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Performance Evaluation of Military Airfield Pavement Drainage Layers

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Abstract: A performance evaluation of drainage layers was conducted during the period of August to November 2008 at three U.S. Air Force bases to determine if the in-place performance justifies their required use on military airfield pavements. Evaluation procedures included the artificial introduction of water into the pavement structure and observation of outflow. Flow and time measurements were recorded and analyzed to determine if the provided permeability of each drainage layer satisfies the current design criteria. Results from this evaluation showed that design and construction, as well as maintenance have important roles in the functionality of airfield pavement drainage layers. Several pavement areas tested were not functioning properly. However, permeability rates through the drainage layers meeting the aggregate gradation specifications were within acceptable limits. It was concluded that the use of drainage layers in military airfields is beneficial, but should be required only on areas where climatic conditions represent a potential of water entering and causing problems in the pavement system. Historical pavement surface condition data were also analyzed, but not enough surface deterioration was observed because the drainage layers studied had not been in place long enough to show any differences in performance from pavements constructed without drainage layers. An additional evaluation of long-term pavement performance was recommended to be considered in the future.

***Key words**: Pavement drainage layers, Pavement evaluation, Subsurface drainage.*

Introduction

Placement of a drainage layer beneath the pavement surface is the most commonly used method to remove water from airfield pavements. The drainage layer's permeability converts the vertical inflow from precipitation into horizontal flow, which is moved away from the subgrade material and collected by a longitudinal collection system.

The use of drainage layers to improve the subsurface drainage in military airfield pavement systems has become a common practice. However, as the construction and installation of drainage layers has increased, so have the discussions of their performance. Some of the issues under discussion are constructability, cost, and maintenance.

The objective of this study was to evaluate the performance of in-service drainage layers in airfield pavements. Three airfield pavements constructed with drainage layers were evaluated. The evaluation consisted of artificial infiltration of water into the drainage layer followed by observations of flow rates and pathways. Flow rates were determined by measuring input and discharge rates of water through the drainage system. Ground Penetrating Radar (GPR) was used to determine changes in moisture in the drainage layer to determine the flow path. This paper provides field testing procedures, data analysis, and conclusions to address the observed performance of airfield subsurface drainage systems.

Background

Several studies have evaluated pavement subsurface drainage systems [1-6]. These studies recognized that water has a detrimental effect on pavement performance. In the design of pavement subsurface drainage systems, water is considered to come from two sources: infiltration of surface water and subterranean water. Surface water is usually the principal source. Surface water from precipitation infiltrates the pavement surface and enters through cracks or joints in the pavement or through shoulders from adjacent areas. Subterranean water can come from a high water table, capillary forces, artesian pressure, and freeze-thaw action.

One of the main causes of flexible pavement failures is the weakening of the base, subbase, or subgrade from saturated or partially saturated conditions [3]. In rigid pavement, the main cause of water-induced failures is the pumping of the subgrade material to the surface. Pumping occurs when free water, trapped between the bottom of the rigid concrete layer and the impermeable subgrade, moves due to pressure caused by loading. This movement erodes the subsurface material, creating voids beneath the concrete layer [5].

In seasonal frost areas, subsurface water can contribute to frost damage by heaving during freezing and weakening the subgrade during thawing. Secondary damages caused by poor drainage include D-cracking and swelling of subsurface materials.

Hall and Crovetti [6] conducted an evaluation of the effects of subsurface drainage on pavement performance for the National Cooperative Highway Research Program (NCHRP). A procedure for field testing the rate of flow of water through a permeable base with edge drains and outlets was developed from this study. They assumed a flow plume width away from the core hole and the permeability calculated was a function of that plume. This method showed the necessity to include some type of radar equipment in the evaluation to measure the width of the flow plume through the drainage layer. Results from this evaluation showed that some of the drainage systems were not functioning properly due to lack of maintenance. At many of the sites evaluated, the outlet headwalls were unmarked and obscured by tall vegetation. Some were completely covered by dirt, gravel and vegetation that had to be dug out with hand tools. The lack of outflow in these sites led the

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authors to conclude that water never moved laterally from the base into the edge drains and to the outlets, but rather flowed downward into the subgrade soil due to any blockage along the flow path. However, no construction or design issues were observed. The performance of drainage layers with measurable outflow was good and flow measurements provided an idea of the functioning of the whole drainage system.

All drainage studies agree that water infiltration into the pavement structure cannot be completely stopped by most practical means. Subsurface drainage systems are required to move the water away from critical pavement layers at an acceptable rate without compromising the strength of the pavement system. The U.S. Army Corps of Engineers provides guidance for planning, designing, constructing, sustaining, and restoring subsurface drainage systems in Unified Facilities Criteria (UFC) 3-320-06A [7]. The next paragraphs give an overview to the airfield pavements subsurface drainage design criteria.

Overview of the Subsurface Drainage Design Criteria

The design of a subsurface drainage system (using drainage layers) consists of selecting a material with sufficient permeability to provide rapid drainage and yet provide sufficient stability to withstand load induced stresses. The design criteria establish that a material with a permeability of 305 m/day (1,000 ft/day) will provide sufficient drainage for most application. Other important design components consist of the base material, a separating filter layer to prevent contamination, and a collection and removal system (e.g., edge drains). However, the designer must have an understanding of the environmental conditions (rainfall and frost penetration) and subsurface soil properties (permeability, frost susceptibility, and groundwater conditions) to ensure the success of the subsurface drainage system.

Current criteria require all airfield pavements not meeting the following criteria to have a subsurface drainage system:

- pavements in non-frost areas and having a subgrade with permeability greater than 6.1 m (20 ft.) per day, and
- flexible pavements in non-frost areas and having a total thickness of structure above the subgrade of 20.3 cm (8 in.) or less.

Even when a pavement meets the exemption requirements, a drainage analysis should be conducted for possible benefits of including the drainage system.

The subsurface drainage system must be capable of handling infiltrated water from a design storm of 1-hour duration at an expected return frequency of 2 years. The water inflow is the product of the storm index (*R*) multiplied by an infiltration coefficient (*F*) that can be obtained from tables in the drainage criteria.

Pavement drainage layers are designed based on two capacities: 1) the capacity of the drainage layer to serve as a reservoir for the excess water entering the pavement, or storage capacity (q_s) and 2) the capacity of the drainage layer to drain water during a rain event, or drainage capacity (q_d). The storage capacity of the drainage layer is a function of the effective porosity (n_e) of the drainage material and the thickness (*H*) of the drainage layer. If it is considered that not all water will be drained from the drainage layer, then the storage capacity will be reduced by the amount of water in the layer at the start of the rain event. UFC 3-320-06A requires 85 percent of the water to be drained from the drainage layer within 24 hours; therefore, it is conservatively assumed that only 85 percent of the storage will be available at the beginning of a rain event.

Table 1. Design Properties of Materials used for Drainage Layers.

Property	RDM	OGM
Material Gradation		
Sieve Designation, mm (in.)	Percent Passing	
38.1 (1-1/2)	100	100
25.4 (1)	70-100	95-100
19 (3/4)	55-100	--
12.7 (1/2)	40-80	25-80
9.5 (3/8)	30-65	--
No. 4	10-50	0-10
No. 8	0-25	0-5
No. 16	0-5	--
Permeability, m/day (ft/day)	305 – 1,524 (1,000-5,000)	> 1,524 > (5,000)
Effective Porosity	0.25	0.32
Percent Fractured Faces (COE Method)	90% for 80 CBR 75% for 50 CBR	90% for 80 CBR 75% for 50 CBR
Uniformity Coefficient (C_u)	> 3.5	--
LA Abrasion	< 40	< 40

The amount of water which will drain from the drainage layer during a rain event is a function of the duration of the rain event (*t*), the permeability of the drainage material (*k*), the slope of the drainage layer (*i*), and the thickness of the drainage layer (*H*).

The time required for drainage is controlled by the material type and the length and slope of the drainage path. Providing a more open drainage material would decrease the time for drainage, but it can also decrease the stability of the layer for construction. Therefore, the drainage material must be as dense as possible to avoid pavement performance problems. The slope of the drainage path depends on the geometry of the pavement surface, since it is usually placed parallel to the surface. Another way to reduce the drainage time is to reduce the length of the drainage path by placing longitudinal and transverse collector drains. In summary, the design of the drainage layers involves matching the drainage material type with the drainage path and slope to meet the criteria for the drainage time.

For most drainage layers, the materials should have a minimum permeability of 305 m/day (1,000 ft/day). Rapid draining material (RDM) and open graded material (OGM) are two materials that are used in drainage layers. Their gradations and design properties are given in Table 1.

The RDM has sufficient permeability (305 to 1,524 m/day (1,000 to 5,000 ft/day)) to serve as a drainage layer and will also have the stability to support construction traffic and the structural strength to

Fig. 1. Field testing procedures.

serve as a base or subbase. The OGM has a very high permeability (>1,524 m/day (>5,000 ft/day)), but normally requires stabilization to support vehicle traffic during construction. Stabilization is accomplished mechanically by the use of choke stone or by the use of a binder such as asphalt or Portland cement.

In summary, material properties, design, and construction all are important to provide an adequately performing subsurface drainage layer. This paper describes an evaluation conducted to determine if in-service pavement drainage layers are functioning according to the design criteria.

Field Test Procedures

The main objective of the field tests was to evaluate the efficiency and performance of in-service drainage layers in military airfields by measuring the water flow and accumulation. Test locations were selected by identifying military airfields containing subsurface drainage layers. Once the airfields were selected, construction drawings, airfield pavement condition survey reports and non-destructive testing evaluation reports were used to identify the specific airfield pavement sections to test. Construction drawings were used to determine the pavement profile and to locate the outlet structures and manholes.

A core rig with a cutting barrel diameter of 15.2 cm (6 in.) and length of 38.1 cm (15 in.) was used to core a cylinder through the pavement surface (Fig. 1-a). For asphalt concrete pavements, base course above the drainage layer was removed by hand. Pavement material was removed until the drainage layer was exposed. A 1.5 m (5 ft.) section of PVC pipe with a diameter of 10.2 cm (4 in.) was placed on top of the drainage layer. The gap between the pipe and the pavement in the core hole was sealed with polyurethane foam (Fig. 1-b). After the foam set (20 min), a 5.1 cm (2-in.)-diameter hose was placed in the PVC pipe (Fig. 1-c). The hose was connected to a flowmeter (Fig. 1-d) that was connected to the water truck. PVC pipe was filled with water to increase the pressure head. The initial flowmeter reading was recorded. Water flow was initiated and allowed to reach the maximum that the drainage layer could accommodate without water overflowing the PVC pipe. The water flow was then reduced to a steady-state rate, maintaining a water column inside the PVC pipe. Water volume and time were recorded periodically as water was allowed to flow into the pavement. Once water outflow was observed at the nearest outlet, a tracer dye was added to the inflowing water and, when observed, the outflow water was collected at the outlet structure (Fig. 1-e). The following times were recorded: (1) time water input began, (2) time when outflow was first observed, (3) time when tracer dye was added, (4) time when tracer dye outflow was observed, (5) time when water inflow was stopped (6) time when observed water outflow ceased.

During the test, a GPR manufactured by Pulse Radar, Inc. with a 1 GHz antenna (Fig. 1-f) was used to establish moisture lateral extents underneath asphalt concrete pavements. The moisture lateral extents were monitored by collecting measurements in a grid pattern to plot a two-dimensional moisture lateral extent. The changes in the moisture lateral extents were documented during saturation of the drainage layer.

Once the test was finished, the PVC pipe was removed and material from the drainage layer was collected from the hole for characterization. Subgrade material was also collected at each airfield for characterization.

Test Sites

The field evaluation of in-service drainage layers began in August 2008 at the Elmendorf Air Force Base (AFB) in Anchorage, Alaska. A second field evaluation was conducted at Tinker AFB in Oklahoma City, Oklahoma, in September 2008. Field testing concluded in November 2008 at Biggs Army Airfield (AAF) in Fort Bliss, Texas. The three locations represent specific regions of the country. Elmendorf AFB, Alaska, was chosen as a location where the subgrade is subjected to freezing and thawing cycles of the soil. Frost heave from freezing and weakening during thaw periods are concerns that warrant inclusion of drainage layers at this location. Tinker AFB, Oklahoma, is located in a moderate semiarid climate where the natural subgrade materials are expansive soils. In the pavement structure, preventing water from reaching this type of subgrade is expected to reduce swelling problems. Finally, Biggs AAF, Texas, is located in a desert climate. This type of climate receives minimal rainfall during the year and may not benefit from the incorporation of drainage layers. Table 2 presents a description of each test site at each test location.

Field Observations

Table 2. Test Sites Description.

Site No.	Description	Year Constructed	Pavement Structure Design	Drainage Layer Description
Elmendorf AFB				
E-1	Fuel Cell Taxiway	2004	10.2 cm (4 in.) AC 15.2 cm (6 in.) Aggregate Base 10.2 cm (4 in.) Drainage Layer	Asphalt Stabilized Drainage Layer Daylighted to the Pavement Shoulders
E-2	C-130 Apron		10.2 cm (4 in.) AC 15.2 cm (6 in.) Aggregate Base 10.2 cm (4 in.) Drainage Layer	Asphalt Stabilized Drainage Layer with Edge Drains
E-3	Weather Shelter Apron		34.3 cm (13.5 in.) PCC 15.2 cm (6 in.) Drainage Layer	RDM with Edge Drains
Tinker AFB				
T-1	Taxiway Bravo	2005	38.1 cm (15 in.) PCC 10.2 cm (4 in.) Drainage Layer 20.3 cm (8 in.) Stabilized Aggregate Base 15.2 cm (6 in.) Lime Stabilized Subbase	RDM with Edge Drains
Biggs AAF				
B-1	DAACG Ramp	2002	40.6 cm (16 in.) PCC 15.2 cm (6 in.) Drainage Layer	RDM with Edge Drains

Elmendorf AFB, Anchorage, Alaska

The evaluation at Elmendorf AFB in Anchorage, AK, was conducted from 23 to 26 July 2008. Pavement drainage layers evaluations were performed on the Fuel Cell Taxiway, the C-130 Hangar Apron, and the Weather Shelter Apron. Descriptions of each pavement area are given below.

E-1

The drainage layer beneath this pavement is “daylighted” to the pavement shoulders. Daylighted drainage layers are those that are openly exposed to the environment at the pavement edge. Water is expected to flow transversely to the traffic direction and flow out of the pavement shoulders. This type of drainage design is sometimes used in highway pavements but is not recommended as a drainage system in UFC 3-230-06a.

For the evaluation, the core hole was drilled slightly offset from the centerline of the taxiway to allow only one direction of flow from the introduced water. The core was removed along with the base course to expose the asphalt stabilized drainage material. A grid was outlined on the pavement surface from the centerline to the pavement shoulder parallel to the direction of traffic for surveying the section with the GPR. Initial scans with the GPR were made to provide baseline data.

To evaluate the permeability of the drainage layer, water was placed in the pipe at a constant rate as it flowed into the drainage layer. The discharge rate was adjusted initially to provide a constant 0.6-m (2-ft.) head of water in the pipe.

Permeability testing was conducted on the dense graded base course between the asphalt concrete layer and the stabilized drainage layer to provide data for comparison. The same water flow measurement procedure was followed. The resulting flow rate into the base course was 1.9 L/min (0.5 gal/min).

The GPR was used to visualize the moisture profile in the pavement section during the introduction of water. Data were

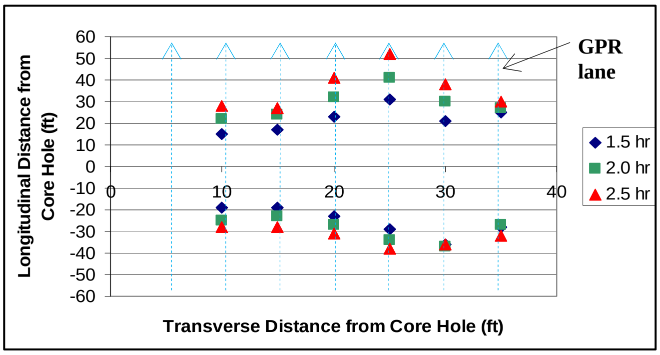

Fig. 2. Moisture Profile in Drainage Layer from GPR Data.

collected by scanning the parallel lanes at different time intervals. The lanes were spaced 1.5 m (5 ft.) apart. Data were analyzed to determine the point in the lane where moisture was detected by the GPR. Additionally, the point was recorded where moisture was no longer detected. Recording these points for each lane provided the ability to create a 2-dimensional map of the moisture in the drainage layer. The moisture profiles for the pavement section at different time intervals are shown in Fig. 1. Only the points along the lane where the appearance and disappearance of moisture are noted, and all of the space between these points contain moisture. These data were used to determine the width of the area through which the water was moving. As the water was introduced into the core hole, it spread uniformly in all directions. As equilibrium in flow was established, the plume of water was fixed as indicated in Fig. 2. Only small changes in the width were observed in subsequent scans.

The GPR did an excellent job at detecting the location of water moving through the drainage layer. The flow was observed to form a plume of approximately 15.2 m (50 ft.) nearest the core hole and approximately 27.4 m (90 ft.) at a distance of 7.6 m (25 ft.) from the core.

After approximately 2.5 hours and the introduction of 3,407 L (900 gal.) of water, moisture was noticed emerging from the daylighted edge of the drainage layer. However, GPR data indicated that the water had reached the pavement shoulder after 1.5 hours of flow.

E-2

The drainage layer beneath this pavement was designed to flow towards a collection pipe and then discharge into a drainage basin adjacent to the apron area. Water was expected to flow underneath the apron pavement until it reached the drain pipe. A visual inspection of the drainage basin showed no evidence of a discharge pipe. According to UFC 3-230-06a, a headwall should be installed at the discharge pipe to protect it from damage and allow access for maintenance. No such structure was located.

For the evaluation, the core hole was drilled 7.6 m (25 ft.) from the expected location of the drainage pipe. In this section, the GPR data did not show moisture in the pavement distinctive of a flow pattern. After monitoring the area several times with no evidence of flow, the GPR data collection attempts were discontinued.

The area adjacent to the pavement section where the outflow pipe was expected to be located was observed for evidence of discharge. The inflow water was treated with a dye to impart an intense color for observation. After 2.5 hours and the introduction of 3,028 L (800 gal.) of water, no visual evidence of outflow existed.

E-3

The drainage layer beneath this pavement was designed to flow toward a collection pipe and then discharge into a drainage basin adjacent to the apron area. Water was expected to flow underneath the apron pavement until it reached the drain pipe. A large drain pipe set in a head wall was identified and observed during the evaluation.

For the evaluation, the core hole was drilled 59.4 m (195 ft.) from the end of the drainage pipe. In this case, flow into the drainage layer was limited by the maximum discharge rate of the gravimetric flow from the water truck. Less than a 1-ft head of water was maintained in the pipe.

At this location, the GPR was not used to observe the moisture profile in the drainage layer. The GPR was unable to penetrate through the thick PCC pavement to provide discernable differences in moisture.

The area adjacent to the pavement section where the outflow pipe was located was observed for evidence of discharge. After nearly 2 hours and the introduction of 3,028 L (800 gal.) of water, no visual evidence of outflow existed.

The parking apron had been extended after initial construction in 1992. A new pavement section was added to the apron where the outflow pipe was located. The pipe may have been damaged during the construction of this addition.

Tinker AFB, Oklahoma City, Oklahoma, T-1

The drainage layer in Taxiway B was asphalt stabilized. According to a sieve analysis of extracted material, the gradation corresponded to a RDM as shown in Table 1, and the expected corresponding permeability (Table 1) for a RDM was between 305 and 1,524 m/day (1,000 and 5,000 ft/day). The gradation curve also shows 23 percent sand, which falls outside the limits of the specification band. However, drainage layer permeability did not appear to be affected by this high sand percentage. This could be related to particle breakage during the process of extracting compacted drainage material from the core hole.

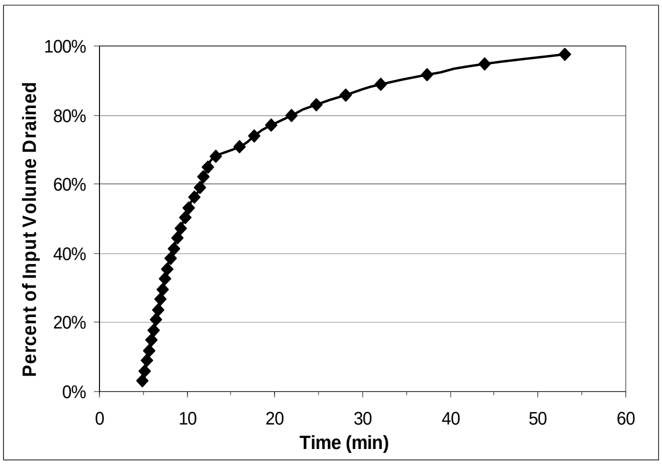

Fig. 3. Percent of Total Input Volume Collected at the Outlet Over Time.

Water was placed into the drainage layer through a core hole. The water flow rate was first adjusted to the maximum that the permeable asphalt-treated base could accommodate without water overflowing the PVC pipe. The flow was then reduced in such a way that a water column of 1.2 m (4 ft.) was maintained inside the PVC pipe. Water was allowed to flow into the drainage layer until it was observed flowing out of a storm drain pipe at the inlet box. This process took approximately 5 min.

A total volume of 644 L (170 gal.) was added from the time of the addition of tracer dye until the water inflow was stopped. The tracer dye outflow was collected with a 19-L (5-gal.) bucket, and then the time to fill each bucket was recorded. This procedure was used to determine time required to drain the porous layer. It can be seen from Fig. 3 that the input volume (644 L (170 gal.)) was almost completely drained in about one hour, which indicates that water retention was minimal or negligible. No flow obstruction was observed.

Biggs Army Airfield, Fort Bliss, Texas, B-1

The drainage layers evaluation at Biggs AAF at Fort Bliss, Texas, was conducted from 17 to 20 November 2008. The drainage layer beneath the DAACG Ramp was selected for testing. The drainage layer consisted of RDM directly beneath the PCC surface layer.

An outflow pipe was located on the northwest corner of the apron. The pipe led from a manhole to a drainage basin. Two pavement drainage pipes were located under the shoulder running parallel to the west and north edges of the apron. These pipes emptied into the manhole. The overall layout of all pipes underneath the pavement was not known. The pavement sloped towards the northwest corner at a slope conducive to flow. The collector drainage pipes had a diameter of 20.3 cm (8 in.). They were made of PVC and contained uniformly spaced holes for water entry. They were wrapped with a geotextile to prevent clogging.

Table 3. Flow Measurement Results.

Site No.	Input Flow Rate L/min (gal/min)	Assumed Flow Plume Width m (ft)	Flow Length m (ft)	Estimated Permeability[1] m/day (ft/day)
E-1	22.7 (6.0)	15.2 (50)	18.3 (60)	634 (2,079)
E-2	19.7 (5.2)	15.2 (50)	7.6 (25)	229 (750)
E-3	28 (7.4)	15.2 (50)	30.5 (100)	865 (2,837)
T-1	89 (23.5)	1.2 (4)	2.4 (8)	1,227 (4,026)
B-1	12.5 (3.3)	---[2]	---[2]	---[2]

[1] Calculated using Darcy's Law: $k = Q/i.A$, where Q is the maximum inflow rate (ft^3/day), i is the hydraulic gradient (elevation head divided by the flow length), and A is the cross sectional area of flow (thickness of drainage layer multiplied by the assumed width of flow plume).
[2] Permeability was not estimated because field observations showed that water was flowing in the opposite direction, which could have affected the flow measurements.

An area of exposed soil down slope from the outflow pipe was experiencing erosion from water flow. The erosion was thought to originate from water flowing from the drainage system. However, closer inspection revealed soil erosion on top of the outflow pipe and the observation that all surface runoff travels through the location. The erosion could have occurred even if no water was flowing through the drainage system.

Water was introduced into the drainage layer through a core hole at the maximum rate to sustain a constant 1.2 m (4 ft.) head of water in the pipe. Water was placed in the core hole at a constant input rate of 12.5 L/min (3.3 gal/min). A total of 3,028 L (800 gal.) of water was pumped into the core hole. No flow from the drainpipe at the manhole was observed.

The following day, a core was taken near the edge of the PCC slab in a corner of the apron. Removal of the core hole revealed only subgrade soil beneath the PCC. Water placed in the core hole did not drain during 15 minutes of observation.

An additional core was taken on the opposite side of the PCC slab. Removing the core exposed the drainage layer beneath the PCC. Some material was removed for testing. A constant input rate of 9.5 L/min (2.5 gal/min) was placed into the core hole. A total of 2,271 L (600 gal.) of water was pumped into the core hole. No flow from the drainpipe at the manhole was observed.

A total of 5,300 L (1,400 gal.) of water was placed underneath a small corner of the apron pavement with no observed flow through the drainage pipes. The research team decided to core an additional hole within 0.3 m (1 ft.) of the drainage pipe in an attempt to induce flow. This core was taken in the shoulder pavement area. The asphalt concrete surface was 7 cm (2.75 in.) thick. Beneath was a similar material to the drainage layer. The material was disturbed with a metal rod and removed to a total depth of 0.61 m (2 ft.). Drilling beneath this depth contacted subgrade soil. Water was placed in the hole until the level reached that of the asphalt concrete surface. After 5 min, no visible evidence of drainage was observed. The base material beneath the asphalt concrete shoulder pavement did not have sufficient permeability to promote flow.

The low permeability of the material underneath the shoulder prevented flow to the drainage pipe. The water placed underneath the slabs was trapped and likely remained in a saturated state in the drainage layer. Additionally, aggregate gradations of the drainage material show that the gradation falls outside the limits of the specification band given in UFC 3-260-06. The material used at Biggs AAF contains too much fine aggregate. The excessive portions of fine aggregate fill the void spaces and reduces the permeability of the drainage layer. Some vertical flow through the subgrade was expected given the soil type. It is important to recognize that only a very small area was observed in respect to the overall drainage system. Additional testing would be required to definitively assess the performance of the pavement drainage system.

After the evaluation, water was placed in the manhole to observe the flow through the outlet pipe. At this time, researchers noticed that water was flowing into the drainage pipes. The pipes had an inverted slope at the manhole. Water eventually filled the pipe to the point where flow proceeded in the expected direction. It was expected that the pipe was raised to meet the elevation of the manhole. Some water cannot escape the drainage system as a result of this construction error.

Permeability of the Drainage Layers

Permeability of the drainage layer on each test site was estimated using Darcy's Law and assuming the width of the water plume through the drainage layer. In the cases where the GPR provided moisture lateral extents, the plume width was estimated from the GPR measurements. Table 3 presents the results from the flow measurements and permeability estimation for each test site evaluated.

From Table 3 it can be observed that most of the sites evaluated meet the design criteria for design of the system and permeability (>305 m/day (>1,000 ft/day)). However, in most of these cases, lack of maintenance was observed, which may have caused obstruction to the water flow. Three cases (E-1, E-2 and B-1) failed in meeting the design and, thus, the permeability criteria. In one site (E-2), no headwall or outlet pipe was observed, and in the other (B-1) the slope of the pipes was inverted at the manhole structure and the soil around the edge drain was not permeable. This prevented water from traveling through the drainage layer to the edge drain. In these two cases it could be expected that the water was retained in the drainage layer until it reached its maximum storage capacity, then it could have started flowing downward to the subgrade. This problem can cause failures in the pavement structure as traffic is applied to it. Test site E-1 failed meeting the design criteria; however, the design used in this case proved to satisfy the permeability requirements and promises better results with less issues related to maintenance.

These observations show that sometimes failing to meet the design criteria can affect not only the performance of the drainage layer, but also that of the whole pavement system.

Discussion

Elmendorf AFB, Alaska

1. Not all pavement drainage systems were designed and constructed to the UFC criteria. The following are specific examples:
   a. E-1 was constructed with a daylighted drainage layer. This type of system is not allowed according to the criteria. Researchers acknowledge that subsequent construction will widen the taxiway and that alternate designs were not feasible.
   b. The outlet pipe carrying water from E-2 was not constructed with a protective headwall.
2. Maintenance of the drainage layers did not occur. The outlet pipe at E-2 could not be located. Only regular grass cutting was performed at the outlet pipe from E-3. The drainage system at E-1 did not require maintenance, since water could escape through the entire length of the taxiway from the daylighted drainage layer.
3. During testing of E-1, water flowed from the center of the taxiway to the end of the drainage layer in approximately 2.5 hours. The total travel distance was 18.3 m (60 ft.). No water was observed flowing out of the pavement aprons at E-2 or E-3.
4. The outlet pipe at E-2 was likely covered with soil and vegetation. Its location could not be determined. Personnel familiar with the construction indicated its supposed location.
5. Subsequent construction at E-3 was thought to have damaged the drainage pipes that removed water from the apron.

Tinker AFB, Oklahoma

1. Pavement drainage systems appeared to have been designed and constructed according to the UFC criteria. Outlet pipes were constructed with protective structures and coverings.
2. Maintenance of the drainage system was not evident. The condition of the drainage system on T-1 was excellent. However, this pavement was newly constructed.
3. The rate of flow through the drainage system was observed to be very rapid. The fast rate of flow was evident by the rate at which the water dye was observed at the outlet structure.

Biggs AAF, Texas

1. The pavement drainage layer material was not designed and constructed according to the UFC criteria. The gradation of the drainage layer was not within the specifications. Too much fine aggregate was present. The excess fine aggregate inhibited permeability. Other portions of the drainage system were built according to UFC criteria. The outlet pipe was constructed with a supporting and protective headwall. Drainage pipes were wrapped with geotextile fabric to prevent clogging. Geotextile fabric was also observed as a filter at the interface of the drainage layer and subgrade.
2. Maintenance of the drainage system was not evident. Vegetation and soil surrounded the outlet structure.
3. Quality assurance was not successful at achieving satisfactory construction of the drainage layer. At one location, only subgrade was found beneath the PCC. Also, the slope of the drainage pipes was inverted where they met the manhole, allowing some water to flow back into the drainage system. The base course beneath the pavement shoulder was not permeable. This prevented water from traveling through the drainage layer to the drainage pipe at the location tested. These types of construction flaws could have been prevented with adequate oversight.
4. No flow was observed from the drainage pipe after two days of introducing water into the drainage layer. The system was determined to not be operating effectively.

The observations made at each of the testing locations were used to determine conclusions and recommendations for this research. Several of the observations were similar at each location. Others specifically address an issue encountered at individual testing locations.

A lack of maintenance of the drainage systems was common during testing. Drainage structures become clogged over time because of a lack of adequate maintenance. Unmaintained drainage systems will likely provide little performance benefit.

Drainage systems were not always designed and constructed according to the UFC criteria. Issues such as improper construction of outlet pipes and improper aggregate gradation were observed. In these cases, drainage was sometimes not effective due to restricted flow. Personnel responsible for construction must consider the impacts of altering designs on the overall system. Similarly, quality assurance procedures must be in place and followed to ensure construction practices provide the intended product.

Although daylighted drainage systems are not specified by the UFC criteria, they provide an alternative construction method that requires less maintenance than using drainage pipes. They have a much greater area where water can escape the pavement in case some of the drainage layer becomes clogged. This type of design could be effective, especially on areas such as taxiways where the width of the pavement is small relative to the length.

Conclusions

The evaluation presented in this paper provided sufficient data for qualifying and quantifying the functionality of the drainage systems. The following conclusions were made based on the evaluation results:

1. The GPR is a useful tool for determining the location of moisture in the drainage layer beneath asphalt concrete pavement but, its depth of penetration is too shallow to locate moisture beneath thick PCC pavements.
2. Design and construction both play important roles in the functionality of pavement drainage layers. Improper oversight of either can lead to a poorly performing system. Several pavement areas observed in this study were not functioning properly as a result of poor design or construction. Therefore, construction should be closely monitored to ensure that the drainage layers will be functional after construction.

Specifications should be followed for all material properties and design considerations.

3. Evidence of routine maintenance of pavement drainage systems was not observed on any of the airfields evaluated in this study. The lack of maintenance could inhibit the flow of water and reduce the functionality of the drainage system. A routine maintenance program should be implemented for pavement drainage systems on airfields. Maintenance should include clearing all soil and vegetation from the flow path to prevent clogging.
4. Pavement drainage layers that are daylighted to the edge of the pavement are able to remove water through multiple pathways and are less likely to have flow interrupted by a lack of maintenance. This type of drainage system should be included in the design criteria.

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