Appendix L

Literature Review

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The literature review focusses on historical and practical aspects of OGDC as base material for rigid pavement systems.

Appendix L LITERATURE REVIEW

1. Background

In the mid-1980's, the Michigan Department of Transportation (MDOT) made a major shift in the design of portland cement concrete pavements (PCCP), switching from the use of dense graded (effectively non-draining) untreated granular bases to drainable or open graded untreated granular bases. The terms "open graded" and "drainable" are used synonymously in this report. It is noted that some researchers have defined drainable materials as having permeability's between 305 m/day and 1,525 m/day (1000 ft/day and 5000 ft/day) while open graded materials are defined as having permeability's in excess of 1,525 m/day (5000 ft/day). The movement by MDOT toward open graded bases reflects a national trend in which drainable pavement systems have been embraced nationally by the pavement industry under the assumption that the rapid removal of water from the pavement system would eliminate or significantly reduce many moisture related pavement distresses. It was anticipated that the higher cost associated with the construction of these pavements would be offset by improved pavement life and performance, reducing the overall life cycle cost.

In the early to mid 1990's, MDOT noted that transverse cracks that are a normal feature of long jointed reinforced concrete pavement (JRCP) were suffering excessive opening and deterioration on some of the sections constructed on open graded bases. This literature review discusses the historical background and rationalization that led to the national shift in policy regarding the use of drainable bases. The basic design features of drainable pavement systems are then discussed along with the importance of maintaining the drainage system after construction. National literature regarding the performance of in-service pavements constructed on drainable bases is also reviewed.

1.1. Historical Perspective

Since the construction of the first pavements, it has been noted that the presence of free water was detrimental to pavement performance. The ancient Romans (approximately 300 BC) mitigated the impact of water by constructing roads above the surrounding terrain, placing them on thick subbases of sand prior to cementing large rocks together to form the surface. Some of these roads are still in use today. roughly 2,300 years after construction, attesting to their durability (Cedergren 1987). In the early 1800's, John McAdam (1820) stated that if water were allowed to pass through the road into the subgrade, loss of support would occur regardless of the pavement thickness. McAdam also linked poor road performance in Great Britain in the 1800's to ignorance towards the necessity of adequate pavement drainage.

The advent of automobiles and trucks in the early 1900's necessitated the construction of all weather-surfaced roads. Engineers assumed that they could easily design pavements to withstand the large pore water pressures created by free water under the higher load levels. Needless to say, many of these pavements failed prematurely due to water associated distresses. Although the Highway Research Board (HRB) recognized that free water created distress, they did not alter road designs to account for it. In the 1950's, the HRB performed numerous road tests (HRB 1952; HRB 1955; HRB 1962) to determine the effects of axle loads on pavement distress and performance. Unsurprisingly, it was found that the largest amount of damage to the pavement occurred when the underlying structure was in a saturated state. Unfortunately, even though these observations were made, drainage systems were almost entirely disregarded as a fundamental design feature until mid to late 1980's (ERES 1996).

Up until mid 1980's, it was common practice in the United States to use a dense-graded granular base material directly beneath PCCP. Although this material could be compacted to a high density, the high amount of fine material passing the 75 μm (No.200) sieve resulted in poor drainage characteristics. One example of this type of specification is that formerly used by the Corps of Engineers (COE). Their concrete pavement design criteria required the use of a dense-graded granular base that drained to 50 percent saturation within 10 days (Army 1965). It was found that the gradation and drainage requirements were in direct conflict as the base was effectively impermeable if the gradation was met. This was confirm by a COE study which found that the subsurface pavement layers of most pavements designed using this criteria remained near or in a saturated condition throughout their service life (Nettles and Calhoun 1967). Former Secretary of Transportation Federico PeZa reported that the cost of repairing all backlog highway deficiencies existing at the end of 1991 would be $212 billion dollars, which was $7 billion more than in 1989. It is believed by some that the primary reason for many premature pavement failures are distresses associated with saturated subsurface pavement layers (Grogan 1994). According to Cedergren (1994), "it is the undrainage philosophy pervading the pavement-design profession that is responsible for the premature failure of thousands of miles of pavements." Thus, it has been argued that good drainage design practices could have averted much of the premature damage incurred, saving billions of dollars in highway repair.

In 1973, Harry R. Cedergren, along with Ken O'Brien and Associates, completed the Federal Highway Administration (FHWA) report titled *Guidelines for the Design of Subsurface Drainage Systems for Highway Structural Sections*. This report concluded that the primary cause of distress in numerous cored pavement sections is the abundance of free water within the pavement structure. It put forward the need to drain free water from the pavement structure as a precursor to improved pavement performance. This seminal work became the foundation for a major shift in pavement design practice in the early to mid 1980's, with Cedergren spearheading the revolution.

Recent reports by Forsyth (1993) and ERES (1996) indicate that most States have adopted subsurface drainage procedures. At the time of his report, Forsyth found that 33 States were using drainage systems with their PCC pavements. In the more recent report, ERES obtained survey results from 37 highway agencies, 31 of which were using drainable bases. This major shift occurred over a relatively short time span and with little long-term performance data demonstrating the effectiveness of drainable pavement systems. Only recently have results of studies of in-service pavements constructed on drainable bases become available, although in many cases, the pavements under study have been in service less than 10 years.

1.2. Sources of Moisture in Pavement Structures

Water can enter a pavement structure through many different avenues. Figure 1 illustrates a number of sources including infiltration through the pavement surface, seepage and lateral moisture transfer, and capillary movement upward from the water table through fine-grained soils (FHWA 1973). Another source of pavement moisture is vapor movements from groundwater (FHWA 1990). Many highway engineers believe that subsurface sources of water are the primary contributors to pavement distress, yet it can be shown that infiltrating surface water is a major source of moisture in the pavement structure (ERES 1994).

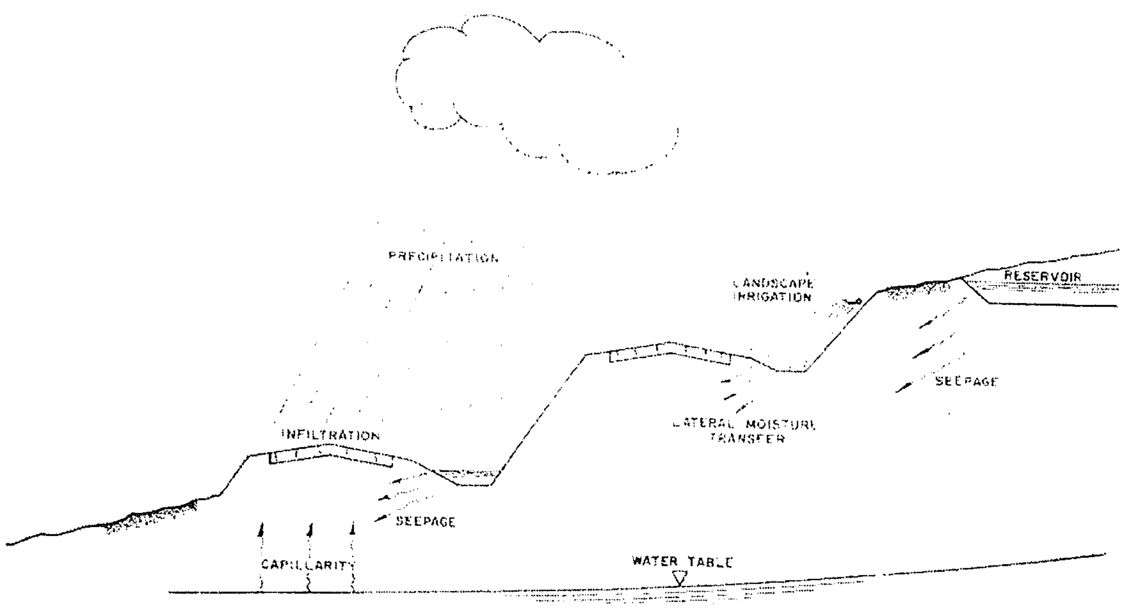


Figure 1. *Sources of moisture in the pavement structure (FHWA 1973).*

1.3. Moisture Related Distress

It is evident that a number of pavement distresses can be directly or indirectly attributed to the presence of moisture in the pavement structure. Pumping, faulting, void formation, and corner breaks are structural defects in concrete pavements that can be directly linked to the presence of free-water beneath the slab (FHWA 1994). Durability related distresses, such as freeze-thaw damage, D-cracking, and ASR also require moisture. In fact, it is beyond question that the presence of free water in the pavement system is detrimental to pavement performance, leading to a wide variety of pavement distresses (FHWA 1994).

Once the untreated underlying pavement layers exceed 85 percent saturation, they become highly unstable and vulnerable to the effects of dynamic loading. This includes a significant decrease in strength and stiffness, with increasing susceptibility to non-recoverable strain (Dempsey et al. 1982). At saturated conditions, the effective weight of the soil is reduced, thereby decreasing the effective frictional strength within the soil structure. In his book *Drainage of Highway and Airfield Pavements*, Cedergren (1987) describes in great detail the direct relationship between excess water and decreased pavement life. Some of the adverse effects are manifested in premature rutting, cracking, faulting, increased roughness, and the relative decrease in the level of serviceability (Baldwin 1987) (FHWA 1994).

When the AASHO Road Test was conducted in 1958-1960, one of the major distresses reported in the PCCP sections was pumping. Pumping results when free water present within the pavement structure is ejected from beneath the slab under the action of moving wheel loads. This forceful ejection of water commonly causes erosion, resulting in void formation beneath the corner of the leave slab and subsequent deposition of material under the approach slab. Ultimately, joint faulting results as the leave slab rises due to the build up of material beneath it. This mechanism is illustrated in Figure 2.

It is known that faulting is significantly reduced when free water is eliminated from beneath the slab. This is reflected in the AASHTO design guide, which addresses drainage condition through two factors: a loss of support factor (LS) and drainage coefficient (C_d) (AASHTO 1993). The LS factor is used to modify the effective k-value, reducing it if erodible, untreated granular base is used. The C_d is based on quality of drainage and the percent of time that the pavement structure is exposed to moisture levels approaching saturation. In situations where erodible, non-draining base is used in a location where high levels of saturation are expected, the AASHTO design procedure requires that a thicker slab be used. This is contrary to early findings of engineers such as McAdam who warned that increased pavement thickness is not a substitute for good drainage. Many researchers have investigated the mechanisms leading to pumping and what design elements can be used to mitigate it (Gulden 1974; Ray and Christory 1989;

Van Wijk et al. 1989). In high traffic areas subjected to wet environmental conditions, it has been concluded that the most effective method to alleviate pumping is through the installation of a drainage system that rapidly removes free water from beneath the slab.

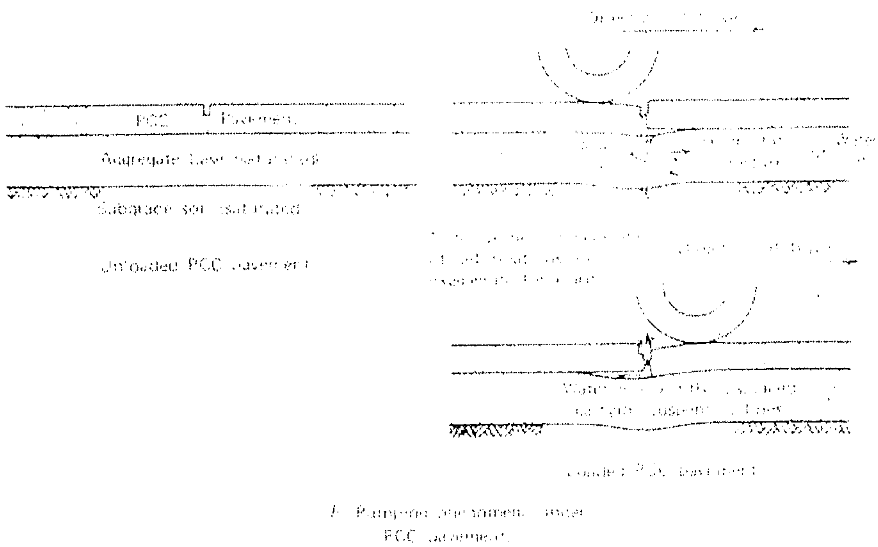


Figure 2. *The effects of wheel loads on saturated PCC pavement (FHWA 1973b).*

Others have proposed that the use of drainable pavement systems will reduce material-related distress (MRD) because initiation and progression is dependent on the PCC being at or near saturation. The need for high saturation is true of both physical deterioration, such as D-cracking or paste freeze-thaw damage, and chemical deterioration, such as alkali-silica reactivity (ASR). This trend has been observed in some pavement performance studies which noted a decreases in the incidence and severity of D-cracking in pavement sections constructed on drainable bases (Darter and Becker 1984; Crovetti and Dempsey 1991). At this time, the relationship between pavement system drainability and the initiation and progression of MRD is uncertain and further study is recommended (Bunke 1990; ERES 1996; Moss et al. 1997).

As a result of the potential improvement in pavement performance, many States have modified their specifications away from dense-graded, poorly draining base material to those featuring more open-graded, drainable base materials.

2. Basic Drainable Pavement System Design Features

Drainable PCCP's are designed to provide rapid, efficient removal of water from the pavement structure. A number of extremely informative references are available providing both a justification for the use of positive drainage for PCC pavements and information regarding the design of drainable systems. Some of the most helpful references are: *Drainable Pavement Systems* (FHWA 1992), *Technical Guide Paper on Subsurface Pavement Drainage* (FHWA 1990), *Development of Guidelines for the Design of Subsurface Drainage System for Highway Pavement Structural Sections* (Cedergren et al. 1973), *Highway Subsurface Design* (Moulton 1980), *Pavement Subsurface Drainage Systems* (Ridgeway 1982), *and Subgrades and Subbases for Concrete Pavements* (ACPA 1995). Additionally, most State highway agencies (SHAs) that are currently using drainable pavement systems have excellent design information (ERES 1996).

As illustrated in Figure 3 (FHWA 1990), a positive pavement drainage system must consist of the following three primary components:

- A permeable base layer that provides rapid drainage of free water entering into the pavement structure.
- A longitudinal edge drain collector system and adequate transverse outlet pipes to convey accumulated water from the permeable base to ditches or drains.
- A filter/separator layer that prevents migration of fines (material passing the 75 µm [No. 200] sieve) into the permeable base from the subgrade, subbase, or shoulder material.

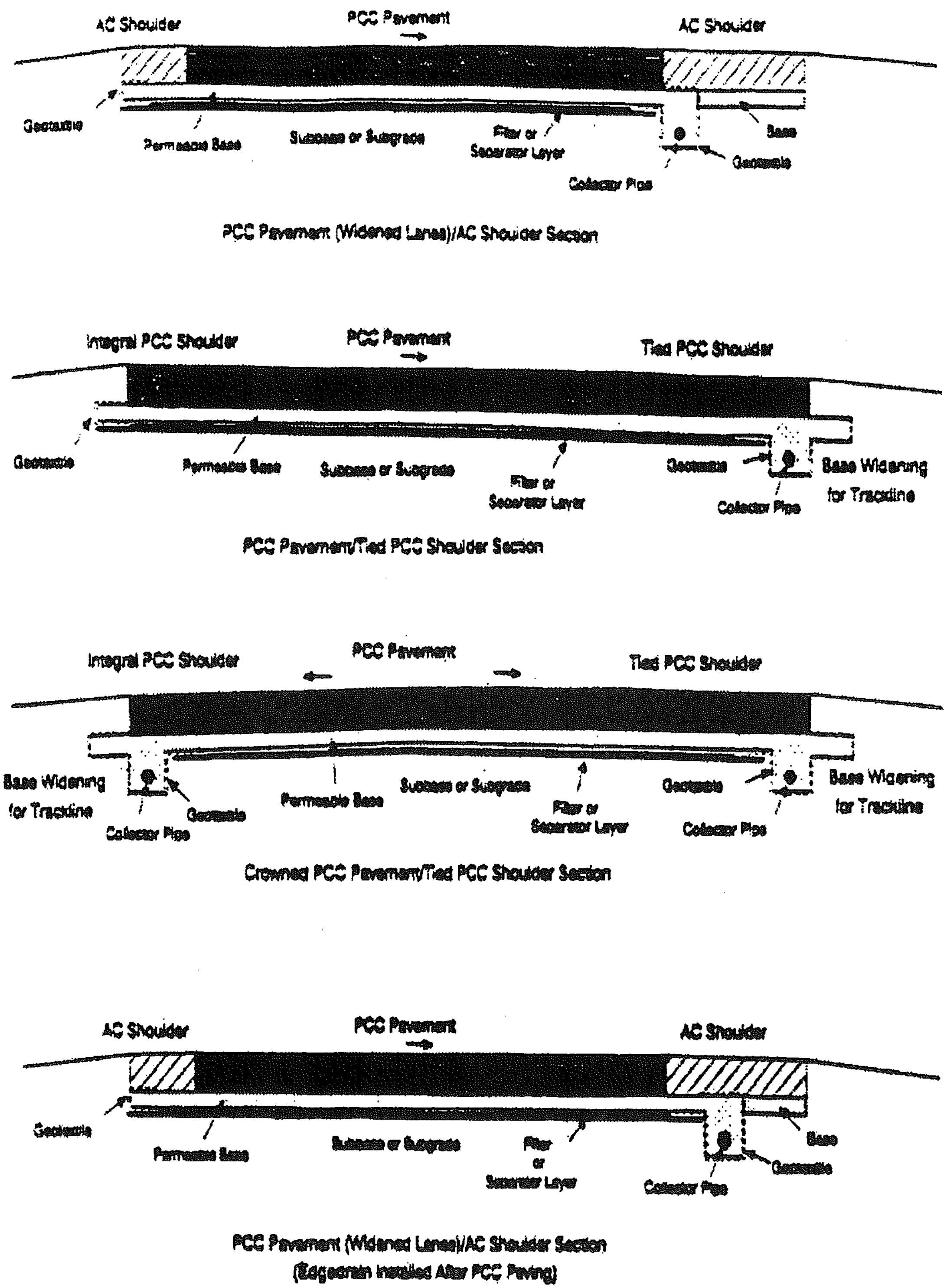


Figure 3. Four permeable base sections (FHWA 1990).

2.1. Drainage Approaches

Two different approaches are commonly used to determine the drainage time for a given pavement layer: the steady-state approach and the time-to-drain approach (FHWA 1992). In the steady-state approach, all sources of water inflow and outflow are quantified and the drainage system is designed to meet the outflow requirements. The time-to-drain approach is a simplified variation of the steady-state approach in which only moisture infiltrating the system is considered. Currently, the time-to-drain approach is the most popular amongst SHAs.

In the time-to-drain approach, it is assumed that the base becomes saturated under a rainfall event, at which point additional precipitation is assumed to run off the pavement surface. The key is to design a drainage system that will drain quickly once the rain ceases, minimizing damage to the pavement by limiting the time of saturation. Drainage times on the order of one-half to one hour are considered adequate (ERES 1994). The method considers the drainage path, including distance and slopes, followed by water through the underlying drainage layer.

The drainage layer permeability can be measured or calculated from material properties and drainage times calculated. The specific yield and degree of drainage are used to compute the water drained, which in turn determines the time required to reach a saturation level at or below 85 percent. The overall drainability of the system can then be assessed as the percent of time the pavement approaches saturation, considering both spring thaw and average rain events throughout the course of the year. This method has been computerized in a program called DAMP (Carpenter 1990) and is available from the FHWA. It is noted that if groundwater is present, special design considerations must be made.

Too often, pavement engineers concern themselves solely with the characteristics and design of the drainage layer, forgetting about the equally important considerations that the must be made in the design and construction of the filter/separator layer, longitudinal drainage pipe (including the trench), transverse outlet pipe, headwalls, and ditch. Each component of the drainage system is equally important, and it must be understood that a failure to properly design and construct any one element may lead to failure of the entire system. The following provides a brief description of each component, focusing on critical attributes that are required for effective performance.

Drainage Layer

The drainage layer is the most talked about component in the drainable pavement system. It is commonly referred to as the drainable base, permeable base, or drainage blanket. This layer facilitates the movement of infiltrating moisture from beneath the slab to the longitudinal drain through the use of highly permeable material (from 305 to 30,500 m/day [1,000 to 100,000 ft/day]). It has been suggested by some that the drainage layer must have a coefficient of permeability of many thousands of feet per day in order to provide high levels of protection from excess water (Cedergren 1987). Although drainable bases with coefficients of permeability greater than 10,000 ft/day are not uncommon, the FHWA recommends that a minimum permeability of 305 m/day (1000 feet/day) is more than adequate under most circumstances (FHWA 1992).

There are two basic types of permeable bases; untreated and treated. Both should consist of hard, durable, crushed aggregate with an open gradation possessing essentially no fine material (material passing the 75 µm [No.200] sieve) (FHWA 1990). Figure 4 presents an example of an acceptable drainable base gradation (FHWA 1992).

It is commonly stated in the literature that a well designed drainable base composed of high quality, crushed aggregate will supply adequate support for construction vehicles without degradation to the aggregate. Table 1 presents six gradations used for permeable bases, including the estimated permeability (K) in ft/day for each (FHWA 1990). Untreated drainable base relies solely on the stability inherent in the aggregate structure to resist excessive deformation under construction and in-service traffic while maintaining sufficient in-situ permeability. Treating the drainable base with a small percentage of asphalt or portland cement provides a more stable working platform for construction without significantly affecting the permeability of the layer. Treatment also prevents problems with sloughing that may occur if the longitudinal drainage trench is installed after paving. In general, due to enhancements in stability resulting from the use of a stabilizing agent, a more open material can be used. This allows treated permeable bases to have higher permeability's than untreated bases (Crovetti, 1991).

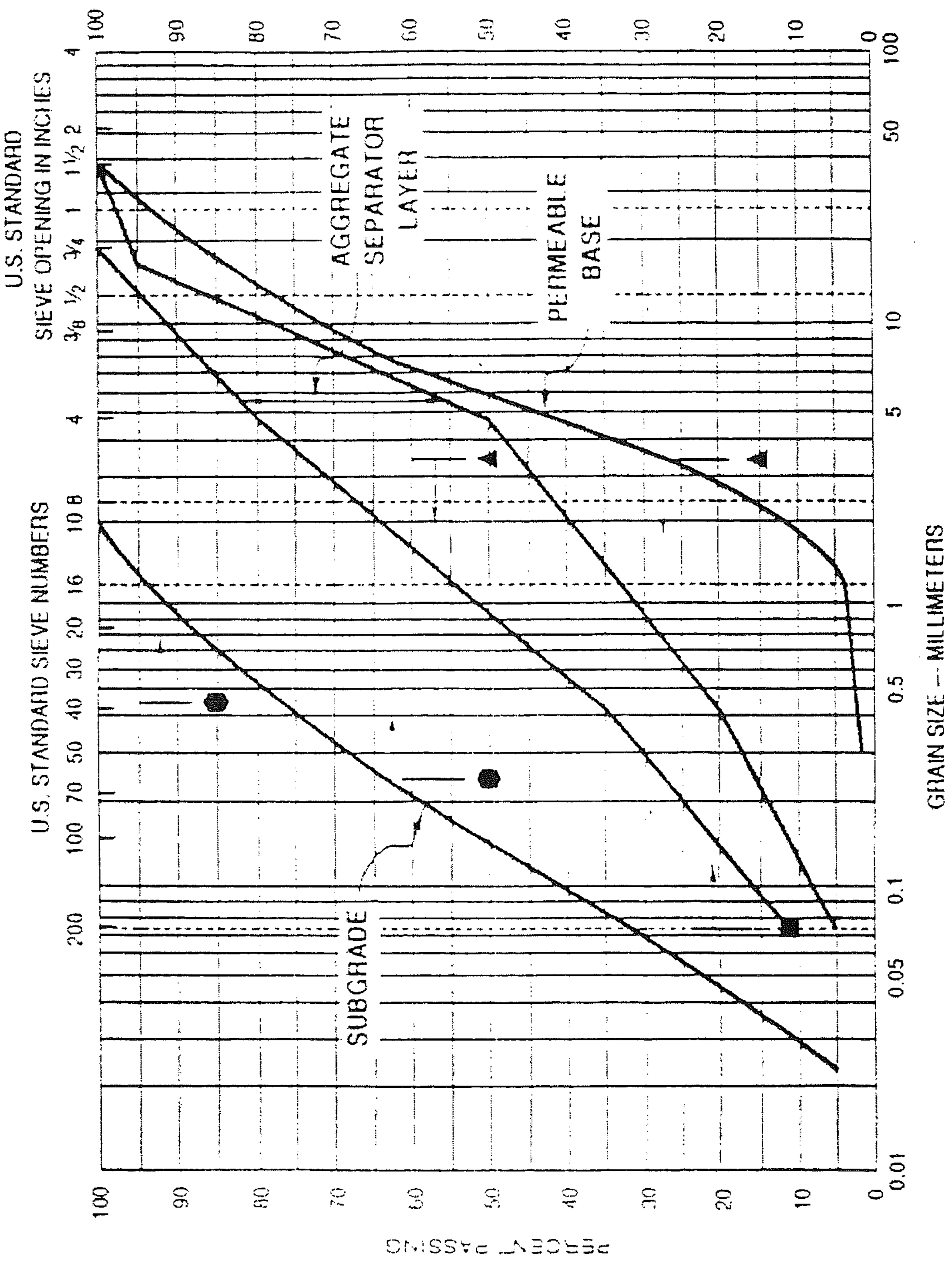


Figure 4. *Particle size distribution curves for permeable base and separator layer (FHWA 1992).*

Table 1. *Permeable base gradations and permeability's (FHWA 1990)*

Sieve	Percent Passing					
	No. 57[1]		California		Wis.	NJ
	Untreated	Treated	AC Treated	PC Treated	PC Treated	AC Treated
1 ½ in	100	100	-	100	-	-
1 in	95-100	95-100	100	86-100	-	100
¾ in	-	-	90-100	X ± 22	90-100	95-100
½ in	60-80	25-60	35-65	-	-	85-100
3/8 in	-	-	20-45	X ± 22	20-55	60-90
No. 4	40-55	0-10	0-10	0-18	0-10	15-25
No. 8	5-25	0-5	0-5	0-7	0-5	2-10
No. 10	-	-	-	-	0-5	-
No. 16	0-8	-	-	-	-	2-5
No. 50	0-5		-	-	-	-
No. 200	-	0-2	0-2	-	-	*
Est. "K" (ft/day)	1,000	20,000	15,000	4,000	10,000	1,000

[1] Many States use an AASHTO No. 57 gradation treated with asphalt or portland cement.
X is the gradation, which the contractor proposes to furnish for the specified sieve size.
* Add two percent (by weight of total mix) mineral filler.

Filter/Separator Layer

The filter/separator layer is a second vital component in the drainable pavement structure. This layer is designed to prevent subgrade fines from migrating into the permeable base. It also provides support for construction equipment, the permeable base, and the PCC pavement. The absence of a filter/separator layer within a drainage system allows fines to migrate upward into the drainage layer, thereby decreasing its permeability. This migration of fines also adds to instability and loss of support as fine material occupies void space in the drainage layer. It has also been speculated that this could lead to premature pavement distress (Heckel 1997).

It is recommended that this filter/separator layer be composed of a dense-graded base material having a minimum thickness of 100 mm (4 in) (FHWA 1990). To ensure functionality, the gradation of the filter/separator layer must be careful designed using criteria used established by Cedergren (1962). The general procedure requires that a mechanical sieve analysis be performed on the subgrade soil and the proposed drainable base and filter/separator material. The particle size distribution curves are compared and Terzaghi's gradation matching criteria is used to determine whether the filter/separator material is satisfactory (FHWA 1994).

The criteria below are recommended to relate the filter/separator layer to the underlying subgrade (Moulton 1980):

$$\frac{D_{15}(filter\ /\ separator)}{D_{85}(subgrade)} \leq 5$$

$$\frac{D_{50}(filter\ /\ separator)}{D_{50}(subgrade)} \leq 25$$

where D_x is the diameter at which x percent by weight of the particles are finer.

Similarly, these same equations can be used to relate the permeable base and the underlying filter/separator layer as follows (Moulton, 1980):

$$\frac{D_{15}(base)}{D_{85}(filter\ /\ separator)} \leq 5$$

$$\frac{D_{50}(base)}{D_{50}(filter\ /\ separator)} \leq 25$$

It is also recommended that maximum percent passing the 75 µm (No. 200) sieve not exceed 12 percent and that the coefficient of uniformity (D_{60}/D_{10}) be greater than 20 and preferably greater than 40 (FHWA 1990). Figure 4 depicts an example of a well-designed filter/separator layer given the particle size distributions for the subgrade and permeable base layer.

Geotextile filter/separator layers may also be used in place of the dense-graded aggregate layer, although most States recommend against it. Although the use of a geosynthetic filter may reduce cost of construction, similar design criteria must be met to match the fabric to the subgrade and base. This can be difficult, and it is recommended that the

FHWA's *Drainage Pavement Systems Notebook* be consulted when using a geosynthetic filter/separator layer (FHWA, 1992).

Longitudinal Edge Drain

The water collected in the drainable base must be quickly moved to a longitudinal edge drain collection system, which in turn will move the water rapidly to ditches or other drainage structures. The edge drain system must have adequate capacity to handle anticipated flow. The longitudinal edge drain should be open directly to the drainable base, yet protected from infiltration of subgrade and filter/separator material. The FHWA (1990) recommends that the longitudinal edge drain be able to drain a permeable base within two hours of a rain event. In pre-pave installations as illustrated in Figure 5, the trench backfill is the same material as the drainable base. In post-pave installation, all backfill material within the edge drain trench must be designed to accommodate all runoff that enters the pavement and should be at least as permeable as that used in the drainable base. A cross section of this design is shown in Figure 6. The critical aspect of this design is that the drainage path is not interrupted with less permeable materials, otherwise it will act as a dam, retaining free water beneath the slab.

A number of different materials are commonly used for longitudinal edgedrains including clay tile, concrete tile and pipe, vitrified clay pipe, perforated plastic pipe, bituminous fiber pipe, perforated corrugated metal pipe, corrugated polyethylene pipe, and slotted PVC pipe, with the later two being the most common (FHWA 1994). Geocomposite fin drains are commonly used in drainage retrofits, but are not recommended for use with drainable bases (FHWA 1990).

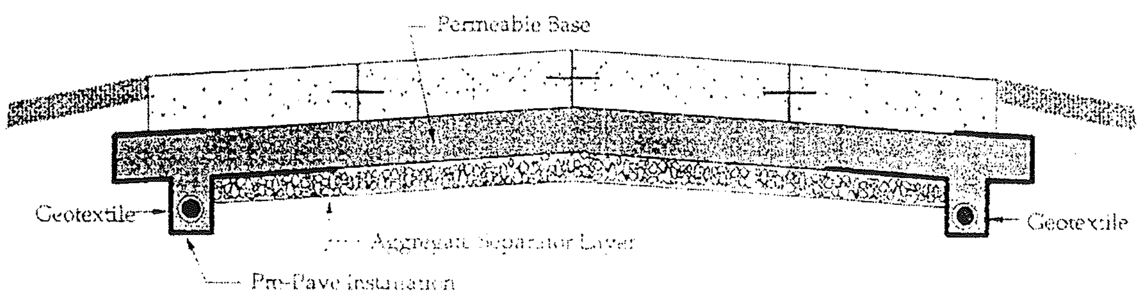


Figure 5. *Pre-pave geotextile installation (FHWA 1992).*

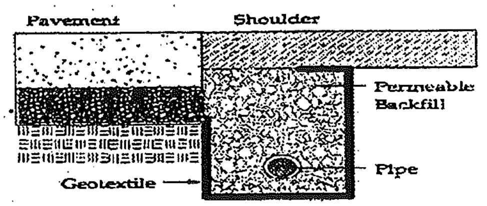


Figure 6. Geotextile wrapped edgedrain, post-pave installation (FHWA 1990).

Other Drainage System Components

Other features of the drainage system include the trench cap, lateral outlet pipe, headwalls, rodent screens, and outlet markers. Spacing of the outlets should be designed, with maximum spacing of 75 m to 90 m (250 to 300 feet) (FHWA 1990). In order to maintain positive drainage to the ditches, the longitudinal drains must have adequate elevation above the ditch line. It is recommended that the bottom edge of the outlet pipe lie at least 150 mm (6 in) above the 10-year flow level in the ditch (FHWA 1992). If this condition cannot be met, the use of outlet pipes to ditches may not be feasible and enclosed drains would have to be installed (FHWA 1990).

Headwalls should be installed at each outlet for protection of the drainage system and to prevent erosion of the surrounding soil. Care should be taken when installing the headwalls to ensure they are sloped properly. During their study, Fleckstein and Allen (1996) located numerous headwalls that were sloped incorrectly due to settling of the foundation. As a result, they recommend that 200 mm to 250 mm (8 to 10 in) of dense graded aggregate be placed under the headwall for additional foundation support. Headwalls should be clearly marked with flags so that summer mowing operations do not damage the structures. Figure 3 shows four designs of permeable base cross-sections with drainage pipes installed.

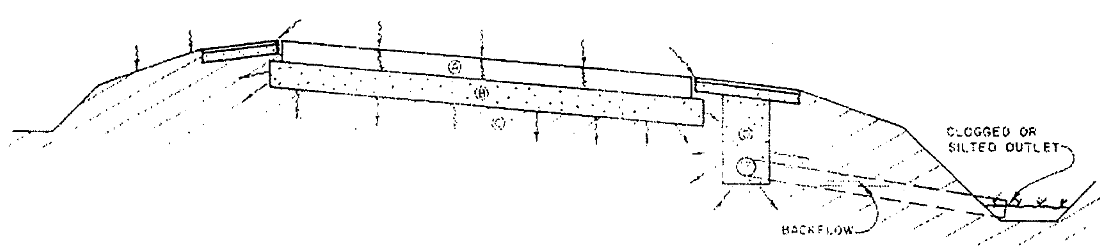
Summary

It is absolutely critical that the drainage system be viewed holistically, and not as an assemblage of unrelated parts. Too often, the focus is only on the drainable base. It must be remembered that even a well designed, highly permeable, stable drainable base will not function if other elements of the drainage system are improperly designed or constructed. For example, if the filter/separator layer is poorly designed, fine material will infiltrate into will infiltrate into the drainage layer, eventually clogging it. If the backfill material is not as permeable as the base, or if a filter fabric is improperly positioned, the free flow of water will be hindered and potential failure will result. After all, the drainage system is only as effective as its weakest link and a failure of any one component will result in a poorly draining pavement and premature pavement deterioration.

2.3. Drainage System Maintenance

Once constructed, a functional drainage system must be maintained. If routine maintenance is not conducted, the system will become clogged and the free flow of water from beneath the slab will be compromised.

In order to ensure that the drainage system is functioning properly routine maintenance must be performed. All maintenance personnel associated with the roadway should have a general knowledge of outlet pipe location and understand the need for keeping them unobstructed and operational. Headwalls must be clearly marked to prevent damage from mowing or other heavy equipment. Fleckstein and Allen (1996) recommend that the headwall trough, screen and ditch lines be inspected and cleaned twice a year. Clearing the outlet pipes of trash, vegetation and sediments will allow water to flow uninhibited to the ditch. Without this free flow of water the system will begin to back up, leaving free water within the pavement structure and causing unneeded distresses. This is illustrated in Figure 7.



NOTE: PERMEABILITY OF COLLECTOR TRENCH BACKFILL ⓓ > PERMEABILITY OF PAVEMENT ⓐ > PERMEABILITY OF BASE COURSE ⓑ > PERMEABILITY OF SUBGRADE ⓒ.

WATER IS STORED IN BASE COURSE ⓑ AND IN THE INTERFACES ⓐ/ⓑ AND ⓑ/ⓒ.

Figure 7. *The impacts of a plugged outlet pipe (FHWA 1973).*

The Indiana Department of Transportation (INDOT) recommends using drainage systems only in areas where thorough maintenance can and will be performed (Hassan 1996). They report several incidences were lack of maintenance caused premature distress with severe cracking and pumping. In one case, recommended maintenance (clearing of clogged drains) was delayed for three years, during which time the pavement failed rapidly and major reconstruction was required. Overall, without proper maintenance, treated and untreated permeable base materials will become saturated and unstable, leaving the pavement structure with little support.

3. Performance

Assessing the performance of drainable bases is not a trivial task. One of the major problems is in how performance is defined. One definition of performance focuses exclusively on how well a drainage system drains free water from beneath the pavement surface. A broader definition of performance encompasses the impact that a drainable pavement system has on overall pavement performance as evidenced by a reduction in distress and improved ride quality. A third definition of performance goes one step further by considering the cost effectiveness of drainage; i.e. "Is the additional cost associated with constructing a drainable pavement system justified through long-term improvement in pavement performance?"

Although irrefutable evidence does not currently exist, trends presented in the literature seem to indicate that good performance has been met as defined by the first two definitions. This belief was stated by Baldwin (1987) who reported in an early study of pavement drainage system performance that 78% of the states using drainage systems report excellent or good performance. But recently, some issues have been raised concerning the cost-effectiveness of drainable pavement systems, but a definitive study on the cost effectiveness of drainable bases has not yet been completed.

Assessing performance as defined by the drainability of the system is not easy because measurement of in-situ moisture contents generally require the use of in-place instrumentation or destructive testing. In either case, the testing is expensive and may be disruptive to traffic. This means that only a few sites can be monitored, thus the data collected may not be representative of the performance of the system as a whole.

Difficulties in assessing pavement performance on drainable systems stems from the fact these sections have only been in existence for a relatively short period of time. It is only within the last decade that the use of drainable pavement systems have gained widespread acceptance, and thus there is little long-term information available regarding the effectiveness of drainable pavement systems in reducing pavement distress as compared with pavements constructed on dense-graded bases. As a result, little information related to long-term cost effectiveness is available. The following provides information obtained from published literature regarding the three definitions presented above.

3.1. Drainage System Performance

There is considerable literature available regarding the permeability of drainage base materials. Without question, both untreated and treated granular materials can be designed to have very high permeabilities, easily in the range of 305 m/day to 3,005 m/day (1,000 ft/day to 10,000 ft/day). But difficulties arise in trying to assess in-situ drainability of the system. A number of field tests have been proposed to measure permeabilities in the field, but difficulties surrounding accuracy and repeatability have plagued the acceptance of a single test. Other researchers have used both destructive and non-destructive methods to estimate in-situ moisture contents.

Because of the difficulty involved in accurately measuring permeability in the field, many investigators have simply abandoned these efforts and have taken a more pragmatic approach: focusing instead on measuring outflow from the drainage system in comparison to inflow. One common research technique is to install instrumented tipping buckets at outlets, continually monitoring both precipitation and outflow. As an investigative tool, it is possible to simply pour a known volume of water into a hole cored through the pavement surface, measuring the time to drain and outflow volume. This last approach is appealing in both its simplicity and meaningfulness. A non-draining or clogged system will drain slowly compared to a highly permeable, properly maintained drainage system. Currently, it seems that this is the approach most often taken by those investigating pavement drainage systems.

A recent study by the U.S. Army Pavement Systems Division performed numerous tests to assess the performance of drainable pavements (Grogan 1994). In this study, three pavement sites were instrumented with weather stations and tipping buckets at outlets.

Outflow from the drainage system was measured and compared to rainfall events. It was found that precipitation quickly penetrated the pavements during and immediately after a storm event and that drainable pavements systems were able to rapidly remove this water. Additional monitoring at one site included a Magnarule that measured the depth of free water in the permeable layer. It was observed that free water drained from the base within 0.5 days for even the largest rain event. Grogan concluded "drainage layers perform their intended function by allowing free water to drain rapidly from the pavement system."

Cedergren (1987) provides a number of case studies in his text *Drainage of Highway and Airfield Pavements*. One such study features an experimental design constructed in Humbolt County, California in 1968. A drainable design was used after the original non-drainable pavement section failed rapidly due to moisture related distress. This pavement was continuing to perform well in 1986 after 18 years of heavy logging truck use. Outflow from the lateral outlet pipes was heavy after heavy rains indicating the effectiveness of the drainage layer. In another case study, Cedergren (1987) talks about the excellent performance of a heavily trafficked aircraft taxiway constructed as a drainable section. Water poured into a core hole would not build up head due to the rapid drainage capability, which are estimated at 30,500 m/day (100,000 ft/day).

Hagen and Cochran (1996) studied various drainage systems and their effect on pavement performance. Comparisons were done between an asphalt treated base (permeability of 305 m/day to 610 m/day [1000 ft/day to 2000 ft/day]) with a dense graded base (Mn/DOT class 5: permeability of 0.12 m/day [0.4 ft/day]). Both sections were constructed with edge drains. Volumetric outflow of water was measured using tipping buckets and the moisture content of base and subbase were established using time domain reflectometry (TDR). They conclude that "the permeable asphalt-stabilized base usually drained the most water within two hours after rainfall ended and provided the driest pavement foundation." Based on measurements from the TDR, the dense graded base remained at or near saturated even after water ceased to drain from the outlets.

In a Kentucky study, Fleckenstein and Allen (1996) found that subgrade moisture contents were decreased by 28% through the addition of subdrainage. This translated to a 64% increase in subgrade resilient modulus as backcalculated from falling weight deflectometer (FWD) data. It is speculated in their report that the decrease in moisture content associated with subdrainage installation should lead to significant improvements in pavement life.

A study conducted in Ontario by Kazmierowski et al (1994) found that although laboratory permeabilities of an untreated, asphalt treated, and cement treated permeable base materials were good, that the results of in-situ drainage test on in-service pavements were less than satisfactory. Only 50% of the water introduced through a corehole drained from the outlet within 30 minutes. In considering their drainage system design, it is noted that the permeable base is drained directly into a fabric wrapped, geocomposite fin drain which was backfilled with a non-drainable, dense-graded material. The use of fin drains in new design is specifically mentioned as undesirable by the FHWA (1990). Potential clogging of the geotextile fabric from the fines in the non-permeable backfill was mentioned as a concern by the researchers, and additional studies are underway to improve this situation.

A study conducted by Hall (1995) investigated the durability of cement-stabilized permeable bases under construction traffic. Although he did not conduct in-situ permeability tests, he did examine permeability of the base using cores obtained from the field. His study found that very high permeabilities existed in the as-built base material and that consolidation and/or degradation under construction traffic had little impact on permeability.

Hossam et al. (1996) recently completed a study evaluating the effectiveness of drainable pavement systems for the Indiana Department of Transportation (INDOT). Rain gauges and outflow devices were installed, as were a number of non-destructive moisture measuring sensors. INDOT is committed to the use and maintenance of subdrainage systems. Changes in policy include elimination of fin drains, strict adherence to subdrainage inspection and maintenance, and implementation of subdrainage video inspections immediately after construction to verify proper installation.

3.2. Pavement Performance of Drainable Pavement Systems

A number of studies have focused on the positive impact that improved pavement drainage would have on pavement performance. Cedergren (1987) presented the argument in great detail in his text *Drainage of Highway and Airfield Pavements*. Others have supported this argument with equal enthusiasm, citing the well-documented relationship between the presence of free water beneath the PCC slab and accelerated deterioration. The following discussion presents results of studies examining the relationship between pavement drainage and pavement performance.

Cedergren (1987) presents five case studies describing improved pavement performance resulting from the use of drainable pavement systems. In all cases, he reports a significant reduction in pavement distress as a result of improved pavement drainage. In a more recent article, Cedergren (1994) reports additional case studies in which pavements constructed on drainable systems were performing in an exceptional manner. Many of his citations are anecdotal, and are not part of an organized study in which drainable and non-drainable systems are directly compared.

Baldwin (1987) conducted a National survey to obtain feedback from States that had installed drainable pavement systems. Through surveys, this study found that "on the sole basis of performance the vast majority (78%) of respondents rated their drainable pavement systems as either excellent or good".

Illinois has recently detailed some problems with the performance of continuously reinforced concrete pavements (CRCP) constructed on open graded cement treated bases (Heckel, 1997). Premature distress including deteriorated transverse cracks, punchouts, and patching have called into question the applicability of drainable bases for use with CRCP. An investigation into the problem has included visual inspections of the pavement and drainage structures, coring, shelby tube sampling, and FWD defection testing. Although the underdrains appeared to be in good condition, it was noted that in many cases "the soil at the base of the outlet is higher than the flowline of the outlet." This suggests that during rainfall events, the outlets are likely underwater and water is backing up into the drainage system. An internal investigation of the drainage system was not conducted nor was in-situ drainability assessed. It was also noted that in two of the three projects suffering premature distress, no filter/separator layer was used "due to the added cost." Further, it was stated that a significant amount of subgrade infiltration into the drainage layer had occurred. Although the report does not draw absolute conclusions as to why failure occurred, it speculates that one of the following might be responsible:

the CRCP is incompatible with drainage layers.

the lack of a filter/separator layer,
the cement content in the cement treated drainage layer was insufficient,
the steel was improperly designed or constructed, or
the design of the CRCP and/or shoulders was inadequate.

This study has direct relevance to the current MDOT study and should be followed closely, as more information becomes available.

Hagen and Cochran (1996) studied various drainage systems and their effect on pavement performance on a reconstruction of I-94. Comparisons were done between an asphalt treated base (permeability of 305 to 610 m/day [1000 to 2000 ft/day]) with a dense graded base (Mn/DOT class 5) both with edge drains. This study found that the least amount of early distress occurred on the permeable asphalt-stabilized base sections. They report that after only six years, jointed reinforced concrete pavement (JRCP) constructed on dense graded bases had five times the mid-panel cracks than that constructed on asphalt treated permeable base. Also cited was another study conducted on TH 15 in southern Minnesota. This section of pavement was constructed in 1983 and examined in 1994. Negligible mid-panel cracking was observed in the pavement sections constructed on asphalt treated permeable base compared to 95 percent cracking of slabs on the section constructed on dense graded base. It was noted that the drainage systems were well maintained and properly constructed and were draining as desired. Overall, this study recommends that "all concrete pavements need some type of positive subsurface drainage system."

Crovetti (1991) cites five recent cases in which States monitoring the performance of pavements constructed on open-graded and dense-graded bases universally report that pavement distress was significantly reduced on the open-graded pavement sections (Crovetti 1991). In California, PCCP constructed on drainable bases have shown consistently lower slab cracking rates than those constructed on dense graded bases. A PCCP test section was constructed in Michigan in 1975 to compare permeable, bituminous, and dense graded bases. It was observed that the pavement constructed on the permeable base had the least amount of recorded faulting, slab cracking, and D-cracking. Similarly, a Minnesota study conducted in 1983, which compared drainable and non-drainable PCCP sections, found significantly less slab cracking on the drainable sections after five years of service. Crovetti also cited studies in New Jersey and

Pennsylvania in which drainable PCCP sections had significantly less distress than pavements constructed on dense graded base.

Crovetti (1995), frustrated with the limited performance data available due to the relatively short time-frame for which drainable bases have been used, developed non-destructive testing methods to provide insight into design efficiency. These analytical techniques quantify the uniformity of support under a slab utilizing slab dimensions, measured center, edge, and corner slab deflections, and in-situ temperature gradients. Crovetti used the results of this analysis to examine the potential performance of pavements constructed with drainable bases on USH 18/151 in the fall of 1994. At the time of testing, the test pavement was five years old. The base types investigated were untreated drainable, cement-treated drainable, asphalt-treated drainable, dense-graded, and lean concrete. The only sections found to have evidence of poor support due to densification or erosion of the base layer was constructed on untreated drainable base, although additional data would need to be collected to confirm this finding (Crovetti 1995; Crovetti, 1996). At this time, long-term performance data is needed to verify the applicability of the test method.

California found that the use of subdrainage significantly reduced faulting of jointed plain concrete pavement (JPCP) (Wells 1985). This study also found that slab cracking was reduced through the use of drainage. Forsyth et al. (1987) showed that in California, slab cracking was 2.4 times greater on undrained pavement sections than on drained pavement sections. More recent examination of data from California (Wells 1991) have shown that drainage pavement systems are capable of draining large quantities of water, but suggest that long-term pavement performance has not been investigated, noting that there are some concerns in this area.

In an FHWA study, Smith et al (1990) concluded that drained concrete pavement sections appeared to have improved performance over adjacent undrained sections, although no definitive estimates of extended life were provided. This original study was later expanded to include over 300 in-service PCC pavements. In this more recent study, drainage was not found to be a significant factor contributing to slab cracking, but lead to a decrease in D-cracking in some cases (Smith et al. 1995).

In a recent study completed by Northwestern University (Moss 1997), drainage was found to be a significant factor in the development of premature distress in concrete pavements. This study focused exclusively on the development of undiagnosed materials-related distress, but a thorough statistical analysis determined that improved drainage through the use of drainable pavement systems resulted in a decrease in the incidence of premature distress.

3.3. Economic Advantages of Drainable Pavement Systems

The general consensus, based on a thorough analysis of available data, is that PCCP performance is enhanced through the use of drainable base systems (ERES 1996). But the larger question of cost effectiveness has not been addressed.

Studies conducted in the early to mid 1980's suggested that drainable pavement systems were without a doubt the more cost-effective approach to PCCP design. Cedergren (1987) contributed an entire chapter in his book to this issue, concluding "well-drained pavements which provide longer, more-trouble free service than their poorly drained counterparts, are less costly in the long run." Forsyth et al. (1987) echoed these findings, stating that the use of drainable pavement systems would increase JPCP life by 10 years, resulting in a 41 percent reduction in costs (not including user and maintenance costs).

In 1990, States' experience with drainable pavement systems was quite positive, with many stating that improved performance provided economic incentive for their use (La Hue, 1990). New Jersey believed that the use of permeable base resulted in longer pavement life, making concrete pavements more economically attractive. Wisconsin stated that although there is a modest increase in cost associated with the construction of drainable pavement systems, they are cost-effective due to the additional life incurred.

Since 1990, there have been some concerns raised about the long-term performance of drainable pavement systems and whether they are cost-effective. Recently, Larry Cole of the American Concrete Paving Association (Cole 1997) raised these issues at the Annual Meeting of the Transportation Research Board. A study sponsored by the National Cooperative Highway Research Program entitled, *NCHRP Project 1-34 — Performance of Subsurface Pavement Drainage*, is currently underway. The contractor, ERES Consultants, Inc., stated in the Interim Report (ERES 1996), that "the key question is how much benefit the drainage system will provide, not whether there will be a benefit." The emphasis of this project is to determine the effect that subsurface drainage has on pavement performance, assessing overall effectiveness. Hopefully, this study will help address the critical issue of cost effectiveness.

4. Summary

Based on the review of available literature, there is no question that drainable pavement systems that rapidly remove free water from beneath the PCC slab can be constructed. These pavements are more costly than those constructed on non-draining bases and the construction sequence is more difficult. One difficulty is the instability of open graded drainable material, although this has been largely overcome through optimization of the gradation and through the use of 100 percent crushed, durable aggregate. Rounded aggregate should not be used, as it will not provide adequate interlock to ensure stability. Additionally, it is common to treat the drainage material with either asphalt or portland cement to enhance stability and constructability (prevent edge sloughing). The recommended minimum permeability of the drainage layer is 305 m/day (1000 ft/day).

Even with a highly permeable, stable drainable base material, it is absolutely critical that the placement of the individual drainage components is done with care. Base contamination, improper positioning of the filter fabric, incorrect slope or damage to the longitudinal drainage and/or transverse outlet pipes, or poorly positioning and constructing the outlet headwalls can prevent the rapid drainage of free water. A 150 mm (6 in) freeboard between the 10-year flow level in the ditch and the outlet pipe opening is required. If any one component is designed or constructed incorrectly resulting in blockage to the system, premature pavement failure may ensue.

Once properly designed and constructed the main body of evidence suggests that enhanced pavement performance will result if the system is maintained. Of the States using drainable pavement systems, those reporting the best pavement performance have an established maintenance program consisting of routine internal inspections using video cameras, flushing out the drainage pipes using high pressure water, and removal of debris and vegetation from outlets and ditches. It has been stated that if the system is not going to be maintained, then it should not be constructed because enhanced performance will not be obtained

Due to the uncertainty regarding long-term performance of drainable pavement systems, the cost-effectiveness of this design over conventional nondraining design is unproven. A number of studies are underway investigating this topic, and it is hoped that within a year or so, better information will be available.

In conclusion, the literature suggests that drainable bases are performing as expected, but little evidence exists to support the widely held belief that they are a dramatic improvement over non-drained pavement systems. The inability to answer this question at this time is primarily a result of the relatively short time frame that drainable pavements have been in service. The literature suggests that design, construction, and maintenance are all critical elements impacting the effectiveness of drainable pavement systems, and that enhanced long-term performance can be expected only if each element is executed with care.