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SUBSURFACE DRAINAGE OF HIGHWAY PAVEMENTS
(KYSPR 92-142)

by

David Q. Hunsucker
Transportation Research Engineer

and

Bobby W. Meade
Senior Transportation Research Investigator

Kentucky Transportation Center
College of Engineering
University of Kentucky

in cooperation with
Kentucky Transportation Cabinet

and

Federal Highway Administration
US Department of Transportation

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David Q. Hunsucker and Bobby W. Meade

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16. Abstract

Properly designed and constructed drainage layers can be used for effective control of surface water infiltration. Former pavement design methods often have resulted in base courses that have not drained well, thereby resulting in some premature failures of the pavement structure. The Kentucky Department of Highways is currently reviewing proposed guidelines for design of highway pavements. The guidelines propose the use of open graded, free draining, aggregate bases for controlling infiltrated surface water. However, interim design guidelines do not specifically address the design of aggregate drainage blankets. The purpose of this study was to develop recommendations relating to the specification, design, and construction of pavement drainage layers as an integral part of the pavement structure.

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EXECUTIVE SUMMARY

Properly designed and constructed drainage layers can be used for effective control of surface water infiltration. Former pavement design methods often have resulted in base courses that have not drained well, thereby resulting in some premature failures of the pavement structure. The Kentucky Department of Highways is currently reviewing proposed guidelines for design of highway pavements. The guidelines propose the use of open graded, free draining, aggregate bases for controlling infiltrated surface water. However, interim design guidelines do not specifically address the design of aggregate drainage blankets. The purpose of this study was to develop recommendations relating to the specification, design, and construction of pavement drainage layers as an integral part of the pavement structure.

Considerable monitoring, testing, and analyses were performed during this study. The effort to develop an appropriate apparatus and procedure for flow rate testing of open graded materials was successful. Test results for the flow test apparatus were repeatable for flow rates ranging from 20 m/day to more than 6,100 m/day (70 ft/day to more than 20,000 ft/day).

The current "Special Note For Pavement Drainage Blanket" provides for the optimum gradation for both drainage and stability in an asphalt treated drainage blanket. Asphalt treated specimens compacted to densities typical of field conditions, 1,685 to 1,765 kg/m^3 (105 to 110 lbs/ft^3), indicate flow rates ranging from 3,355 to 4,270 m/day (11,000 to 14,000 ft/day). At these densities, structural stability of the blanket, as measured by laboratory resilient modulus tests, is approximately one third that of a Class I base which results in a structural coefficient of 0.15 to 0.16 for the asphalt treated blanket. Backcalulated layer moduli of treated drainage layers, determined from in-situ tests with the FWD, ranged from 0.14 to 0.22. Compaction of the asphalt treated blanket during construction soon after placement would increase density and provide increased stability with more than sufficient drainage capability and result in higher structural coefficients. Untreated drainage blankets provide good drainage (4,575 to 4,880 m/day) {15,000 to 16,000 ft/day} but presented construction problems. Backcalulated structural layer coefficients of untreated drainage blankets constructed of 57 gradation aggregates were not as variable as asphalt treated drainable base layers and exhibited similar values, ranging from 0.18 to 0.22. However, because of the enhancement provided to the construction process, drainage layers are recommended to be constructed with asphalt treated aggregates.

Maintaining the collector system and it's outlets is of extreme importance. A regular preventative maintenance scheduled should be developed and implemented at the District level to ensure optimum performance of the drainage system. Training opportunities should be made available to District personnel to facilitate maintenance operations.

Based on observations made during this study, daylighting the drainable base layer is a viable alternative to a drainage blanket that incorporates a collector system. Initial concerns of siltation and vegetation in the daylighted blanket appear to be unfounded based on the performance of a daylighted blanket on the AA highway. However, untreated blankets that are daylighted should be afforded some means of protection from traffic encroachment to prevent raveling of the base layer.

1.0 INTRODUCTION

The Kentucky Department of Highways is currently reviewing proposed guidelines for design of highway pavements. The guidelines propose the use of open graded, free draining, aggregate bases for controlling infiltrated surface water. However, interim design guidelines do not specifically address the design of aggregate drainage blankets. Former pavement design methods often have resulted in base courses that have not drained well, thereby resulting in some premature failures of the pavement structure. Properly designed and constructed drainage layers can be used for effective control of surface water infiltration. The purpose of this study was to develop recommendations relating to the specification, design, and construction of pavement drainage layers as an integral part of the pavement structure.

The principal objective of the research study was to develop recommendations for optimal structural and material design procedures for free draining aggregate bases. The principal objective was achieved by conducting a literature search and review to ascertain current state-of-the-art design and evaluation procedures; conducting field evaluations encompassing subsurface drainage designs currently used and proposed for use in Kentucky and correlating past performance with these designs; and, conducting laboratory investigations relative to requirements for aggregate gradations, filter materials, hydraulic parameters and engineering properties of bound (stabilized) and unbound drainable base materials.

The literature review was conducted to evaluate current state-of-the-art structural and material design procedures, and field and laboratory evaluation procedures for free draining aggregate bases. A comprehensive literature search was conducted through the facilities of the University of Kentucky Technology Applications Program and Kentucky Transportation Center. The detailed literature review documented current techniques for structural and material design procedures, design of collection systems, and field and laboratory methods utilized to evaluate pavement subsurface drainage systems.

Both subjective and objective performance condition evaluations of highway pavements constructed above drainable bases were performed and correlated to the design approach. Selected routes, wherein drainable base designs had been utilized, were visually surveyed and performance conditions subjectively rated. Objective evaluations included, but were not limited to, determining information related to the design, construction, and, if available, the cost of the completed pavement structure; determining maintenance histories for the route; obtaining rideability indices, pavement roughness measurements, profilograph measurements, and determining traffic characteristics.

The quality of materials used in constructing the drainage layers were quantified relative to strength properties (resilient modulus and shear strength properties), densities, and permeabilities of samples obtained from the drainable base. Field permeability testing of the in-service pavement was not attempted. Extensive falling weight deflectometer evaluation of the pavement structures allowed further determination of in-situ structural properties of the subgrade, drainage layer, and asphaltic concrete or Portland cement concrete paving layer. The effective behavior of the pavement section may be expressed as elastic moduli for each individual layer of the pavement structure using a methodology developed under study KYHPR 86-109, "Pavement Deflection Evaluations."

Evaluations employing similar methods to those used for in-service pavements were performed on pavements under construction. Pavements under construction were tested at various stages of construction to provide valuable information relative to the range of modulus of elasticity values for each layer of the pavement structure as it is constructed.

Laboratory investigations for optimal gradation requirements for bound (stabilized) and unbound aggregate drainage layers and filters were performed. The optimum gradation was evaluated relative to the effective grain size (D_{10}), porosity (n), and the percent passing the 75 μm (No. 200) sieve. Aggregates were evaluated for size, shape, toughness, and specific gravity. Optimum gradations for open graded drainage layers and filter materials were developed based upon Kentucky's soil characteristics relative to grain size distribution, plasticity characteristics, and soil classification. Both natural and modified soils were considered in the analysis. Engineering properties of the mixtures evaluated included, but were not limited to, permeability, effective porosity.

Specimens prepared in the laboratory were tested for shear strength, resilient modulus, indirect tensile strength, and stability. The goal was to optimize shear resistance and permeability properties of the open graded aggregate mixtures (both stabilized and non stabilized).

Recommendations for specifications relative to structural and material design and construction of open graded drainage layers, including optimum placement of collection systems, were developed using information gained during the study.

2.0 BACKGROUND

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

Capillary water, bound moisture, and water vapor move through soils by various mechanisms and they are not greatly affected by gravity. Only free-water conditions can be significantly altered by gravity drainage systems. It is convenient to consider drainable subsurface water in two broad general categories: groundwater and infiltration. Groundwater is defined as the water existing in the natural ground in the zone of saturation below the water table. Infiltration is generally defined as surface water that gets into the pavement structural section by seeping down through joints or cracks in the pavement surface, through voids in the pavement itself, or from ditches along the side of the road.

Seepage is defined as the movement, or flow, of a fluid through a permeable porous medium. Porosity is the ratio of the volume of the pore spaces to the total volume of the material. The extent to which a porous medium will permit fluid flow, that is, its permeability, is dependent upon the extent to which the pore spaces are interconnected and the size and shape of the interconnections. The flow of water through a porous medium is governed by a simple linear law, commonly called Darcy's Law, which relates the flow rate to the porous medium's coefficient of permeability, hydraulic gradient, and cross-sectional area. The validity of Darcy's Law is contingent upon laminar flow. For most natural soils and low permeability granular materials, this condition is satisfied over a wide range of hydraulic gradients. However, for more open graded granular materials the flow may become nonlaminar. Under these circumstances, it is still possible to use Darcy's Law for practical seepage analysis provided appropriate consideration is given to this phenomenon in evaluating the coefficient of permeability.

The ability of the pavement structural section to transmit the dynamic loading imposed by traffic can be greatly diminished if the pavement structural section and subgrade becomes saturated by groundwater and/or infiltrated water. Free water in the pavement structure is of particular concern because it can reduce the strength by reducing the apparent cohesion through reduction of capillary forces, reduce the friction by decreasing the effective mass of the materials below the water table, and reduce the strength by developing large pore pressures. Previous studies have indicated that high pore pressures can be developed by the dynamic action of the wheel load on the pavement surface. Movement of the wheel along a pavement with a saturated subgrade can produce a moving pressure wave, which in turn can create large hydrostatic forces within the structural section. These pulsating pore pressures significantly influence the load-carrying capacity of all parts of the pavement structure. When high pore pressures are developed in a base or subbase material, its load transfer properties are altered considerably so that the stresses applied to the subgrade are not reduced to their expected level. When a pavement structure and the underlying subgrade are subjected to excessive moisture, the result may be manifested in a variety of problems including rutting, cracking, faulting, increases in roughness, and rapid decreases in serviceability levels.

A horizontal drainage blanket is a very permeable layer whose width and length (in the direction of flow) are very large relative to its thickness. A drainage blanket, if properly designed, can be used for effective control of infiltrated water and collection of capillary water. A horizontal drainage blanket can be used beneath, or as an integral part of the pavement structure, to remove infiltrated water. Horizontal drainage blankets require sufficient thicknesses of materials with very high coefficients of permeability, positive outlets for the water collected, and, in most instances, use of protective filter layers.

Open-graded bases utilized for subsurface drainage must be constructed of hard, durable aggregates and stabilized when necessary. These types of bases have high permeabilities and can have excellent structural properties. The use of pavement subdrainage, reportedly, can extend the fatigue life of flexible and rigid pavements by as much as 33 and 50 percent, respectively. Recent surveys have indicated that as many as 27 states have used bituminous-stabilized, open-graded aggregate bases for drainage layers. However, only six of those states consider the structural credit for bituminous-treated, open-graded aggregate bases to be greater than that of untreated drainage layers.

A collection system removes water from the drainage layers and transports the water to outlets outside the roadway limits. Design of collection systems requires attention to the type and size of collector to be used, location and depth of longitudinal and transverse collectors and their outlets, the slope of the collectors, and provisions for sufficient filter protection to prevent flushing of drainage aggregate into the collectors yet provide adequate drainage volume. Selection of collectors depends upon specific soil properties at the site, load and durability requirements, and environmental considerations. For these reasons, design of the drainage layer and collection system must proceed simultaneously.

The durability of roadway pavement layers and their required level of maintenance is dependant on several inter-related parameters. Such parameters include load distribution capability; drainability of free water, capillary water, bound moisture, and water vapor from above and below the pavement structure - all of which depend on horizontal and vertical road geometrics, soil conditions, and climatic conditions; stability of the pavement structure from construction equipment loadings, traffic loadings, and frost action; section density and level of compaction at the time of construction; modulus of elasticity and/or resilient modulus of pavement materials; and layer material gradations - which affects the material's susceptibility to clogging, and also its stability versus drainability optimization.

Often, stability and drainability parameters oppose each other, that is, designing for sufficient drainage of a roadway layer section often comes at the expense of stability, layer density, and how prone the layer is to clogging. Therefore, to avoid these dilemmas, pavement designers usually separate the drainage parameter from the rest of the pavement design. This has resulted in separate, independent layers in pavements whose sole purpose is nothing more than drainage. Consequently, the load distribution capability, stability, elastic and/or resilient moduli, and the densities and gradations that relate to design parameters of drainage layers appear to be inconsequential and not usually considered.

The positive results of these designs are demonstrated through the construction of better, longer lasting highway pavement systems. Frequency of maintenance and the associated costs have been reduced. These designs do, however, increase initial construction costs. For example, pavement layers that directly interface with the drainage layer must be of a gradation that will not clog (choke) the drainage layer as water passes. If a suitable, cost effective gradation cannot be established, then synthetic geotextile mats must be used at interfaces to prevent choking. The gradations of drainage layers are open graded, which means that they are extremely lean in fine material (material passing the 150μm and 75μm {No. 100 and No. 200, respectively} sieve sizes). This is the main reason for the lack of stability in these layers. As a result, these layers are sensitive to rutting and shoving as construction traffic moves over them. To prevent these problems, drainage layers are often stabilized by asphalt or Portland cement, and this also increases construction costs.

With better understanding, innovations in technology and design, and better and more reliable testing equipment, we now have the capability to effectively incorporate the drainage layer design and performance with the other layers (structural) of the pavement system. This would reduce installation costs by lowering the labor, material, and equipment costs. It would also lessen construction time. And note that this is accomplished without sacrificing pavement drainage requirements. In other words, substantial initial construction costs may be reduced if a pavement design that acts monolithically as a structure and a drainage system could be specified (versus designing for structural and drainage requirements into separate pavement layer sections).

3.0 SUMMARY OF LITERATURE REVIEW FINDINGS

Information accumulated during a review of literature pertinent to this research study was identified categorically as current state-of-the-art structural and material design procedures, design of collection systems, or current field and laboratory methods utilized in the evaluation of subsurface drainage systems for highways. To understand the history and development of subsurface drainage systems for highways, the literature review encompassed articles extending into the 1950's.

3.1 GENERAL HISTORY

The Highway Research Board issued a report during 1951 prepared by the Committee on Subsurface Drainage entitled "Present Practice in Subsurface Drainage for Highways and Airports," [1]. As part of this study, questionnaires were sent to the highway departments of all states, to the division offices of the U.S. Bureau of Public Roads, the U.S. Corps of Engineers, Department of the Army, the U.S. Civil Aeronautics Administration and the U.S. Bureau of Reclamation. Nearly 90 percent of these organizations replied to the questionnaire. The consensus was that faulty subsurface drainage caused pavement failures, including rutting and shoving in flexible pavements, pumping in concrete pavements and frost heaves and boils in both types of pavement.

In 1959, the Highway Research Board's Committee on Subsurface Drainage issued a report indicating that the importance of controlling subsurface water was generally acknowledged; however, control of the subsurface water was often inadequate due to lack of design and the difficulty of predetermining conditions that show up during or after construction, [2]. The Committee stated that while road alignment was often determined by factors other than soil conditions, they should be considered in the preliminary location of any route. The Committee recommended that if a subsurface drainage system was found to be too expensive, relocation of the route should be considered.

In a 1961 presentation at the annual meeting of the Western Association of State Highway Officials, Minor asserted that drainage problems increase in a geometric ratio as roadway and shoulder widths increase and vertical curvature decreases, [3]. Furthermore, the problems were magnified even more in areas of continuous rainfall where water seeped through the pavement faster than it could be discharged through the shoulders. Minor advocated placing extremely open-graded material in the shoulders as the most economical way to prevent water build-up.

In 1973, Slaughter was commissioned to evaluate methods currently used in designing and constructing drainage facilities for the removal of subsurface waters from the immediate vicinity of Georgia's highways and to recommend appropriate changes in the Georgia State Highway Department's design methods and construction procedures, [4]. Slaughter found that subsurface drainage had a low priority in the overall design of Georgia's highway system and concluded that a designer of subsurface drainage facilities needed more data made available, not only prior to the design phase but also after the facility had been constructed. Slaughter deemed verification of the performance of subsurface drainage facilities extremely important if real advances were to be made in subsurface drainage design. Slaughter recommended further study to devise an overall integrated drainage system that took into account not only surface and excess surface water plus the subsurface waters in saturated and unsaturated porous media but also all the components of the complete highway system as well.

Cedergren, in a 1978 *Engineering News Record* article, indicated that pavements designed without good internal drainage were doomed to an early failure the very day they were completed because failure mechanisms were built into the pavement system, [5]. However, Cedergren also stated that rapid drainage of the pavement structure could easily double or even triple the useful life of most pavements and suitably designed, open-graded drainage layer, protected from clogging and provided with suitable collectors and outlets would not add greatly to a pavement's initial cost. Dhamrait and Schwarts determined from an Illinois study conducted in 1979 that longitudinal drainage systems placed along the edge of a stabilized subbase was most efficient in terms of removing free water from the pavement shoulder structure, [6]. Forsyth, et al, citing studies involving edge drains and the effect of permeable bases on PCC pavement performance, concluded that an extension of a pavement's service life of just four years reduced pavement costs by about 21 percent, [7]. Studies conducted in California and Spain on the effects of retrofitted edge drains on PCC pavement performance suggested that an extension of a pavement's service life of ten years (50%) equaled a cost reduction of about 41 percent.

West Virginia constructed its first free-draining base in 1982, [8]. Baldwin reported that although the subsurface drainage system was performing as intended, it was concluded from the experience gained from monitoring the project that the continued effectiveness could have been better ensured if a more positive and protected means of outletting water from the system had been employed.

More recently, an article by Hawks appearing in the January 1992 issue of *SHRP Focus* introduced the goals, intentions, and expectations of the Strategic Highway Research Program's (SHRP) long-term pavement performance studies, [9]. Hawks implied that the benefits of permeable bases were all too clear. However, less clear was the degree to which those benefits could be realized in different design situations, or whether there were interactions that posed unacceptable risks. According to Hawks, the costs of using of drainable bases are not well defined, and this lack of clarity generally inhibits their use. With these reasons in mind, SHRP will monitor the ability of permeable or drainable bases to extend pavement life or reduce pavement thickness in actual-use situations where interactions could be observed. The overall objective of the research is to resolve design issues that inhibit the knowledgeable and effective use of drainable bases.

3.2 DESIGN CONSIDERATIONS

The Federal Highway Administration issued an implementation package for drainage blankets in highway pavements in 1972, [10]. The report concluded that positive removal of water from a pavement structure would minimize the problems of subgrade softening and weakened pavement structures. The use of drainage blankets, which are normally installed during original construction, was encouraged when pavement sections were to be reconstructed because of deterioration. The drainage layer, designed to serve as a subbase, was recommended to consist of an asphalt-treated drainage layer (open-graded material) 100- to 150-mm (4- to 6-in.) thick, and a perforated pipe underdrain system. Use of a single size aggregate material was not recommended. Further, it was established that filter protection from migrating fines either from above or below was essential to prevent plugging of the drainage layer. Underdrain collector pipes consisting of 100- to 200-mm (4- to 8-in.) diameter perforated pipe, were recommended to be placed longitudinally along each shoulder. Lateral discharge drains were recommended to be placed at intervals of approximately 30 to 46 m (100 to 150 feet) (centerline) for disposal of collected water at selected points of discharge.

Dempsey, et al, reported in 1982 that although improvements in the structural design of pavements had been made, investigations of rigid and flexible pavement systems indicated that water was still a major factor causing distress and loss of serviceability, [11]. These investigations largely resulted in a renewed emphasis on improving pavement drainage methods. The idealized pavement drainage system would be one that not only minimized infiltration of surface water into the pavement structure but provided efficient methods for draining water that did infiltrate the pavement system. The researchers reported that pavements on both non-stabilized and bituminous stabilized open-graded layers performed well under repeated wheel loads. Pavements on well-graded crushed stone bases apparently displayed the poorest performance. This was illustrated on a test track as well as in the laboratory. Field investigations indicated that using load transfer systems at pavement joints, non-erodible base materials, good drainage practices, and appropriate consideration given to climatic conditions typically resulted in rigid pavements that would perform well during the design life. The researchers recommended that several factors be considered in detail before selecting a drainage method. The factors included anticipated distress, climate, geology, pre- and post-construction methods for extending the pavement life, and the level of traffic.

Ridgeway, in a National Cooperative Highway Research Project (NCHRP) Synthesis report issued in 1982, indicated that subsurface drainage systems must be considered an integral part of the pavement structure and provided recommendations for design of the overall pavement structure,

[12]. Ridgeway recommended designing the drainage layer and/or the base and subbase to meet pre-established criteria for the amount of free water that will enter the pavement structure and the rate at which it must be removed. If lateral flow is required and design permeability is less than 305 meters per day (1,000 ft/ day) or if vertical flow is used and the design permeability is less than 0.6 meters per day (2.0 ft/day), the analysis and design criteria must be reviewed carefully. At the time of the report, California had adopted a standard design for subgrade drains, and had issued a memorandum instructing personnel to consider the need for longitudinal drains in both new and existing pavements for the purpose of discharging infiltrated surface water to reduce pavement failures. The state required the use of either asphalt-treated or cement-treated (porous concrete) permeable material for longitudinal drains. There were, and are currently, two particularly important conditions that effect the successful use of longitudinal edge drains in existing pavements. First, the edge support for the pavement must not be damaged when the drain is installed and secondly, the material that is adjacent to the drain and needs to be drained must be sufficiently permeable to allow the free water that is causing the problem to reach the longitudinal drain. Where longitudinal drains will not work, it is important that extra effort be made to seal all joints and cracks.

The Asphalt Institute published design guidelines for subsurface drainage systems in 1984, [13]. In order to design a reliable, economic and adequate subsurface drain, the manual recommends collecting detailed information prior to the design process. During the preliminary soil survey, the location of all seepage areas which may cause water to enter the structural elements of the pavement must be determined. The maximum rate of flow of water which may enter the structural section from any seepage and infiltration areas must be determined. A source of aggregate suitable for filter material to prevent clogging of drains by water-borne soil must be found, or the suitability of using a filter fabric must be established. A source of aggregate which may be used as drain rock to remove the water from beneath the pavement should be established. Finally, climatic data with respect to frost heaving must be obtained and evaluated. These data are then combined into the subsurface drainage design producing an adequate flow capacity to meet all the requirements for the projected life of the pavement.

Kozlov noted that research by the New Jersey Department of Transportation (NJDOT) established that the use of a drainage layer immediately below the lower bound layer of a pavement was the most effective means of achieving the necessary degree of internal drainage, [14]. The report suggests that the drainage layer be open enough to drain water in a reasonable length of time, yet with low enough flow rates to prevent internal erosion. The drainage layer must be dense enough to support traffic loads yet it must possess filtration characteristics compatible with base and subbase materials. Kozlov placed requirements for design and application of subsurface drainage into four categories. The geometry of the flow involves the geometric design of the highway, related subsurface drainage geometry, and prevailing conditions. The fundamental properties of the drainage material, such as permeability, density, geological characteristics, and particle shape define the performance of the flow of water, properly support loads, and, most importantly, must retain these characteristics for a reasonable life span of a road. Proper use of such characteristics in the design and application of the drainage facilities also requires suitable lifetime maintenance. Climatological data provide insight into the fundamental source of all subsurface water and the potentially adverse effects of frost action.

During the Fourth International Conference on Concrete Pavement Design and Rehabilitation, held at Purdue University, on April 18 through 20, 1989, Daniel Mathis of the FHWA presented an overview of state-of-the-practice in pavement drainage for new or reconstructed asphalt concrete and Portland cement concrete pavements, [15]. Mathis conducted reviews in States that were known to have recently constructed permeable base pavements. The states included were California, Iowa, Kentucky, Michigan, Minnesota, New Jersey, North Carolina, Pennsylvania, West Virginia, and Wisconsin. Topics addressed in the presentation included types of permeable base, degree of permeability, thickness and width of the permeable base, methods used to drain the permeable base, types of filter layer used, structural value, construction considerations, stability, performance of existing permeable base pavements, and cost. Relative to the topics addressed, Mathis found that the states typically used untreated aggregates or aggregates treated with asphalt cement or Portland cement for the drainage layer. It was found that permeabilities, determined using either constant head or falling head methods in accordance with standard procedures, of untreated aggregates were typically lower than treated aggregates. Mathis's review showed that permeable base pavements could be designed and constructed to rapidly drain moisture that infiltrates the pavement surface without significant changes to conventional practices.

Bentsen, noted in a 1990 edition of *Asphalt* that both new construction and rehabilitation projects can be plagued with problems if proper consideration is not given to the removal of the water that makes its way into the pavement system, [16]. Bentsen advocated a full-depth asphalt pavement for an effective solution to moisture problems in granular bases. The reduced load-carrying capacity associated with water infiltration into untreated aggregate bases can be eliminated since the full-depth asphalt pavement constructed directly on the prepared subgrade. A filter fabric or filter aggregate layer placed on the prepared subgrade is usually required to prevent intrusion of fines into the permeable base. In a 1991 article, the American Concrete Paving Association (ACPA) issued design guidelines for permeable bases, [17]. First of all, stability and constructability of the permeable layer must be considered. An AASHTO #57 or #67 will quickly drain water. However, because they contain virtually no fines they are not stable under construction traffic. Therefore, the ACPA recommended the aggregate be stabilized with cement

(90 - 165 kilograms/cubic meter {150-280 pounds/cubic yard}) or asphalt (2.0 to 2.5 percent by weight). If unbound aggregates are used, then more intermediate aggregates must be present than is found in AASHTO #57 or #67 gradation in order to make these aggregates stable under construction traffic. Care must be exercised by drivers during turning because overworking the aggregate could cause degradation of the materials. A geotextile fabric as well as a dense-graded base layer may be used as the filter (separation) layer. Whichever filter layer is chosen, it must keep the permeable base unclogged over an extended period of time. With regard to collection system for the permeable base, the ACPA recommended extending the permeable aggregate base about 0.75 to 1.0 m (2.5 to 3.0 ft) on each side of the pavement edge for stability, the use of 100-mm (4-in.) polyethylene pipe, outlet pipes spaced every 75 to 120 m (250 to 400 ft) and the use of strong pipe at the outlets 100-mm (4-in.) polyvinyl chloride or 150 mm (6-in.) corrugated metal pipe located on a three percent grade and at least 150 mm (6 in.) above the ten-year design flow. It was recommended that the drain outlets be fitted with a headwall and rodent screen. The ACPA article stressed that above all else maintenance of the system is critical to its life cycle. Outlets must be cleaned periodically to provide longevity to the system.

The Federal Highway Administration published Research Report FHWA/RD-72/30 in June 1972, [18]. The purpose of the study and subsequent report was to demonstrate how to design drainage layers. Drainage layers were to rapidly drain entire roadbeds to effectively reduce the exposure period of the pavement structural sections to excess water. The basic design methodology considered the subsurface drainage layers as a conveyor of water. Open-graded bases utilized for subsurface drainage should be constructed of hard, durable aggregates and stabilized when deemed necessary. The report indicated that stabilized aggregate bases have high permeabilities and can have excellent structural properties (stability) and may be substituted on an equal structural basis for currently accepted base course materials. A follow-up study by Cedergren indicated that the provision of subsurface drainage systems can greatly reduce, if not virtually eliminate, damages caused by excess water in structural sections, [19]. Cost studies revealed that effective subsurface drainage systems were usually economically and technically feasible under the environmental conditions within the continental United States. Further, it was determined that subsurface drainage systems should be designed for the requirements of each specific drainage problem, rather than relying on a standard design. Subsurface drainage systems should be designed using the basic principles of seepage and hydrology. It is very important that sources of water inflow into structural sections be identified and considered. The optimum thickness and permeability of the drainage layer and appurtenances are determined by Darcy's Law or by the use of flow nets. Majidzadeh, in a 1976 report to the Ohio Department of Transportation, recommended the use of very pervious drainage blankets having a permeability in the range of 305 to 3,050 meters per day (1,000 to 10,000 ft/day), [20]. Ring recommended typical drainage layer permeabilities to be

1,525 meters per day (5,000 ft/day) or higher to provide a drainage time of one hour or less, [21].

Work by the Army Corps of Engineers in 1987 investigated the relationships between permeability and stability of open-graded aggregate bases, [22]. The report noted that for open-graded aggregates to function as drainage layers, they must have voids sufficient to permit rapid drainage and yet have sufficient stability to prevent displacement or distortion because of construction operations and traffic on the completed pavement. Airfield pavements constructed with open-graded bases were successfully constructed and performed well in field installations. The open-graded bases provided adequate permeability. Although certain types of open-graded materials did give stability problems in support of rolling thin cover layer, stabilizing with asphalt increased the stability of the open-graded aggregate layer and improved pavement performance. The stiffness of the pavement system with an open-graded base, as measured by a Falling Weight Deflectometer (FWD), was comparable to the stiffness of a pavement system having a conventional base.

Tayabji and Barenberg defined the characteristics of a pavement drainage system in a 1975 report, [21]. They implied that rationally designed pavement drainage systems should have adequate capacity to drain a pavement rapidly and retain that capacity for some realistic life, should be resistant to plugging and possess sufficient stability so that the behavior of the drainage system itself does not interfere structurally with the behavior and the performance of the overall pavement system.

3.3 MATERIALS CONSIDERATIONS

Highlands and Hoffman reported that the use of crushed, densely graded aggregate subbase in Pennsylvania had resulted in numerous problems of premature pavement and shoulder distress due to excess water in the pavement system, [23]. An experimental project was devised in an effort to develop an open graded aggregate gradation to demonstrate the feasibility of providing good construction and pavement support as well as good internal drainage at a competitive cost to the conventional dense-graded aggregate subbase. An additional, long-term objective of the research project was to determine the significance of the permeability of the subbase materials on pavement performance. The reported research demonstrated that subbase materials with significantly high permeabilities (three or more orders of magnitude) could be produced with adequate quality control at a competitive cost. Adequate stability to support construction equipment was provided by the more porous, open-graded base materials. Pavement Serviceability Index (PSI) values of the pavement in the unstabilized, open-graded materials sections were approximately equal to sections containing the conventional dense-graded subbase. The roughness comparisons were similar after 15 months, six years, and after seven years of service with only 0.2 to 0.3 variation in PSI magnitudes among the sections during each respective testing. Average total deflection measurements, indicating relative strengths of the pavement sections, showed the aggregate cement section to have the lowest deflections and the conventional dense-graded aggregate subbase section exhibited the highest pavement deflections. The authors stated that the deflection data would tend to indicate that the open-graded subbases would out perform the dense-graded material from a structural standpoint under the same loading conditions. As a result of this study, the Pennsylvania Department of Transportation changed its specifications and standards to require the use of open-graded subbase interlayers immediately beneath rigid pavements, [23].

In 1991, the Norwegian Road Research Laboratory reported on the effects of fines on the stability of base gravels, [24]. Base gravel with differing amounts of fines (passing the 75μm {No. 200} sieve) and fines ratios (percent passing a 20μm {No. 635} sieve divided by the percent passing a 75μm {No. 200} sieve) were stabilized in order to prepare thin sections and study the pore structure by microscope. The influence of both the fines ratio and the total amount of fines passing the 75μm (No. 200) sieve was investigated in order to determine the amount of fine material passing the 75μm (No. 200) sieve that a base gravel could tolerate before loosing strength properties and also how the fines ratio influenced strength properties. Results of this study demonstrated that if the percent passing a 75μm (No. 200) sieve was below seven percent, a well drained pore system existed and high pore pressures were absorbed by a widespread pore channel system. If the percent passing the 75μm (No. 200) sieve was between seven and nine percent, the pore channel system was more narrow and less interconnected, but the drainage capability still appeared to exist. When the percent passing the 75μm (No. 200) sieve exceeded nine percent, the grain structure was densely packed and the pore system lacked interconnection. Layers of fines surrounding the grains resulted in a decrease in both shear strength and drainage capability.

Gonzalez examined and reported upon the stability of open-graded bases of various gradations and aggregate types when subjected to traffic, [25]. A small scale test box was designed and constructed to contain the base materials to be tested. Traffic was applied with a tire load directly on top of the bases. Rut depths at the deepest point of the wheel path were taken and used as a measurement of the stability of the material. Six different gradations of two types of materials were tested and compared with the performance of the U.S. Army Corps of Engineers standard crushed stone base coarse gradation. None of the gradations evaluated were stabilized. Based on the results of the tests conducted, Gonzalez concluded that the aggregate gradations utilized to create specimens CS-V and CS-VI were suitable for use as open-graded bases. These gradations provided an acceptable permeability without sacrificing strength or stability under direct traffic loads. Because open-graded base specimens comprised of rounded aggregates resulted in a dramatic reduction in stability, Gonzalez recommended that rounded aggregates not be used for open-graded bases. Gonzalez also found that the permeability, at least as determined in his evaluations, can be as much as 12 times greater for open-graded bases than for well graded bases.

Nichols informed the crushed stone industry about the benefits of permeable base layers in a 1991 article published in the *Stone Review*, [26]. Traditional pavement design typically used dense graded aggregates in the base layer design. However, Nichols told readers that current design was moving toward a combination of dense-graded and open-graded layers in base design. Nichols reasoned that the shift from exclusive dense-graded aggregate bases to more open-graded bases should not be viewed by producers as an increased cost factor that would have to be combated by the industry (the chief cost resulting from coarser aggregate gradations is disposal of the increased amounts of fine materials). Instead, Nichols encouraged industry officials to view this development as a new market for its products. Because a filter layer is essential to prevent intrusion of fines into the voids of open-graded drainage layers, future road construction projects will continue to use the dense-graded aggregate layer as a filter layer. Nichols pointed out that geotextile fabrics could be used as filter layers, but probably at no less cost and certainly no more effectively than a dense-graded aggregate layer. Additionally, the dense-graded layer provides a more uniformly stable platform for the layers above than does thin fabrics. Nichols indicated that the combined thicknesses of the two aggregate layers (dense-graded and open-graded) should be rated at least equal to the same total thickness of dense-graded aggregate alone when considering structural credit (structural number). If the usual coefficient for aggregate base is upgraded for superior drainage, as described in the *AASHTO Design Guide*, the final structural number may be superior to the same thickness of dense-graded aggregate. The AASHTO manual provides modifications to the normal coefficients of relative strengths assigned to untreated base and subbase materials in proportion to the quality of drainage provided, upgrading them as much as 40 percent where the material is most effectively drained.

Manz reported on the use of a geotextile fabric for separation between a free-draining aggregate layer from the soil subgrade, [27]. Manz states that one of the major causes of pavement distress is inadequate drainage of water from a pavement structural section. The case study reported by Manz in the article focuses on the design considerations using a free draining base layer whose performance was assisted by the use of a needle punched nonwoven geotextile on a 8.4 km (5.2 mi) section of U.S. 119 between Charleston and Madison, West Virginia. Inclusive to this study, it was decided to incorporate the free draining layer just above the existing subgrade for handling intrusive groundwater as well as water migrating from the pavement surface. A conservative 100-mm (4-in.) thickness for the free-draining layer was specified. A "V" ditch was designed to concentrate the water to allow it to pass through controlled outlets. The geotextile was lapped back over the free draining base to encapsulate that portion which would eventually be overlain by the shoulder material. The design was expected to enhance the life of the roadway.

The West Virginia Department of Highways constructed this initial project using a free-draining approach during the summer of 1982, [28]. The concept of using a drainage layer in pavement systems was reportedly a worthwhile venture. Even though measurable free water had been documented in the subpavement collection trenches (located at the edge of the pavement), water was never found to accumulate in the free-drainage base within the actual pavement structure itself. The most effective method of outletting the water from the pavement was still largely undecided. West Virginia's original free-drainage project, which used a subpavement "V" shaped collection ditch coupled with aggregate filled engineering fabric underdrains was continuing to be effective, but the increasing number of underdrain outlets that appeared to be becoming clogged or blocked on that project was a source of concern. It was concluded from the experience gained from monitoring this experimental project that the continued effectiveness could have been better ensured if a more positive and protected means of outletting water from the system had been employed.

Better Roads magazine published an excellent summary on the use of geotextiles in the highway construction industry during 1988, [29]. The article notes three basic functions that geotextiles perform relative to pavement construction: separation, drainage, and soil reinforcement. Geotextiles have been shown to prevent intermixing of an aggregate base and the underlying subgrade soil. This intermixing of the soil and aggregate destroys the effectiveness of an aggregate section. When a subgrade soil is subject to persistent or even occasional wet conditions, a geotextile placed over the subgrade must be highly permeable. This facilitates rapid drainage of the water from the subgrade soil up into the free draining aggregate base. The reinforcement function of a geotextile is developed through the mechanisms of restraint or confinement, friction, membrane effect, and local reinforcement.

Prefabricated subsurface drains were developed in the late 1960s and early 1970s, [30]. A subsurface drain system that utilized synthetic materials and fulfilled requirements for filtration and water flow was fabricated in lengths that were easily handled and installed in the field. This drain system eliminated many of the construction problems that had been encountered with the use of mineral aggregate drains. A fine mesh cloth was determined to be an effective filter for a wide range of soil types. A thin channelized core allowed free movement of water into the outlet pipe. Additionally, the prefabricated subsurface drains allowed placement where conventional drains would have been difficult to construct. Prefabricated subsurface drains also were found to be economically competitive with conventional mineral aggregate systems.

In 1967 the Office of the Chief of Engineers and the U.S. Army Engineer Division, Lower Mississippi Valley authorized a study by the U.S. Army Corps of Engineer's Waterways Experiment Station to develop acceptance specifications and design criteria for the use of filter cloths to replace certain granular layers of graded filters in drainage systems, [31]. Calhoun reported that woven filter cloths could satisfactorily replace granular filter materials. However, it was found that non-woven filter cloths or woven cloths with less than four percent open area were not effective where silt was present in sandy soils. Calhoun recommended that minimum tensile strengths in the strongest and weakest directions of the cloths be not less than 2,415 and 1,725 kPa (350 and 250 psi), respectively, when stones or rubble are to be dropped directly on the cloth. Cloths made of polypropylene, polyvinylidene chloride, and polyethylene fibers do not appear to deteriorate under most conditions. When filter cloths are to be used to wrap collector pipes or in similar applications, backfill materials should consist of clean sands or gravels graded such that 85 percent of the backfill material is equal to or greater in size than the equivalent opening size (EOS) of the cloth. Calhoun recommended that cloths be made of monofilament yarns and absorption of the cloth not exceed one percent.

3.4 PERMEABILITY TESTING INFORMATION

Permeability computed on the basis of Darcy's Law is limited to the conditions of laminar flow and complete saturation of the voids. In turbulent flow, the flow is no longer proportional to the first power of the hydraulic gradient. Under conditions of incomplete saturation, the flow is in a transient state and is time-dependent. However, laboratory procedures presented for determining the coefficient of permeability are based on the Darcy conditions of flow. Departure from the Darcy flow conditions to simulate natural conditions is sometimes necessary; however, the effects of turbulent flow and incomplete saturation on the permeability must be recognized and taken into consideration. The U. S. Army Corps of Engineers recommended that a constant-head method be utilized when determining the permeability of remolded samples of coarse-grained specimens such as clean sands and gravels that have permeabilities greater than about 8.5 meters per day (28 feet per day), [34].

Barenberg and Brown described three methods used to test the hydraulic conductivity and permeability of aggregate materials in a 1981 FHWA report, [35]. The first method was a constant-head permeability test. A cylindrical sample was compacted in a cylinder and water was allowed to flow through the sample under a constant head. When the flow reached a constant rate, measurements were obtained and a coefficient of permeability calculated using Darcy's Law. All tests were conducted while using head pressures similar to ones anticipated under field conditions. A second method was used to measure the horizontal permeability of a molded specimen. This procedure was limited to bound, or stabilized materials. Samples were compacted in a steel mold and then packed in an impervious medium (cast in Hydrocal) for testing. Samples were tested for hydraulic conductivity in the same orientation as they were molded. A third test was used to determine the horizontal permeability of non-stabilized granular materials. The materials were compacted directly in the bowl in which the tests were performed. Plexiglass sides on the test chamber allowed the staff to track the contours of the flow net. Darcy's Law was applied to the flow nets and the effective permeability calculated.

Moulton and Seals reported the development of a prototype in-situ test device, designated the field permeability testing device, for determination of the permeability of highway base and subbase courses, [36]. The research consisted of two phases. Phase I involved development and laboratory investigation of feasible in-situ permeability measurement techniques. As a result of information gained during Phase I evaluations, a velocity method of in-situ permeability determination was selected for further development. Phase II involved construction of a prototype field permeability test device and an extensive laboratory and field evaluation program. Based on the results of Phase II evaluations, it was concluded that the field permeability test device satisfied project objectives and provided a convenient means to determine the in-situ coefficient of permeability of highway bases and subbases with reasonable accuracy and reproducibility. The device permitted design considerations of saturated hydraulic conductivity (permeability) of bases and subbases and also permitted the development of construction specifications for the permeability of these materials.

3.5 PERFORMANCE INFORMATION

Dempsey recognized that water is a fundamental variable in most problems associated with pavement construction, design, behavior, and performance, [32]. Research was conducted to determine whether or not moisture was accelerating deterioration of pavements and if so, at what rate? The rate of occurrence of most distress types is nearly always a result of several factors including load, moisture, temperature, freeze-thaw, corrosion, etc. Thus, it could not be concluded from the research conducted that "moisture alone caused this distress" in most cases, since the distress is really caused and propagated by several factors. Therefore, to determine the effect of moisture on pavement performance, its affect on accelerating the "rate of occurrence" of distress was established. Dempsey stressed that the importance of the hydraulic properties of the pavement materials, subgrade, and drainage materials should be more fully understood and appreciated.

Dempsey concluded that gravel shoulders provided no removal of moisture from the pavement edge and also lost support when moist, necessitating continual maintenance, [32]. Paved shoulders would reduce maintenance efforts and improve the performance of pavements by adding lateral support and removing moisture from the pavement edge. The shoulder-pavement joint was determined to be critical to the performance of the shoulder. Because moisture concentrates both under the outer edge of the shoulder and at the longitudinal joint, the problem of frost heave was more serious for the shoulder area. This was where water most often entered the pavement structure and also was where the water could effectively be removed or eliminated. Sealants reduced the infiltration rate initially but their ability to limit ingress of water reduced with time as they deteriorated or lost bond with the pavement. A suggested possible solution to the shoulder-pavement joint is the use of full-width paving to include the mainline pavement lane and shoulder as an integral structural layer in order to eliminate edge joints between the shoulder and mainline pavement. Finally, the study determined that stringent maintenance practices are necessary to keep pavement subdrainage systems operational after they are constructed.

Flynn highlighted Wisconsin's Department of Transportation (WisDOT) efforts relative to open-graded drainage layers in a 1991 *Roads and Bridges* article, [33]. The evaluation by WisDOT was considered to be one of the most in-depth studies of open-graded bases in the nation at the time of this article. WisDOT had decided to use open-graded base course (OGBC) on all of Wisconsin's major interstates and highways over a two-year period. Concurrent with this use WisDOT would evaluate this policy in relation to completed test data. WisDOT chose to use OGBC even though preliminary data on a test section had not been completely analyzed. Because WisDOT chose to use OGBC full time on its highways without the benefit of completed test results, the department developed interim guideline specifications to be used until test data were completed. WisDOT decided to limit its stone specifications to two gradations: OGBC No. 1 concrete stone (AASHTO No. 67) and OGBC No. 2, which WisDOT called "free-draining base." Characteristics of the No. 1 stone were (1) it could not sustain local traffic and only very little construction traffic, (2) it had a permeability of about 3,050 meters per day (10,000 feet per day), and (3) it was used primarily in areas with heavy soil and low permeability. Characteristics of the free-draining base were (1) it could sustain some construction and local traffic, (2) it had a permeability of about 60-150 meters per day (200-500 feet per day), and (3) it was used primarily in those areas where the base course typically had to be used as a haul road or when access to local traffic had to be maintained, such as in urban environments.

WisDOT research addressed five main issues: (1) pavement performance, (2) cost effectiveness, (3) constructability, (4) trafficability, or the ability of the base to hold construction and local traffic, and (5) maintainability. Results from the study indicated there was less faulting of pavements overlying an OGBC when compared to dense-graded base course (DGBC). There were no differences detected between the OGBC and DGBC relative to distress or ride but there were indications the OGBC was reducing some of the freeze-related problems in the northern part of the state. Researchers believed that pavement life may have been extended five to ten years through the use of drained pavements (30 years) versus the use of undrained pavements (20-25 years). At the time of this article, Wisconsin researchers were trying to determine the best aggregate gradation for open-graded base that would achieve adequate flow rates and at the same time provide necessary construction stability. From the research, it was determined that compelling contractors to stabilize the drainage layer was probably the best route (verses giving contractors the option not to stabilize). A major disadvantage of using an OGBC is its inability to support construction traffic loads without sustaining considerable damage. When utilizing non-stabilized OGBC, contractors had to construct and maintain parallel haul roads, adding hidden cost to the project, [33].

WisDOT specifications called for 100- to 150 mm (4- to 6-in.) diameter longitudinal drainage pipes to protect against clogging. These pipes were made of perforated corrugated polyethylene. Outlet pipes were non-perforated polyvinyl chloride pipe. Heavier pipe was used as outlet pipe to prevent crushing by construction and maintenance equipment. Concrete headwalls with rodent screens were placed at the end of all outlet pipes. Outlet pipes were spaced 91-152 meters (300-500 ft) at low points. Regular and proper maintenance of the outlet pipes were deemed critical to the success of the subsurface drainage system. Generally, the cost of using an OGBC was significantly higher compared to a DGBC. However the consensus of the researchers was that the initial extra out-of-pocket expense would be returned due to the longer life expectancy of the pavement. For a typical four-lane divided roadway, a stabilized OGBC generally added about $62,000 - $75,000 per kilometer ($100,000 - $120,000 per mile) to the overall cost. The total cost increase for the use of non-stabilized OGBC on a four-lane divided roadway, including edge drains and fabric, was about $31,000 to $37,000 per kilometer ($50,000 to $60,000 per mile).

WisDOT researchers identified general differences between OGBC projects and other projects as: (1) subgrade construction inspection was critical; (2) thickness and type of DGBC was crucial; (3) haul roads were necessary; and, (4) additional inspection was required. Other points that must be considered when working with OGBC are: (1) OGBC cannot be hauled on without some damage to it - even a stabilized OGBC has limitations in this respect; (2) if stabilizing is not done then a haul road must be provided; (3) there is some loss of concrete or asphalt pavement yield over OGBC; (4) local and construction access during construction is affected by inability to drive over OGBC, and; (5) the dollar cost of negating the above problems could still be eliminated because of the cost-effectiveness of the application and the resulting increased pavement life, [33].

3.6 DESIGN INFORMATION

Allen summarized US Army Corps of Engineers drainage criteria for pavements found in Corps of Engineers documents in a 1991 report, [37]. The report also contained a similar summary of the pavement drainage practices mandated by private, state and federal agencies such as the American Association of State Highway and Transportation Officials (AASHTO) and the Federal Highway Administration (FHWA). The information presented in the report included current practice for the drainage of subsurface structures. A comparison of the two sets of information allowed for discussion of present deficiencies in the Corps criteria, as did additional discussion based on current research at Cold Regions Research and Engineering Laboratory that had not yet been incorporated into Corps criteria. Mr. Allen concluded that the criteria produced by the Corps of Engineers for drainage of pavement structures and the practices of those outside the Corps did not vary greatly. However, when designing drainage systems specifically for cold regions, Corps and other drainage criteria were both lacking. In all sectors, from the Corps through the rest of the pavement community, the principles of good drainage were well known. The high cost of permeable aggregates and the extra care needed to place drainable bases and collectors were identified as the main factors which prevent regular construction of well-draining pavements.

A Federal Highway Administration demonstration project on drainable pavement systems provided State highway engineers with current state-of-the-art drainage guidance on the design and construction of permeable bases and edgedrains for Portland cement concrete pavements, [38]. A blend of drainage design, materials design, and construction and maintenance procedures are presented. Much of the practical guidance on edgedrains presented in the report is based on the study *Concrete Pavement Drainage Rehabilitation*, Experimental Project No. 12, FHWA. The technical guidance presented in this report is based largely on material in Technical Paper 90-01 on Pavement Subsurface Pavement Drainage by the FHWA. The material presented in the demonstration included information relative to identifying sources of water and points of infiltration and pavement distress types typically caused by moisture. The design information presented included considerations of roadway geometry, water infiltration rates, gradation analysis of the permeable base layer and porosity, effective porosity requirements, and percent saturation of the permeable base course. Darcy's Law to calculate flow rates are identified along with the necessary precautions for its use. Considerable discussion is given to identifying permeable base materials, the separator or filter layer, longitudinal edgedrains and their capacity and outlet spacing. One section of the demonstration materials stresses the importance of scheduled maintenance of outlet systems. The summary section of this publication is highly detailed and complete. This section should be referenced for specific guidance in justifying and designing for permeable bases for Portland cement concrete pavements.

Detailed designs for highway subsurface drainage are presented by Moulton in a 1982 report, [39]. The design manual contains general design considerations, data requirements for analysis and design of susbsurface drainage systems, methods and recommended criteria for control of groundwater and infiltration in pavement structural sections, control of groundwater away from the pavement, and a discussion of the construction and maintenance considerations required of subsurface drainage systems.

4.0 LABORATORY AND FIELD EVALUATIONS

A previous report issued during this study documented laboratory and field investigations performed as part of this study, [40]. Potential drainage blanket materials were evaluated in the laboratory. Flow rates for several different aggregate gradations, both unstabilized and stabilized with asphalt and Portland cement, were determined. The aggregate gradations conformed to standard gradations contained in the Kentucky Standard Specifications for Road and Bridge Construction, [41]. Resilient moduli of the various materials used in the pavement structure were evaluated in an effort to assign a structural coefficient to those materials. Field evaluations included monitoring construction practices associated with drainage layers and engineering performance of subgrade, filter, drainage blanket, asphaltic pavement and Portland cement pavements. Monitoring construction of pavement systems involving drainage blankets included documenting construction problems, successes, and techniques. Monitoring engineering performance of the sites included determination of in-place densities, conducting falling weight deflectometer (FWD) tests, performing pavement distress surveys, determining rutting, rideability indices (RI), and monitoring in-place drainage. Performance and maintenance histories (up to 16 years) of pavements utilizing drainage blankets were also documented.

4.1 LABORATORY PERMEABILITY TESTS

The first effort during the laboratory evaluation was determining appropriate methods and apparatuses for measuring permeabilities or flow rates of the materials studied. The terms permeability and flow rate are interchangeable but permeability is generally used in reference to materials having lower flow rates, such as filters, and flow rate is used in reference to materials having higher flow rates, such as drainage blanket materials. Materials evaluated during this study included the filter layer separating the drainage blanket and subgrade, various aggregates tested for possible use in the drainage blanket, bituminous concrete mixes placed on the drainage blanket, and other construction materials. Permeabilities of these materials range from less than 0.3 meters per day (1.0 ft/day) to several thousand meters per day (ft/day). For materials having low permeabilities, the test method used was the falling head method developed by the Army Corps of Engineers, [42].

Materials used for drainage blankets require a different method and test apparatus for determining flow rates. The large aggregate dimensions of some gradations require large specimen dimensions and the flow rates of such specimens far exceed the capacity of conventional test apparatuses. Initially, a 200-mm (8-in.) diameter specimen was used to insure an acceptable specimen dimension to particle size relationship. As laboratory testing progressed, additional information prompted the deletion of certain gradations having larger top size aggregate and test specimens were reduced to 150 mm (6 in.) in diameter.

The equation used for calculating flow rate or permeability is based on Darcy's Law and is contingent upon the existence of laminar flow. Laminar flow cannot be assured for high flow rates through aggregate, but by keeping the hydraulic head very low, turbulence can be reduced and field conditions may be approximated. Initial efforts were directed toward developing an apparatus for testing flow rates of drainage blanket gradations.

Drainage and strength characteristics of a material may change with prolonged flow of water through it. These changes could be precipitated by stripping, if asphalt binder is used, or flushing of smaller particles. The changes may increase or decrease permeability or decrease strength characteristics of the material. Since long-term tests were desirable to monitor possible changes in materials, a constant head permeability test was used. Also, this type test permited the selection of low, but variable hydraulic gradient (head) values to approximate field conditions.

Initially, the materials considered for use in drainage blankets ranged from Number 4 gradation (maximum particle size of 50 mm (2 in.) and 0 to 5 percent passing the 9.5-mm (3/8-in.) screen) to Number 610 gradation (maximum particle size of 37.5 mm (1.5 in.) and up to 40 percent passing the 4.75-mm (No. 4) screen). Based on the 50-mm (2-in.) particle size, a 200-mm (8-in.) diameter specimen size was chosen. The length to diameter ratio was reduced to 1.5 to 1 for flow rate testing. Specimens to be tested for strength maintained the 2 to 1 length to diameter ratio.

The flow test apparatus consisted of a shallow (250 mm) {10 in.} reservoir having a large cross section (1.2 m^2 {12.5 ft^2}), a 100-mm (4-in.) supply line to the specimen, a movable specimen holder, and a manometer. The reservoir permitted establishment of a constant depth of water in the tank by having an adjustable, high volume supply (water main) to the reservoir, an overflow, and an on/off valve for the 100-mm (4-in.) specimen supply line. Once a specimen was in place and flow through the system began, input to the reservoir was adjusted so supply to the tank was balanced to the flow through the specimen and overflow combined. Head was monitored by attaching one side of a manometer to the reservoir and the other side to the overflow or tail water side of the specimen. Due to changes in the specimen during testing, the flow rate and thus the head sometimes changed. The large tank cross section and overflow minimized the rate of head change and the manometer permitted precise and constant monitoring of the head. The adjustable specimen holder allowed adjustments to the head when specimens of various lengths were tested. Flow through the specimen was monitored by directing the tail water or flow from the specimen into a calibrated container and the collection was timed with an electronic timer. A schematic of the flow test apparatus was presented in Research Report KTC 94-13 [40]. Calculated flow rates and permeabilities were based on Darcy's Law. Although laminar flow cannot be assumed for open graded materials, test results may be assumed to approximate field values by maintaining head values near anticipated field values. When the basic requirements of the apparatus were determined and the apparatus had been constructed, functionality testing and calibration of the apparatus were initiated. Upper and lower functional limits were established. The upper limit was established by running the system with no specimen in place and at a maximum head of 200 mm (8 in.) Under these conditions, the system permitted a flow rate of approximately 27,432 m/day (90,000 ft/day).

Since some of the gradations to be tested contained significant amounts of fine material, retention screens were necessary at each end of the specimen. Frames were machined to fit inside the specimen chamber and fitted with wire cloth corresponding to test sieve aperatures of 150 µm, 600 µm, and 2.00 mm (US Standard Sieve Numbers 100, 30, and 10). Tests indicated that the 150 µm (No. 100) screen significantly reduced flow, the 600 µm (No. 30) screen tended to clog with time, but the 2.00-mm (No. 10) screen did not noticeably affect flow at flow rates less than 9,144 m/day (30,000 ft/day).

Since permeability of filters, subgrades, and denser asphaltic concrete may be tested by conventional methods, common concrete sand, meeting the gradation requirements of ASTM C 33 [43], was chosen to determine lower end performance characteristics of the test apparatus. Nine tests were performed with a smaller collection container and the resultant flow rate was about 22 m/day (72 ft/day) for all tests.

The apparatus was calibrated against the flow rate of various gradations published in FHWA-TS-80-224, *Highway Subdrainage Design*, [39]. Figure 29 of the design manual charts gradations and flow rates for several filter and open graded materials. Gradations with flow rates of 1,830, 4,265, 6,095, and 10,975 m/day (6,000, 14,000, 20,000, and 36,000 ft/day) were selected for comparison. The *Highway Subdrainage Design* manual did not provide information on the particular permeability test method used or how specimens were prepared to derive Figure 29. A search of articles referenced in the figure was made but these did not reveal what test method was used either and only a general statement of specimen preparation typified as "moderate" compaction was identified. Specimens for the calibration tests were composed of crushed limestone which was screened and recombined to the gradations indicated in Figure 29 of the design manual. Compaction for all specimens was standardized at one minute (maximum force) on a vibration table with a 12.7-kg (28-lb) surcharge. Specimens were compacted in one lift with 2.00 mm (No. 10) retaining screens placed at both ends after compaction. Compacted specimens exhibited densities between 1,445 and 1,605 kg/m^3 (90 and 100 lbs/ft^3).

Results of the calibration flow tests indicated that the apparatus devised by KTC yielded values comparable to FHWA's tests for gradations at flow rates of 1,830 and 4,265 m/day (6,000 and 14,000 ft/day). At higher flow rates, KTC values were somewhat less than values reported by FHWA. This difference is possibly due to turbulent flow. Since KTC tests were conducted on relatively large specimens and with head conditions expected in the field, researchers were confident that KTC laboratory flow rate test results were representative of field conditions. Since expected flow rates within drainage blankets were less than 6,095 m/day (20,000 ft/day) and results from calibration tests were repeatable, the apparatus was used as constructed.

Initial efforts to determine flow rates of possible drainage blanket gradations involved obtaining a quantity of crushed limestone aggregate, sizing it, and recombining the aggregate to the gradation requirements contained in the Kentucky Standard Specifications for Road and Bridge Construction, [41]. Gradations were recombined to the center and fine side of the specification band. Gradations originally selected for evaluation included 57's, 610's, 67's, 68's, 710's, 78's, and 8's.

The current drainage blanket gradation specification is a Number 57 gradation for untreated or Portland cemented treated blankets and a gradation very similar to Number 57 (allows additional minus 4 material) for asphalt treated drainage blankets. A gradation meeting specification requirements for both asphalt and Portland cement treatment was prepared and specimens of each type treatment were prepared for flow tests. Flow test results of laboratory recombined gradations indicated that the Number 57 gradation (or the gradation specified for asphalt treatment) provided the highest flow rate, 4,300 m/day (14,100 ft/day) and the Number 610 gradation provided the lowest flow rate, 1,220 m/day (4,000 ft/day). Asphalt treatment of the Number 57 gradation reduced the flow rate by about 37 percent to approximately 3,140 m/day (10,300 ft/day). However, Portland cement treatment increased the flow rate to approximately 7,925 m/day (26,000 ft/day). The increased flow rate observed in the Portland cement treated specimen was attributed to a decrease in unit weight of the specimen. The Portland cement treated specimen did not densify as much as the asphalt treated specimen under the same compaction effort. For each recombined gradation, the specimen prepared at the finer boundary of the gradation specification indicated decreased flow rate.

Flow rate characteristics of aggregate gradations from Kentucky aggregate suppliers were also evaluated. Aggregate samples taken from the stockpiles of several central Kentucky suppliers were obtained. Aggregate gradations evaluated included 57's, 610's, 67's, 68's, 8's (from 2 suppliers), and 11's. Sieve analyses were performed to determine adherence to specification requirements by Kentucky Method 64-602-91, [44]. Test results revealed that Numbers 57 and 8 were generally within gradation specification requirements but the remaining gradations were found not to be within specification requirements. In most cases, the stockpiled material contained more fine material than permitted by the specifications. Since materials used to construct drainage layers often do not meet specified gradation requirements, flow tests were conducted on specimens sampled from producer stockpiles. Quantities of the stockpiled materials were obtained and specimens were prepared with asphalt treatment, Portland cement treatment, and no treatment. Care was taken with material obtained for both flow rate and gradation testing to maintain representative portions for test specimens. Materials obtained from stockpiles were reduced to specimen size portions using ASTM C 702, Method A, [45]. Because some gradations are not commonly stockpiled by all suppliers, four common gradations were selected for flow rate testing of treated and untreated specimens. Those gradations included Numbers 57, 67, 8, and 610. It was determined during flow testing activities that gradations having aggregates larger than 37.5 mm (1-½ in.) (Number 57 gradation) were not necessary to obtain sufficient flow rate and specimen dimensions were reduced to 150 mm (6 in.) in diameter and 300 mm (12 in.) in length.

Flow rates of the stockpiled specimens were found, in some cases, to differ from flow rates obtained from recombined gradations. All gradations except Number 57 indicated the highest flow rate in the untreated condition with some reduction of flow rate for asphalt or Portland cement treatment. In most cases, the reduction in flow rate was 610 to 915 m/day (2,000 to 3,000 ft/day). The Number 57 gradation, when treated with Portland cement, indicated an increased flow rate. The increased flow rate was attributed to the decreased unit weight of the Portland cement treated specimens. Initial analyses of all density versus flow rate data indicated a moderate correlation, i.e., an increased flow rate typically occurs at lower specimen densities. It was not possible to prepare an asphalt treated Number 610 gradation specimen. The large amount of fine material in the Number 610 absorbed the asphalt and did not permit coating of the larger particles.

4.1.1 Field Compacted Drainage Blanket Specimens

Several construction projects, utilizing both treated and untreated aggregate drainage blankets, were ongoing while the evaluation of different gradations for flow characteristics continued. Asphalt treated material was obtained from the asphalt spreader at one project and specimens were compacted at the site. Results of flow test for these specimens further established that unit weight significantly impacts flow rate. Field specimens having unit weights ranging from 1,413 to 1,782 kg/m^3 (88 to 111 lbs/ft^3) had flow rates ranging from 8,534 to 3,353 m/day (28,000 to 11,000 ft/day), respectively.

Also during flow rate evaluation of field specimens, it became apparent that flow rates of asphalt treated specimens tended to decrease as the specimens were subjected to longer periods of flow. After flow tests had been conducted, specimens were broken and examined for asphalt stripping.

Stripping had occurred in the specimens and the stripped asphalt clogged the voids causing decreased flow rates in the specimens. Twelve asphalt treated specimens of various gradations were molded in the laboratory and evaluated for potential stripping. Specimens remained the flow-test apparatus with flow through them and were monitored until the flow rate stabilized. In some instances, duration of the stripping test was 200 minutes. All specimens exhibited signs of stripping with some flow rates decreasing to less than one-half the initial flow rate for the specimen. Neither laboratory nor field specimens contained any anti-stripping agents.

4.1.2 Permeabilities of Other Paving Materials

Permeability of pavement structure material above and below the drainage blanket was determined. A nuclear gage was used to monitor the field density of underlying filters and overlying asphaltic pavement mixes. Mix design, specifications, and in-place densities were used to prepare laboratory specimens for testing. The materials included dense graded aggregate (DGA), stabilized aggregate base (SAB), Class I bituminous base, and Class K bituminous base. Permeability of DGA was 2.0 x 10^{-4} cm/sec, SAB was 1.28 and 0.23 x 10^{-7} cm/sec, Class I base was 4.78 x 10^{-5} cm/sec, and Class K base was 3,000 ft/day. Density of the laboratory prepared Class K base specimen was 1,990 kg/m^3 (124 lbs/ft^3) as compared to field densities of 2,328 to 2,408 kg/m^3 (145 to 150 lbs/ft^3). Concrete sand (ASTM C 33) is often used as trench backfill for edge drain collector systems. Flow tests of concrete sand indicated a flow rate of 22 m/day (72 ft/day) or 2.54 x 10^{-2} cm/sec.

4.2 RESILIENT MODULUS EVALUATIONS

Resilient moduli of the various materials used in the pavement structure were evaluated in an attempt to determine a structural coefficient for those materials. The standard test method, ASTM D 4123, was not used since several of the materials being evaluated did not lend themselves to that test method, [46]. Large voids in the Class K base and most drainage blanket specimens did not provide adequate surface area to mount sensors. Non-cohesive materials, such as DGA and unbound drainage blankets, also presented problems when the standard test method was attempted. Because of the nature of the materials being evaluated, the resilient modulus was determined using unconfined compression tests of cylindrical specimens with the conventional 2:1 height to diameter ratio.

All specimens were tested at room temperature and under the same conditions of confining pressure (0.0 kPa {0.0 psi}) and stress (206.8 kPa {30 psi}). Room temperature was normally 21.1°C (70°F). Variations in temperature were recorded and moduli were normalized to 21.1°C

(70°F) using relationships developed through previous research, [47]. The compressive load was applied with a square waveform (instantaneous load and unload) at a frequency of one hertz. Loading time for the specimens was ½ second and the unload time was also ½ second. Total resilient modulus was calculated using the total recoverable strain during the unloaded portion of the cycle. The test apparatus used was an electrohydraulic, closed loop servo-valve, 4,536 kg (10 kip) capacity MTS test machine. Data were collected with an electronic load cell and both external (mounted to the specimen) and internal (test machine) linear variable differential transformers (LVDTs). Machine strain was isolated and subtracted from the internal LVDT output for modulus calculations. Outputs from the sensors were recorded for all test cycles but data for modulus calculation were taken after 100 test cycles to allow for specimen conditioning.

All specimens tested for resilient modulus were molded specimens, not field cores. Field measurements with nuclear density instruments indicated that in-place densities of asphalt treated drainage blankets ranged from 1,685 to 1,766 kg/m^3 (105 to 110 lb/ft^3). Target densities of molded specimens were within the range of measured in-place densities but specimens were compacted both on site and in the laboratory. Field compacted specimens did not always fall within the target density range. Laboratory molded specimens were of various gradations while field molded specimens were of actual drainage blanket, Class K, or Class I materials.

Laboratory test results indicated that, when the density was constant, resilient modulus did change greatly with the asphalt treated gradations tested. Gradation Numbers 8, 67, and 78 all averaged approximately 379 MPa (55,000 psi) and gradation Number 57 averaged 538 MPa (78,000 psi). Moduli of specimens significantly outside the target density were not included in the analyses.

SAB and DGA filter material specimens and Class I and Class K base mixture specimens were compacted in the field for resilient moduli evaluations. Density of SAB and DGA specimens ranged from 2,344 to 2,424 kg/m^3 (146 to 151 lbs/ft^3). SAB specimens were cured 45 days before resilient modulus testing. Two SAB specimens were cured under damp burlap and two others were cured in water. The two specimens cured under burlap had moduli of 41,368 and 34,474 MPa (6,000,000 and 5,000,000 psi) while the soaked specimens had moduli values of 38,610 and 33,095 MPa (5,600,000 and 4,800,000 psi). DGA specimens were cured seven days and had moduli values of 48, 90, and 97 MPa (7,000, 13,000 and 14,000 psi). These values are low but are comparable with results reported from other studies when tested without confining pressure, [48]. Densities of Class I specimens were comparable to measured in-place densities at approximately 2,344 kg/m^3 (146 lbs/ft^3). Class K specimens were very difficult to compact in the field and densities of the specimens ranged from 1,894 to 1,990 kg/m^3 (118 to 124 lbs/ft^3). The low densities of the Class K specimens resulted in low resilient moduli ranging from 889 to 1,296

MPa (129,000 to 188,000 psi). Resilient moduli values of Class I specimens ranged from 1,303 to 1,600 MPa (189,000 to 232,000 psi).

Specimens of the Number 57 gradation with Portland cement stabilization, conforming to Kentucky Specifications, were prepared for evaluations. Two specimens were cured in the mold with plastic covers and two others were cured in the mold with damp burlap covers. One of the plastic covered specimens was damaged and was unable to be tested. The remaining plastic covered sample had a modulus value of 13,790 MPa (2,000,000 psi). The specimens that were cured covered with wet burlap had moduli values of 13,790 and 9,653 MPa (2,000,000 and 1,400,000 psi).

4.3 CONSTRUCTION AND PERFORMANCE EVALUATIONS

Field evaluations performed during this study included monitoring selected existing and newly constructed pavements wherein special subdrainage layers were incorporated into the design of the pavement structure. Construction and engineering performance of subgrade, filter, drainage blanket, asphaltic concrete pavement and Portland cement concrete pavements were observed. Monitoring construction of pavement systems involving drainage blankets included, but was not limited to, documenting construction problems, successes, and techniques. Monitoring engineering performance included measuring in-place densities during construction, conducting Falling Weight Deflectometer (FWD) tests, performing pavement distress surveys, determining rutting, rideability indices (RI), and monitoring in-place drainage. Performance and maintenance histories (up to 16 years) of pavements utilizing drainage blankets are also documented.

Several sites were included in the evaluation process. At the time, some were under construction and some were approaching 15 years of service. A variety of subgrades, filters, drainage blankets and pavements were inspected. Most sites were located in Central or North Central Kentucky.

4.3.1 Evaluation of In-Situ Layer Moduli of Drainable Base Materials

Falling Weight Deflectometer (FWD) testing was conducted on selected highway projects during the study to evaluate the in-situ layer moduli of various drainable base materials. The FWD is a nondestructive testing device which determines the deflection of the pavement structure under a given dynamic load. A uniform load is applied to the pavement surface and the pavement surface deflections resulting from this load are recorded at several radial distances from the center of the load. Tests were made at selected intervals along each project to provide sufficient data to represent the project.

The deflection data were analyzed using the MODULUS backcalculation procedure developed a the Texas Transportation Institute. The program compares measured pavement deflections with deflections that are determined using a linear elastic pavement analysis program for varying elastic layer moduli. The elastic layer moduli of the theoretical deflection bowl which best fits the measured deflection bowl are then used to represent in-situ properties of the pavement structure.

Pavement cross sections which were evaluated consisted of asphalt treated and untreated 57 grade stone base above a layer of dense grade aggregate. Results of the backcalculation provided ranges of elastic moduli for each material type. The 1993 AASHTO Guide for Design of Pavement Structures was used to determine the structural layer coefficient for the different materials. Figure 2.9 of the AASHTO Guide was used to convert the backcalculated layer moduli for the asphalt treated materials to an equivalent structural layer coefficient. Figure 2.6 of the AASHTO Guide was used to determine the equivalent structural layer coefficient for untreated materials. Table A summarizes the average backcalculated layer moduli of the drainage layers.

Table A

	Layer Moduli		
Material Type	(MPa)	(ksi)	Layer Coefficient
Asphalt Treated 57's	800 - 1,500	116 - 220	0.14 - 0.23
Untreated 57's	310 - 450	45 - 65	0.18 - 0.22

4.3.2 Existing Sites

Existing sites monitored during this study included KY 55 in Taylor County; US 23, Louisa Bypass, in Lawrence County; and the AA Highway in northeastern Kentucky.

4.3.2.a KY 55, Taylor County

A 8.4-km (5.2-mi) section of Ky 55, near Campbellsville in Taylor County, was constructed in 1978 and contained ten experimental sections containing five different designs. The site layout had four sections incorporating untreated drainage blankets and one is a control section where the drainage blanket was excluded. Earlier reports document construction and performance of the site, [48, 49]. Based on that initial attempt to incorporate an untreated drainage blanket in the pavement structure, it was concluded that it was difficult to place the bituminous layers above untreated material, [48]. Pavement deflection tests and analyses performed during the initial evaluation indicated little significant difference between sections of equivalent thickness. However, it was concluded that the drainage system functioned well. Graves performed a subsequent evaluation of the experimental site in 1989, [49]. Graves concluded that after 12 years of service the drainage blanket was in good condition and functioning well; however, outlet headwalls were clogged. The pavement was characterized as in generally good condition with most distress occurring in the thinner design sections.

A subsequent observation made at the site during a heavy rainfall revealed that the drainage system still responded quickly (within minutes) after the onset of precipitation even though nearly 70 percent of the outlets were clogged and in need of maintenance to provide free drainage. Typical obstacles to free drainage were grass and debris in the headwall and rodent screens. Ponding (ditch line blockage) and displaced outlets were also observed.

The KY 55 experimental section went 14 years without overlayment. It received a 25-mm (1-in) surface course in 1990 and, just south of the experimental section, a 25-mm (1-in) surface course in 1991. The maintenance engineer responsible for Taylor County stated that there were no significant differences in pavement condition of the experimental and control sections but that fiscal factors determined the timing of the overlays. The maintenance engineer indicated that rutting or cracking was not the reason for resurfacing but that some raveling of the pavement had occurred.

4.3.2.b US 23, Louisa Bypass, Lawrence County

The Louisa Bypass was completed in July 1989. The pavement consisted of a 25-mm (1-in.) surface course on an experimental, 300-mm (12-in.) thick-base course of large stone mix (Class K base), placed in three (3) courses of equal thickness, above a 100-mm (4-in.) drainage layer of untreated 57's on a 100-mm (4-in.) thickness of densly-graded aggregate. Construction and short-term performance were documented by Mahboub and Fleckenstein, [50].

After two years of service, significant rutting had already developed, especially in areas where heavily loaded trucks moved slowly. Investigations indicated that the pavement rutting (up to 45 mm {1.8 in.}) was primarily in the experimental Class K base. Measurements of pavement cores taken in the rutted wheel paths and between the ruts indicated that the rutting occurred in the top two courses (200 mm {8 in.}) of Class K base. The northbound lanes developed such severe surface irregularities that required milling and resurfacing the lanes in 1994. The irregularities were humped or domed areas, not typical distresses, and were thought due to movement of the untreated drainage blanket beneath the Class K base layer.

4.3.2.c Ashland to Alexandria (AA) Highway

The AA Highway extends from Alexandria in North Central Kentucky to the Ashland area of Eastern Kentucky. The highway was constructed in separately bid sections and incorporates several different pavement designs with approximately one-half involving some type of subsurface drainage. The drainage blanket was either untreated 57's or asphalt treated 57's and included a collection system or was daylighted to the shoulder. Most of the sections were completed between 1987 to 1990. All components of the pavement structure varied depending upon design. Subgrade conditions included no treatment, modification with lime or Portland cement. The base layer was constructed of dense graded aggregate (DGA), stabilized aggregate base (SAB), or deleted (full-depth bituminous pavement). Pavement thickness and mix requirements varied. A filter fabric was used in one section and the drainage blanket was daylighted in another. All the various design sections have been detailed in a previous report, [40]. Because of the number of design sections, the AA Highway provided an excellent opportunity to compare the different combinations relative to one another.

The pavement sections containing subsurface drainage were monitored through pavement deflection testing, pavement distress surveys, rideability indices (RI), visual surveys of drainage during and after precipitation, and outlet condition surveys. Pavement distress surveys indicated that the pavement surface, after five to six years of service, was in good condition. Rutting of the asphaltic concrete pavement typically ranged from 3 to 9 mm (1/8 to 3/8 in.) with little discernable differences between design sections. There was moderate cracking observed with the more significant cracks being longitudinal between the wheel paths. Transverse cracks were significant only in the western 5.6 km (3.5 mi) of the AA highway near Alexandria and at Maysville in Mason County where there higher traffic volumes. Except for the Maysville section, cracking of either type (longitudinal or transverse) was common to all sections having drainage blankets. Conversly, significant cracking was noticeably absent from sections without drainage blankets. Slight raveling was noted in the pavement surface throughout much of the total length of the AA highway but was not distinguishable between the varying design sections.

Visual surveys were performed on numerous drainage outlets revealed good drainage during precipitation. The drainage outlets were remarkably clear and clean when compared to other sites evaluated during this study. Of particular interest was the performance of the section containing the daylighted drainage blanket. An inspection performed shortly after a moderate rainfall indicated that the daylighted section was functioning well. As expected, side slopes in sections having edge drains and an outlet system were dry except below the outlets while the side slopes at the daylighted sections were damp. There were some concerns expressed that the daylighted drainage blanket would clog by encroaching vegetation and the collection of silt. However, based on observations to date, those concerns appear to be unwarranted. Vegetation encroachment has been minimal thus far. One problem with the daylighted drainage blanket was displacement of aggregate by vehicles driving off the partial-width paved shoulder. In areas where guardrail was placed, the exposed blanket looks much as it did when it was placed. However, in areas without guardrail, there was significant displacement of the daylighted drainage layer where vehicles had driven off the shoulder.

FWD data have been collected and evaluated almost continually since the AA highway has been in service. Rideability index (RI) data for the AA Highway were obtained from the Department of Highways' Pavement Management Group and analyzed. Overall, most of the route exhibited good RI values but with some obvious decreases of the values in the older pavement sections within Mason and Lewis Counties.

Changes in RI values with time were compared for the different design sections. The AA Highway has nearly 30 design sections and many of them are identical or very similar. Contiguous design sections were able to be grouped into five groups for comparison purposes. Group One consisted of sections having 275 mm (11 in.) of pavement on an asphalt treated drainage blanket on a lime stabilized subgrade. Group Two had the same layer thickness as Group One and the drainage blanket was unstabilized. Group Three sections had 250 mm (10 in.) of pavement (+/- 12.5 mm {0.5 in.}) on an asphalt treated drainage blanket on a stabilized aggregate base. Group Four sections had varying thicknesses (250 to 350 mm {10 to 14 in.}) of pavement on dense graded aggregate with Monsanto panel edgedrains. Group Five had 213 to 225 mm (8.5 to 9 in.) of pavement on 100 mm (4 in.) of either dense graded aggregate or rock roadbed and no drainage system in place. Group One exhibited a 10 percent decrease in RI initially and little change thereafter during the study period. Groups Two, Three, and Four had only slight decreases. Group Five had a more pronounced and continuing decrease.

4.3.3 Newly Constructed Sites

Newly constructed sites monitored during this study included sections of reconstructed US 127 in Mercer and Franklin Counties and reconstructed I-264 (Waterson Expressway) in Jefferson County.

4.3.3.a US 127, Mercer County

A portion of northbound lanes of reconstructed US 127 in Mercer County was chosen for monitoring during this study. Design for the section included a 275-mm (11-in.) bituminous concrete, a 100-mm (4-in.) untreated Number 57 gradation drainage blanket, a 100-mm (4-in.) dense graded aggregate layer that served as a filter, and a 200 mm (8 in.) thick, lime stabilized (6 percent) subgrade. Deflection testing of the structural layers was performed with the FWD during construction and on the pavement surface at various times after completion of the pavement project for subsequent analysis.

During construction, it was difficult to maintain the profile of the drainage blanket layer due to rutting or displacement and compaction of the first base course of the bituminous pavement. The drainage blanket profile was maintained by shaping and rolling in front of the paving operation. The first course of the bituminous base tended to spread under compaction by nearly one foot on each side of the mat. While some spreading was to be expected, this was excessive and due largely to the movement of the untreated drainage blanket under the base placement action.

A subsequent observation made after two (2) years service, during a light rain, showed the drainage system to function well but in need of outlet maintenance. There was good flow from the open outlets. Fully one-half of the outlets were effectively plugged with grass and debris. In more than one case, grass roots and film-like deposits in the rodent screen plugged the outlet so that when the screen was partially removed water spewed several millimeters (inches) into the air under the pressure. The system obviously was under several millimeters (inches) of head. There were no significant pavement distresses observed at this site during the monitoring period.

4.3.3.b US 127, Franklin County

The realignment of US 127 in Franklin County, from the Anderson/Franklin County line extending north through the I-64 interchange, included drainage blanket throughout the entire 8.0-km (5-mi) section. Four separate designs were incorporated in the project. One design section was 238 mm (9.5 in.) of Class K bituminous concrete on 100 mm (4 in.) of untreated drainage blanket on 200 mm (8 in.) of stabilized aggregate base on 200 mm (8 in.) of lime treated subgrade. The second section was the same design except that the drainage blanket was asphalt treated. Section three had a design section of 262 mm (10.5 in.) of Class K on 100 mm (4 in.) of asphalt treated blanket on 125 mm (5 in.) of stabilized aggregate base on 200 mm (8 in.) of lime treated subgrade. The fourth section extended from Station 309+20 to 364+70 and had 262 mm (10.5 in.) of Class K on 100 mm (4 in.) of asphalt treated blanket on 125 mm (5 in.) of stabilized aggregate base on an untreated subgrade.

Field monitoring of this site included in-place nuclear density tests performed on the lime treated subgrade, stabilized aggregate base and asphalt treated blanket. Material was collected to remold laboratory specimens and specimens were compacted in the field for flow rate testing and resilient modulus evaluation in the laboratory. Falling Weight Deflectometer testing was performed on the different structure layers as construction progressed and on the surface at various times since completion of construction.

A visual survey of the site during a heavy rainfall revealed that more than one-half of the outlets inspected had some obstruction to free discharge of collected water and nearly 40 percent had severe obstruction to free flow. The severe obstruction was usually due to ponding of water at the drainage outlet as a result of the outlet being placed at nearly the same level as the ditch, and in some cases caused the the outlet to be submerged. At outlets with less severe obstructions (headwalls filled with shoulder materials and/or grass), removal of the obstruction permitted free flow. There were some instances of outlets with no discharge and were suspected of being damaged during construction.

4.3.3.c I-264 (Waterson Expressway), Jefferson County

Construction of a rigid pavement (Portland cement concrete) with an asphalt stabilized drainage blanket was monitored at two sites in Jefferson County, Kentucky. The sites were included in the widening of I-264 (Waterson Expressway). Design for both sites was 275 mm (11 in.) of PCC on 100 mm (4 in.) of asphalt treated blanket on 100 mm (4 in.) of dense graded aggregate. At the Breckinridge Lane site, a very soft subgrade was replaced with 300 mm (12 in.) of Number 3 stone (63 mm {2.5 in} top size) and covered with a filter fabric. At the Shelbyville Road site, the subgrade consisted of a mixture of shot rock and soil. During construction, it was difficult to maintain the profile of the asphalt treated drainage blanket layer due to and inability to properly trim the material. The inability to maintain a sufficient profile could lead to overruns or underruns on PCC pavement quanities.

Falling Weight Deflectometer data were collected on the layers as construction proceeded and after the PCC pavement was cured. The high modulus (up to 82,735 MPa {1,200 ksi}) of the PCC pavement prohibited using FWD data to backcalculate underlying layer moduli.

5.0 SUMMARY

5.1 Flow Tests

The apparatus constructed for testing flow rate of drainage blanket materials functioned satisfactorily. In tests involving untreated or Portland cement stabilized materials, flow rate results were repeatable through dozens of measurements. The test procedure, as used, that is with Number 10 retaining screens on both ends of specimens, appears to be accurate from 9,150 m/day (30,000 ft/day) to rates as low as 20 m/day (70 ft/day). Specimens having flow rates less than 20 m/day (70 ft/day) were evaluated using conventional permeability testing procedures.

A series of flow tests was conducted on laboratory recombined specimens. Crushed limestone was screened and recombined to the fine limit and mid range of Kentucky Specifications gradation limits. It was determined that gradations permitting more fine material had significantly reduced flow rates at the fine limit of the specification range.

Gradation specification testing of supplier stockpiles revealed that most gradations are not within specification limits. Those that are not within specification limits, consistently contain more fine material than permitted. Because material that would almost certainly be used in constructing drainage blankets did not match laboratory recombined gradations, supplier gradations were tested for flow rate instead. Four gradations (57, 67, 8, and 610) were selected for testing. Each gradation for the test specimens was sampled from stockpiles and split to the needed amount. Specimens for the flow tests were molded from asphalt stabilized, Portland cement stabilized, and untreated material.

Flow rate tests of these specimens indicated that stabilization of either type reduces the flow rate but usually by only 610 to 915 m/day (2,000 to 3,000 ft/day). Because most of these gradations have high flow rates, stabilization of the aggregate was not deemed prohibitive to obtaining sufficient flow through the materials. Of the gradations tested, the 57 size demonstrated the highest flow rate, in the range of 3,050 to 4,575 m/day (10,000 to 15,000 ft/day). The finer 610 gradation was as low as 245 m/day (800 ft/day) for Portland cement treated material. The flow rate of the 610 gradation was considered below the minimum necessary for a drainage blanket material.

It was determined that density of the in-place material, whether untreated blanket, stabilized blanket, or bituminous pavement, had a greater impact on flow rate than either gradation or stabilization. Flow rates of drainage blankets currently being constructed are approximately 4,575 m/day (15,000 ft/day) for untreated blankets and (3,660 m/day) 12,000 ft/day for asphalt stabilized blankets. Permeabilities of filter materials and Class I base range from 0.23×10^{-7} to 2.0×10^{-4} cm/sec. Satisfactory specimens of Class K base for flow rate testing could not be produced but field experience and initial laboratory data indicate that in-place Class K base could have flow rates of 610 m/day (2,000 ft/day) or greater.

Flow rate of asphalt treated specimens confirmed that asphalt stabilized materials are subject to stripping. Stripping of the asphalt material reduces flow rate but not so sufficiently as to prohibit use of the more open materials.

5.2 Resilient Modulus Tests

Resilient modulus test results indicated that for asphalt treated drainage blanket materials, the Number 57 gradation yields the highest resilient modulus at approximately 540 MPa (78,000 psi) while other gradations yield slightly lower moduli averaging 380 MPa (55,000 psi). Given the same quality of aggregate, the resilient modulus of asphalt stabilized materials depends more on density of the specimen than on the gradation of the aggregate.

The resilient modulus of Class I base ranged from 1,300 to 1,600 MPa (189,000 to 232,000 psi) at a density of 2,325 kg/m^3 (146 lb/ft^3). Class K base was difficult to compact and had lower resilient moduli of 890 to 1,300 MPa (129,000 to 188,000 psi) at densities ranging from 1,895 to 1,990 kg/m^3 (118 to 124 lb/ft^3).

While recognizing that DGA yields low moduli in an unconfined condition, all specimens were tested under the same conditions of stress and confinement. DGA specimens indicate resilient moduli significantly lower than other materials at 50 to 100 MPa (7,000 to 14,000 psi). Stabilized aggregate base yields resilient moduli of 35,470 to 41,365 MPa (5,000,000 to 6,000,000 psi) and Portland cement stabilized Number 57 gradation yields moduli of 9,650 to 13,790 MPa (1,400,000 to 2,000,000 psi). Wet cure versus plastic cure did not significantly affect the moduli of Portland cement stabilized drainage blankets.

5.3 Construction and Performance Evaluations

Evaluations of existing and newly constructed pavements incorporating drainable base layers encompassed monitoring construction and engineering performance of subgrade, filter, drainage blanket, asphaltic concrete pavement and Portland cement concrete pavements. Monitoring construction of pavement systems involving drainage blankets involved documenting construction problems, successes, and techniques while monitoring engineering performance included measuring in-place densities during construction, conducting Falling Weight Deflectometer (FWD) tests, performing pavement distress surveys, determining rutting, rideability indices (RI), and monitoring in-place drainage. Performance and maintenance histories (up to 16 years) of pavements utilizing drainage blankets were also documented.

Overall, it was found that collector system outlets, at both existing and newly constructed sites, were not maintained properly and sometimes were either poorly designed or wrongly installed. Excluding the AA Highway, most outlets were not draining properly due to either siltation in the headwall, vegetation in the headwall, damage to the outlet pipe, or ponding in the ditchline. Ponding is sometimes due to blockage in the ditch but design at two of the sites allowed outlet headwalls to be placed level with the original ditchline elevation. Headwalls were observed with water ponded above the outlet pipe elevation.

6.0 CONCLUSIONS and RECOMMENDATIONS

Considerable monitoring, testing, and analyses were performed during this study. The effort to develop an appropriate apparatus and procedure for flow rate testing of open graded materials was successful. Test results were repeatable for flow rates ranging from 20 m/day to more than 6,100 m/day (70 ft/day to more than 20,000 ft/day).

The current "Special Note For Pavement Drainage Blanket" provides for the optimum gradation for both drainage and stability in an asphalt treated drainage blanket. Asphalt treated specimens compacted to densities typical of field conditions, 1,685 to 1,765 kg/m^3 (105 to 110 lbs/ft^3), indicate flow rates ranging from 3,355 to 4,270 m/day (11,000 to 14,000 ft/day). At these densities, structural stability of the blanket, as measured by laboratory resilient modulus tests, is approximately one third that of a Class I base which results in a structural coefficient of 0.15 to 0.16 for the asphalt treated blanket. Backcalulated layer moduli of treated drainage layers, determined from in-situ tests with the FWD, ranged from 0.14 to 0.22. Compaction of the asphalt treated blanket during construction soon after placement would increase density and provide increased stability with more than sufficient drainage capability and result in higher structural coefficients.

Stripping of asphalt treated laboratory specimens was observed. The long-term effects of stripping on flow rate and stability have not been fully evaluated. Further evaluations of the long-term effects of stripping of asphalt treated drainage layers is recommended.

Untreated drainage blankets provide good drainage (4,575 to 4,880 m/day) {15,000 to 16,000 ft/day} but presented construction problems. Backcalulated structural layer coefficients of untreated drainage blankets constructed of 57 gradation aggregates were not as variable as asphalt treated drainable base layers and exhibited similar values, ranging from 0.18 to 0.22. However, because of the enhancement provided to the construction process, it is recommended that drainage layers continue to be constructed with asphalt treated aggregates.

Portland cement treated drainage blankets have not been used in Kentucky. Laboratory tests indicate that the drainage capability of a cement treated blanket could be greater than an untreated blanket and the resilient modulus would be much greater than bituminous pavement, however, frost susceptibility may be a problem. Curing of cement treated blanket by either covering with plastic or misting, appears to produce similar strengths in laboratory specimens. Construction of a Portland cement treated drainage should be considered and evaluated as an enhancement to the overall pavement structure.

Pavement drainage systems are limited to the capability of the slowest draining component which, in the case of current construction in Kentucky, is the collector system. It was found that collector system outlets are typically not maintained properly and are often poorly designed or constructed wrongly. Excluding the AA Highway, most outlets were not draining properly due to either siltation in the headwall, vegetation in the headwall, damage to the outlet pipe, or ponding. Ponding is sometimes due to blockage in the ditch but design at two of the sites allowed outlet headwalls to be placed level with the original ditchline elevation. Headwalls were observed with water ponded above the outlet pipe elevation. All headwalls should be at least 150 mm (6 in.) higher than the ditchline elevation.

Maintaining the collector system and it's outlets is of extreme importance. It is recommended that a regular preventative maintenance scheduled be developed and implemented at the District level to ensure optimum performance of the drainage system. Training opportunities should be made available to District personnel in this area.

Based on observations made during this study, daylighting the drainable base layer is a viable alternative to a drainage blanket that incorporates a collector system. Initial concerns of Transportation Cabinet personnel of siltation and vegetation in the daylighted blanket appear to be unfounded based on the performance of a daylighted blanket on the AA highway. However, untreated blankets that are daylighted should be afforded some means of protection from traffic encroachment to prevent raveling of the base layer. The Transportation Cabinet should investigate the economics of drainable layers having a collector system versus daylighting the drainage layer.

While properly constructed pavement drainage systems have been observed to remove water from the pavement structure rapidly, pavement performance histories do not necessarily validate the expectations of increased pavement life. All study sites except Ky 55 in Taylor County, are fairly new and have not required rehabilitation at this time; however, distress surveys of the AA highway indicate that sections having drainage blankets might be deteriorating more rapidly than sections having no drainage blanket. Additional monitoring and evaluations should be conducted to assess the effectiveness of drainable layers to increase pavement life.