveys to obtain information for decision making. Many states did indicate that they have conducted research projects, the special care of which tends to reduce the influence of construction and maintenance factors. Unfortunately, only a few documented studies that related alternate pavement subsurface drainage strategies to pavement performance were uncovered by this synthesis (e.g., *2,3,10,18,20*). The results of these studies will be reviewed later in this chapter.

The now optional 1991 federal mandate within the Intermodal Surface Transportation Efficiency Act (ISTEA), which recommends that each state implement a pavement management system, should help in gathering useful statistical information on the effectiveness of pavement subsurface drainage systems. Since the initiation of ISTEA, many states have implemented management systems. An inventory of all pavement section parameters (including subsurface drainage features) keyed to quantitative pavement performance with load accumulations and environmental conditions should go far toward determining the cost-effectiveness of various decisions on pavement subsurface drainage systems. Only two state DOTs indicated that subsurface drainage is a regular part of their pavement management systems, and only three states indicated that subsurface drainage is partially included in their systems.

Some respondents gathered enough information from individual research studies to provide direction on local decision making (*39,55*), and 45 percent indicated that they have established permeable base as their new standard under PCC pavements. Some federally sponsored research has helped clarify a number of issues, such as construction care and maintenance, related to drain performance (*11,19*).

A number of premature pavement failures have been traced to inadequate pavement subsurface drainage. Most of these failures resulted from bad design or damage that took place during construction or in service. It appears that there is ample evidence to justify assigning a high cost to inadequate subsurface drainage, but there is little to quantify the cost-benefit of different strategies and what makes each strategy successful.

Some Strategic Highway Research Program (SHRP) long-term pavement performance studies may provide quantitative performance indicators in the future. Work is ongoing by NCHRP (Project 1-34 Performance of Subsurface Pavement Drainage) to establish pavement performance indicators.

However, on the local level, more work is needed in relation to feedback from maintenance to establish local factors and provide updates for improved performance indicators.

PERFORMANCE APPRAISAL

One of the questions in the survey asked respondents to rate 13 features of a pavement system for their contribution to a long-term, high-performance pavement (see Question 11 in Appendix A). The results are as follows:

- Respondents agreed that the most important feature for long-term, high-performance pavement is "effective load transfer for PCC," for both overall effectiveness and cost effectiveness.
- The use of a concrete shoulder next to PCC pavement was ranked second in overall effectiveness, primarily because of its performance benefits. It ranked eighth in cost-effectiveness.
- PCC with permeable base and edgedrains was ranked third for overall effectiveness because of a high anticipated level of performance, but was only ranked sixth for cost-effectiveness.
- Maintenance of outlets was ranked third for cost-effectiveness and fourth for overall effectiveness.
- Dense subbase under AC pavement was ranked fifth for overall effectiveness. Although it was ranked second in cost-effectiveness, this feature only had an average performance rating.
- Maintenance of joint seals and effective longitudinal and transverse joint seals were ranked similarly, with a middle rating for their importance, but not for control of performance.
- Most respondents were in agreement with the worst alternatives, AC with slurry seals and dense subbase with edgedrains (PCC or AC pavement), which essentially were tied for last place in both performance and cost-effectiveness. Dense subbase under PCC also was near the bottom in both categories.

Many of the other questions relating to performance of subsurface drainage systems were not answered, inferring that there is either little information on performance or that information has not been made available to respondents.

LONG-TERM STUDIES

Smith et al. (*10*) compared 30 permeable base sections with nonpermeable pavement sections across the United States and found that the permeable base sections performed better and provided adequate support when the joints were doweled. The largest effect, however, was the improvement in performance of doweled joints over nondoweled joints. In an evaluation of I-80 in southern Wyoming, Farrar and Stites (*56*) determined that after 8 years, nondoweled PCC with permeable base outperformed nondoweled PCC over asphalt pavement, dense-graded base, and inlay.

The FHWA study on performance of jointed concrete pavements (*11*) found that the provisions for positive subdrainage, such as edgedrains, drainage blankets, or permeable base layers, generally resulted in a reduction in faulting and spalling related to D-cracking.

Pennsylvania DOT evaluated five bases, ranging from an impermeable cement stabilized material to a very permeable, uniformly graded crushed aggregate, during a 7-year period (*57,58,59*). The study documented the manufacturing of materials and unit costs, along with the ability of the contractor to handle, place, and pave over each base. Deflection and roughness measurements were taken on all sections to evaluate long-term performance. The findings indicated that open-graded permeable base materials can be designed to provide adequate constructibility and pavement support as well as good internal drainage at a competitive cost. It was too early, however, to draw performance conclusions.

Kentucky DOT documented the performance of 18 pavement edgedrain installations, including construction and short-term and long-term performance (*60*). The department found that many edgedrain installations were not fully functioning. Even so, based on analysis of ride index data, Kentucky DOT found that the use of edgedrains improved pavement performance by the equivalent of 8 years. FWD data performed on the sections also indicated that edgedrains significantly increased the strength of the subgrade by removing water.

Minnesota DOT and the University of Minnesota have established the Minnesota Road Research Project, which consists of 10 km of two extensively instrumented test road sections (i.e., an interstate section and a low-volume section). Several test sections, which were designed and constructed using pavement drainage alternatives, are being monitored to evaluate long-term performance. Data are still being gathered, but information and publication references are available on the World Wide Web at http://mnroad.dot.state.mn.us.

Long-term studies also have been carried out in Europe and reported by PIARC (*3,18,44*). Some of the conclusions follow:

- Doweled joints in PCC pavement are very important to long-term performance.
- Subsurface drainage systems must have positive outlets.
- Pavement systems incorporating drainage without maintenance performed as if there were no drains (after 14 years on one project).
- Permeable base is most effective when it is placed directly under the AC or PCC surface pavement.

Studies in France (*3,18*) reported that edgedrains that were functioning when the pavement was constructed became almost inoperative after 11 years without maintenance and that pumping started after 7 years. These studies also reported that some sections in the same system that did not have edgedrains started pumping at 4 years, inferring a nearly double life span of pavement with drainage versus pavement with no drainage.

Although there may be a real or perceived lack of cost-benefit data on the use of subsurface drainage, the preponderance of data show a direct relationship between improved performance and extended pavement life.

CHAPTER SEVEN

CONCLUSIONS

Although there are several existing philosophies on pavement design, the study conducted for this synthesis found a preponderance of evidence supporting the philosophy that good sealing and good drainage, along with a commitment to long-term maintenance, will lead to optimum performance of a pavement system. From this study, it was found that the design principles of pavement subsurface drainage systems for both structural and hydraulic requirements are well established in FHWA Demonstration Project 87, as supported by Synthesis 96 (*4*).

One of the most important design elements appears to be the quality (i.e., durability and gradation) of the permeable aggregate. Construction difficulties concerning placement of permeable base and edgedrains do exist; however, as confirmed by the routine, successful installation experiences of many state DOTs, all can be overcome by resourceful contractors and inspection by well-trained construction personnel.

Long-term maintenance also was found to be essential to successful long-term pavement performance. Because the design, construction, and maintenance groups are interrelated, the team approach has been proposed. In this approach, communication between all functional groups is established at the design phase, with feedback provided throughout construction and long-term maintenance.

Several other significant conclusions were drawn from this study, including the following:

- Pavement subsurface drainage is a major factor in extending the life of a pavement.
- Although performance indicators to quantify the benefits of pavement subsurface drainage systems have not been established, use of a permeable base with a free-draining outlet system generally has demonstrated the best performance of all subsurface drainage strategies.
- The cost of pavement subsurface drainage systems is high in terms of material, construction, and maintenance, but the extended pavement life anticipated appears to make these systems cost-effective.
- Asphalt stabilized permeable base is the drainage material of choice of most respondents. Cost-benefit data do not appear to be available to support this choice, but drainage systems built with this material appear to be easiest to construct.
- Caution must be exercised in applying filter criteria to the design of separator/filter layers.
- Aggregate separator/filters increase pavement support; however, they may lead to a saturated zone just above the subgrade.
- Geotextile separator/filters usually have the lowest material cost and allow a full-depth permeable base to be used; however, they do not increase pavement support as do dense-graded aggregate separator/filters. Therefore, a design effort is required to identify when and where these filters are to be used.
- Many premature pavement failures (less than 50 percent of expected life) have been traced to inadequate subsurface drainage. Premature pavement failures can be expected in cases in which free water is allowed to collect within the zone of load transfer from traffic (surface pavement, base, subbase, and subgrade). Although premature pavement failures can be greatly reduced by good subsurface drainage, such drainage cannot eliminate failures.
- Adding edgedrains to a pavement system seldom improves its serviceability, but usually extends pavement life. To be effective, water must get to the drain and the drain must be sufficiently open to allow fines to pass without clogging.
- Permeable base pavement failures have occurred in cases in which water could not get out of the base fast enough (e.g., because of a lack of pipe outlets, plugged outlets, crushed outlets, clogged filters, or clogged drains). Many drainage system failures are traced to poor construction and inspection.
- A plugged subsurface drainage system may be worse than having no drainage system at all because the pavement system becomes permanently saturated.
- Maintenance efforts vary between good and nonexistent within and among states.
- Long-term maintenance is essential for obtaining the anticipated performance benefits of pavement subsurface drainage systems.
- Training of construction and inspection staff is needed to improve drainable pavement performance.

Although several significant research projects on permeable pavement systems are ongoing, as reviewed in Chapter 6, this study identified many needs that must be addressed to advance this technology. It is hoped that the following needs will support ongoing research and provide the impetus for additional research to help engineers design, build, and maintain pavement systems with confidence.

One of the survey questions asked respondents to identify areas in which more study would help them select the best design strategies for pavement subsurface drainage (see Question 21 in Appendix A). There was a unanimous response as to which topic would be most useful to study—Cost-Effectiveness of Edgedrains and Permeable Base. Comments obtained from notes on the survey and telephone conversations indicated that there is uncertainty about whether improved subsurface drainage is the solution for prolonging pavement life. Permeable base and drainage systems add cost to a highway project, and there is little documented data on the costs and benefits of anticipated performance improvements.

Respondents selected Long-Term Pavement Monitoring as the second most useful topic for study, which supports the concern about the costs and benefits of drainable pavements.

Third was the desire to learn more about the topic Effects of Installation, followed closely by Effects of Low Maintenance, Alternate Construction Strategies, and Alternate Maintenance Strategies. These were followed by Life-Cycle Costs and Effects of Shoulder Detail on Performance.

It appears that respondents have an adequate understanding of the following items because they were low in total score and few respondents indicated a need for study:

- Alternate edgedrain designs,
- Better load transfer,
- Inflow and outflow,
- Alternate joint seals,
- Better filters,
- Crossdrains, and
- Better pipes.

The results of the study conducted for this synthesis support the opinions of state DOTs about the need for more documented cost-benefit studies to help define appropriate subsurface drainage strategies (e.g., use of PCC shoulders, stabilized or unstabilized permeable base, pipe flushing, and preventive maintenance). Respondents also indicated the desire for additional cost-benefit information on retrofit edgedrains.

Better performance indicators and performance monitoring schemes are required to fully explore cost-benefit decisions. Information is required on changes in roadway support so that it can be compared with historical information on other undrained sections, joint behavior, and shoulder behavior. The national effort to improve pavement assessment methods (e.g., using radar to predict changes in support and using geographic information systems with other data gathering methods) could help provide this information. Remote methods of collecting inflow and outflow data and rapid assessment of drainage backup also are required to demonstrate drainage effectiveness.

A clear indicator of the costs and benefits of maintenance is needed. In addition, national and local training programs for construction and maintenance personnel are needed to improve drainable pavement performance.

Although not identified as a significant research need in the survey, the structural contribution of permeable base to the pavement section is not fully understood and requires further study. More study also is required to evaluate the effectiveness of permeable base compared with that of dense-graded base for asphaltic pavement. Design guidelines are needed to determine when construction of a drainage system is cost-effective for special climatic conditions (e.g., arid and semi-arid climates with significant snow melt and the positive and negative effects during freeze-thaw events).

The team approach, in which all functional groups are involved in making design, construction, and maintenance decisions, is introduced in this synthesis as a method to fully evaluate and establish the most appropriate subsurface drainage strategy. The team approach requires the development of formal lines of communication to get key information to decision makers before the design has been completed. This approach works if changes are continuously fed back into the system. It is difficult for decision makers to delay projects and recycle information back through the process if the impact of the change is not evident. An excellent method of handling the communication process may be through a quality steering committee, as outlined in Chapter 2.

The team approach appears to be the best method for obtaining a true life-cycle cost-benefit assessment of drained and undrained pavement systems and for providing the information necessary for continuous improvement.

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APPENDIX A

Nationwide Survey: Questionnaire and Results

QUESTIONNAIRE AND SUMMARY OF RESULTS

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
Project 20-5, Topic 25-07

Pavement Subsurface Drainage Systems

*Name of respondent:*________________
*Agency:*________________
*Title:*________________
*Phone No:*________________

Note: For this survey, the following definitions are used:

- **Permeable Base** (Open Graded Drainage Layer) - Free draining material under the complete pavement section (may be asphalt or cement stabilized).
- **Underdrain** - A conduit to provide subsurface drainage (may be pipe, stone, prefabricated geocomposite, or other).
- **Edgedrain** - An underdrain along the edge of the pavement intended to drain the pavement section materials (not subgrade).
- **Filter Layer** - A layer designed to allow water to freely pass through, but retain the soil (may be geosynthetic or natural soil).

Questions and Answers

1) **About how much Underdarain is used per year?**

-12M linear feet---new construction
  -9M plastic
  -2.9M composite
  -.1M metal
  -.1M other

-6.5M linear feet---retrofit
  -4.5M plastic
  -2M composite

2) **About how much permeable base is used per year?**

	Users
-- 2026 lane miles-unbound	34%
-- 1172 lane miles-asphalt stab.	46%
-- 201 lane miles -cement stab.	34%

Thickness used? -unbound -- 54% use 4 inches, 15% use 6in. or 12in
-asphalt -- 82% use 4in., 12% use 3in.
-cement -- 92% use 4in., 8% use 6in.

		under AC	under PCC
Where used?	-unbound --	5	9
(No. users)	-asphalt --	10	15
	-cement --	4	12

3) **About how much filter layer is used per year? (Square yards)**

underdrain-aggregate -- 0.8M square yards (only 6 responses)
-- (thickness- 2-12 in.)
underdrain-geotextile -- 3.4M sq. yds. (10 responses)(mixed types)
permeable base-aggregate-- 4.8M sq. yds.(10 users)
-- (thickness- 4, 6,3,&1 in.)
permeable base-geotextile--4M sq. yds. (4 users)

4) **How many underdrain outlets are used per year?**

prefab-- 30 K
CIP -- 0.8K
other -- 2 K

Spacing? -- 250 to 500ft.
Outlet pipe? -- most use solid PVC (few solid CMP,CPP)
Markings? -- 13 use posts, 3 mark pvt., 3 other, 7 none

5) **a) Has there been an increase in the use of any of these drainage methods in the past five years?**

-permeable base -- 21 yes, 8 no
-filter layers -- 15 yes, 15 no
-underdrains -- 10 yes, 20 no
-edgedrains -- 14 yes, 17 no

b) If Yes, please provide an approximate percent increase for each, as appropriate:

Percent increases estimated

	new	reconstruction	retrofit
permeable base	78%	73%	0
underdrains	56%	64%	28%
filter layers	63%	45%	0
edgedrains	69%	57%	31%

c) If possible, please provide comment and/or details on the increase in use of these methods during the past five years compared to the five years previous.

Comments -- 45% said that permeable base was their new standard under PCC pavement.

6) What has been done in your organization to relate pavement subsurface drainage to pavement performance?

	regularly	sometimes	never
systemwide studies-----------------	2	6	21
project case studies----------------	1	19	9
formal research projects-----------	1	14	13
periodic inspections---------------	2	18	9
maintenance interviews-------------	2	8	20
project selection process info-----	3	7	18
part of pavement mgmt. system------	2	3	24
pavement serviceability index-------	2	2	25
documented benefit studies---------	0	5	24

7) Please send sketches of the pavement subsurface drainage systems you find most successful.

- For both retrofit edgedrains and for new/reconstruction.

- Also please send design guides for the selection of drainage systems, if available.

sketches of successful edgedrains- 29 responses

design guides for selection of drain system- 10 responses

8) a) What is the expected life of an underdrain system?

	underdrain			edgedrain		
	PCC	AC	composite	PCC	AC	composite
with maint.	30	27	29	28	28	31
without maint.	19	17	14	9	10	8

b) Does it meet expected life?

-All answered yes except two feel that underdrains & edgedrains without maintenance don't meet expectations.

Comments
- -fiber & metal didn't last
- -outlet most vulnerable
- -installation & maintenance critical to performance
- -add 5 yrs life if underdrains under PCC

9) What percent of premature pavement failures do you attribute to inadequate pavement subsurface drainage?

	no drains	bad drains	bad outlet
AC----------	38	27	31
PCC---------	41	17	39
Composite---	31	10	31
responses	45%	17%	12%

10) What are the major types of pavement distress on your system believed to be caused by inadequate subsurface drainage?

Pavement cracking----31%
Joint faulting-------53%
Pumping--------------60%
Shoulder drop--------29%
Stripping of AC------30%
Rutting--------------14%
Other--(D-crack)----- 5%

11) Please rate the following features for their contribution to a long term, high performing pavement system. [(a) for cost effectivnéss and (b) for performance only]
(rate all from 1 to 5, with 5 being the best)

	cost effectiveness	performance	rank
PCC-dense subbase---------------	2.4	2.4	10
PCC-dense subbase-edgedrains----	1.8	2	12
PCC-permeable base-edgedrains---	3	3.6	3*
Effective transverse joint seal-	3.1	3.1	6
Effective Long. joint seal------	2.8	3	9
Effective load transfer---------	3.6	4.1	1*
Maintenance of joint seal-------	3	3.1	7
PCC-concrete shoulders----------	2.8	3.7	2*
AC-dense subbase----------------	3.2	3.2	5*
AC-dense subbase-edgedrains-----	1.8	2.1	11
AC-permeable base-edgedrains----	2.7	3.1	8
AC-slurry seal------------------	1.9	2	13
Scheduled outlet maintenance----	3.1	3.3	4*

Please provide any information on cost effectiveness (i.e., study results, reports, memorandum). This will aid in drawing conclusions on the cost effectiveness of various systems.

12) Do you have problems of stability of Permeable Base under construction traffic?_____detour traffic? _______

construction traffic--10 yes, 15 no
detour traffic--5 yes, 6 no

- Please send a copy of your gradation and/or specification

(24 example specs.)

13) Do you test permeable base material for permeability?

10 yes, 15 no
Lab value-3 have values between 200 and 2000 ft./day
5 have values from over 2000 to over 10000 ft./day
4 have horizontal values over 1000 ft./day
Field values-2 have values over 2000 ft./day
1 has value over 500 ft./day

14) Please identify any difference in performance when (a) the underdrain is installed during placement of subbase or (b) after the section is ready for pavement (or has pvt.)

	a-before	b-after
not permitted------------	4	7
less flow----------------	0	0
pavement damage----------	0	0
shoulder sag/crack-------	0	3
higher maintenance-------	0	1
lower installation cost--	0	2

Comments
-permeable base must go in first
-Contractor's option
-no difference if put in right
-no visible difference
-after assures no contamination of drain materials
-note: Big users(Minn.,Ca., Pa., & NY.)require after.

15) a) What is your experience with Prefabricatied Composite Edgedrains (PCED)?

Have not used-------	11	
Standard detail-----	14	Note: One state no longer allows use.
Experimental only--	9	

b) How close to the pavement edge do you place the PCED?

next----------------	20
3 inches------------	5
more----------------	2

c) What is the performance observed?

Performance? (3=good, 2=inconclusive, 1=poor)

	New			Retrofit		
	3	2	1	3	2	1
AC						
next--	3	2	0	3	7	1
3 in.-	1	0	0	2	1	1
more--	1	0	0	0	1	1
total responses	5	2	0	5	9	3
PCC						
next--	2	5	0	8	8	1
3 in.-	1	2	0	1	1	2
more--	0	1	0	0	0	1
total responses	3	8	0	9	9	4

Note: The principal use is retrofit on PCC- 62% use

-71% report good for new AC
-30% report good for retrofit AC
-30% report good for new PCC
-40% report good for retrofit PCC

16) a) Do you conduct any special inspection or testing of subsurface drain systems before construction acceptance?

8 yes
26 no

Note: 3 use video camera, 3 flush, and 2 use visual checks.

b) **Does maintenace have a periodic subsurface drain inspection program? _______ YES or NO)**

9 yes
25 no

Comments
- -clean screen & outlet
- -variable by district
- -outlet visual-rodents, silt, crushing, blockage
- -low priority maintenance item

Frequency
2-6 mo.
4-1 yr.
1-2 yr.
1-as needed
1-rare

c) **What type of inspection is done?**

11-visual inspection
1-some video
3-none

Borescope?
3 yes
15 no

d) **Do you have any data on the cost effectiveness of inspection? _______ (YES or NO) C/B for borescope?**

26 no

17) **What type of maintenace is done on underdrains?**

(3=always, 2=sometimes, 1=never)

	3	2	1
Flush---------	1	10	14
Clean outlet--	2	24	2
Replace-------	1	15	9
Other---------	0	0	1

Comments
- -only failure repair
- -no evidence of maintenance effect
- -replace when mud pumping
- -very little
- -need more

18) **Which of the following do you believe are causes of premature pavement failures from poor subsurface drainage?**

(3=always, 2=sometimes, 1=never)

	3	2	1
Design--------	8	23	2
Construction--	7	26	0
Maintenance---	6	25	0
Unique site---	4	23	2

19) a) **Where do you think the greatest improvement in subdrain systems would come from?**

Research-15
Training-25

b) **Which areas would produce the most impact?**

Rank impact (1 to 5- best)

	research					training				
	5	4	3	2	1	5	4	3	2	1
Design---------	8	4	6	6	1	8	8	6	7	2
Construction---	7	3	7	7	1	14	6	4	6	2
Inspection-----	3	2	9	8	3	12	4	6	5	3
Maintenance----	5	6	7	4	2	16	7	3	3	2
Geotechnical---	5	3	7	2	8	4	3	7	5	10

Note: Many respondents rated, not ranked. Some rated in only one category.

20) **Which choices of possible strategies do you think would make the greatest improvement in pavement performance? strategies of most value?** (1 to 5-best)

	5	4	3	2	1
Thicker pavements----------	3	6	7	13	6
Wider pavements------------	4	6	3	14	8
More permeable base--------	15	5	11	1	3
More underdrains-----------	8	11	9	2	5
Better joint sealers-------	6	6	12	5	4
Better construction practices	14	12	4	5	0
Improved inspection--------	7	13	11	3	1
Better materials-----------	9	10	9	7	0
Improved maintenance-------	14	10	6	5	0
Other----------------------	2	1			

Notes: -stabilize subgrade
-PCC shoulders tied
-impermeable asphalt
-improve AC
-use all CRCP

21) **What items would you like to see studied in more detail to help you select the optimum choice of pavement subsurface drainage strategies?**

future research? (1 to 5-best)

rank	rating	5	4	3	2	1	Sum
2	Long term pvt. monitoring--	17	7	3	2	3	129
10	Inflow/outflow studies-----	3	6	11	6	7	91
1	Cost effectiveness of edge-drains and permeable base	17	4	9	6	3	134
6	Life cycle costs-----------	8	6	9	6	3	106
3	Effect of installation-----	8	8	11	4	2	115
8	Effect of shoulder detail--	3	5	16	4	4	98
4	Effect of low maintenance--	8	8	10	3	4	112
9	Alternate underdrain details	0	9	13	7	4	93
13	Alternate joint seals------	3	6	9	7	7	87
11	Better load transfer-------	3	6	13	3	7	91
7	Alt. maintenance strategies	7	7	9	7	2	106
5	Alt. constr. strategies----	5	11	7	7	3	107
14	Evaluate cross drains------	1	5	8	13	5	80
15	Better pipes---------------	2	2	9	8	12	73
12	Better filters-------------	3	8	5	10	6	88
	Other----------------------	2					10

Notes: - Most installation details submitted are similar and summarized in the text.

- Ten states submitted design guides for selection.

APPENDIX B

Examples of Guidelines for Permeable Aggregate Base Application (From Minnesota DOT)

PERMEABLE AGGREGATE BASE (PAB) APPLICATION GUIDELINES

2/94

SURFACE TYPE	SUBGRADE SOIL >>	PLASTIC/ NON-GRANULAR				GRANULAR SEE NOTE D			
	TRAFFIC LEVEL >>	VH	H	M	L	VH	H	M	L
CONCRETE	INTERSTATE	R	R	NA	NA	R	R/AR	NA	NA
	NON-INTERSTATE	R	R	R	AR	R	R/AR	NR	NR
BITUMINOUS FULL DEPTH	INTERSTATE	R	R	NA	NA	R	R/AR	NA	NA
	NON-INTERSTATE	R	R	R	AR	R	R/AR	NR	NR
BITUMINOUS AGG BASE	INTERSTATE	R	AR	NA	NA	R	AR	NA	NA
	NON-INTERSTATE	R	AR	NR	NR	R	AR	NR	NR

LEGEND:
AR = AS RECOMMENDED (SEE NOTE A)
NA = NOT APPLICABLE (SEE NOTE B)
NR = NOT RECOMMENDED
R = RECOMMENDED
R/AR = SEE NOTE C BELOW

TRAFFIC LEVEL (20-YEAR DESIGN LANE)		
(IN MILLIONS)	BESALS	CESALS
VH (VERY HIGH)	> 10 M	> 15 M
H (HIGH)	3 - 10 M	4.5 - 15 M
M (MEDIUM)	1 - 3 M	1.5 - 4.5 M
L (LOW)	< 1 M	< 1.5 M

NOTES:

A) AR - AS RECOMMENDED. DISTRICT SOILS/MATERIALS ENGINEER SHOULD CONSIDER:

1. PAST PAVEMENT PERFORMANCE AND EXPERIENCE.
2. TYPES OF DISTRESS (D-CRACKING, ETC.)
3. ANTICIPATED PAVING AGGREGATE QUALITY.
4. AVAILABILITY OF MATERIALS.
5. GRADELINE MODIFICATION NEEDED TO IMPROVE GRADELINE/ DRAINAGE WITH RESPECT TO THE INPLACE WATER TABLE.
6. COST DIFFERENTIAL AND ANTICIPATED INCREASE IN SERVICE LIFE THROUGH THE USE OF PERMEABLE TYPE BASES.

B) NA - NOT APPLICABLE APPLIES TO INTERSTATE TRAFFIC LEVELS M AND L. (INTERSTATE HAS ONLY VH AND H TRAFFIC LEVELS)

C) R/AR - MEANS R (RECOMMENDED) IF GRANULAR MATERIAL HAS BETWEEN 12 AND 20% PASSING THE NO. 200 SIEVE (Mn/DOT 3149.2A)
MEANS AR (AS RECOMMENDED) IF GRANULAR MATERIAL HAS 12% OR LESS PASSING THE NO.200 SIEVE (Mn/DOT 3149.2B)

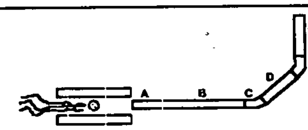
D) GRANULAR SUBGRADE IS A SUBGRADE IN WHICH THE UPPER 3 OR MORE FEET HAS 20% OR LESS PASSING THE NO.200 SIEVE.

E) PERMEABLE AGGREGATE BASE TYPES:
CONCRETE - OPEN GRADED AGG BASE (OGAB) OR PERMEABLE ASPHALT STABILIZED BASE (PASB)
BITUMINOUS - PASB ONLY

APPENDIX C

Example Construction and Maintenance Inspection Forms (From Kentucky DOT)

ROUTE	MILEPOST	DIRECTION	LOCATION & OUTLET TYPE 1. S-H 2. S-B 3. M-H 4. M-B	OUTLET 1. CLEAN 2. PT. COVER. 3. COVER. 4. PLUGGED	COVER MATER. 1. GRAV. 2. DIRT. 3. VEG. 4. CON.	SCREEN CONDITION 1. NONE 2. OPEN 3. PT. OPEN 4. BLOCK	SILT 1. NONE 2. SLIGHT 3. MOD. 4. SEV.	FLOW 1. YES 2. NO	DITCHLINE DRAINAGE 1. GOOD 2. POOR	SURFACE DISTRESS 1. POT HOLE STAINING 2. OUT 3. INSIDE 4. CL 5. CON. JT. 6. SHOULDER	FIELD NOTES	FILM ROLL# & PHOTO #

ROUTE	MILEPOST	DIRECTION	PIPE TYPE 1. FLEX. 2. RIGID	1. SAG 2. SAG W/ STANDING WATER 3. SAG W/ SILTATION 4. COMPRESSED COUPLING 5. COMPRESSED PIPE		6. BACKFILL IN PIPE 7. SEPARATION AT COUPLING 8. RIP IN PIPE 9. COMPRESSED PANEL 10. COMPRESSED AND SILTED PANEL					VIDEO TAPE
				A	B	C	D	E	F	COMMENTS	

THE TRANSPORTATION RESEARCH BOARD is a unit of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. It evolved in 1974 from the Highway Research Board, which was established in 1920. The TRB incorporates all former HRB activities and also performs additional functions under a broader scope involving all modes of transportation and the interactions of transportation with society. The Board's purpose is to stimulate research concerning the nature and performance of transportation systems, to disseminate information that the research produces, and to encourage the application of appropriate research findings. The Board's program is carried out by more than 400 committees, task forces, and panels composed of more than 4,000 administrators, engineers, social scientists, attorneys, educators, and others concerned with transportation; they serve without compensation. The program is supported by state transportation and highway departments, the modal administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

The National Academy of Sciences is a nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce Alberts is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encouraging education and research, and recognizes the superior achievements of engineers. Dr. William A.Wulf is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences, by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Kenneth I. Shine is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce Alberts and Dr. William A. Wulf are chairman and vice chairman, respectively, of the National Research Council.

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