Design and Construction of a Pavement for Tracked Military Vehicles

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SUMMARY

Paving stones typically have compressive strengths of more than 50 MPa which is substantially higher than conventional concrete which is commonly used for paved areas subjected to tracked military vehicles such as personnel carriers and tanks. They are very resistance to degradation and scuffing under aggressive traffic conditions.

This paper outlines the design and construction of a military training field in Colorado, U.S.A. In keeping with the stormwater management and LEED objectives for the project, a permeable pavement section was designed. The two primary requirements for a permeable interlocking concrete pavement system is that it meets the structural requirements to handle the expected traffic operations and that it will meet the hydrological goals for mitigating stormwater.

While the pavement was originally required for a training center and would be subjected to only occasional tracked vehicles, it was desired to have a pavement that could withstand the loading from occasional tank traffic. In addition, the pavement requirements were such that tents would be erected on the site and the openings in the pavement would have to be large enough such that tent spikes could be inserted without damaging the pavement.

Since the site is constructed on low permeability material, the main goal of the permeable pavement system was to capture, store, and slowly release storm water. Since the main peak of the storms in the area were expected to take place within a narrow 2 hour window, the permeable pavement system was designed to mitigate the peak and transform the water outflow to a much more moderate flow over a span of 24 hours or more. Given the relatively low annual rainfall in the area and the poor support clayey type subgrade, the structural capacity of the pavement was determined to be the controlling design parameter not stormwater mitigation (i.e. the thickness of pavement required for structural capacity always exceeds the requirement for stormwater storage.

As there was very little experience in designing permeable pavements for tracked vehicles, a test section was designed and then subjected to aggressive loading of an M1A1 Abrams main battle tank that uses the facility. Design details and the experience gaining from the construction of the facility are outlined in the paper.

Key Words: Paver, Heavy-Duty, Tracked Vehicle, Tank, Permeable Pavement, Structural Design, LEED.

INTRODUCTION

Conventional paving stone systems use sand in the joints between the individual paving units to provide friction and load transfer from vehicular loading over multiple paving units. This results in a semi-flexible pavement system with a hard and durable surface which is very resistance to degradation and scuffing under aggressive traffic conditions. Paving stones typically have compressive strengths of more than 50 MPa which is substantially higher than conventional concrete which is commonly used for paved areas subjected to heavy vehicles. Paving stones are the pavement of choice for ports and intermodal terminals [1-5].

Permeable paving systems have been around since before the 1970s. Early permeable pavements included a variety of systems that typically retained earth and grass in cells constructed of stone, concrete or plastic materials. While this increased the permeability and permitted some rainwater to enter the pavement, they did not provide substantial structural capacity. These types of pavements were easily damaged by frequent or heavy vehicle loading.

Modern permeable interlocking concrete pavement (PICP), has evolved to provide both high infiltration capacity and structural capacity to accommodate relatively high traffic loading. While the loading currently used is not in the range of that of conventional non-permeable pavements, engineers and designers are working to push this barrier higher and higher. In North America, permeable pavement structural design is based on the American Association of State Highway and Transportation Officials (AASHTO), 1993 Guide for the Design of Pavement Structure procedures [6,7]. An Interlocking Concrete Pavement Institute (ICPI) software application provides for both hydrological and structural design [8]. Due to limited experience with permeable pavers subjected to heavy loading in North America, current guidance is to limit the frequency of loading of permeable pavements to less than 1 million equivalent standard axle loads (ESALs). One ESAL is equivalent to an axle load of 80 kN. In Europe, permeable pavement design procedures include axle loading of up to 15 million standard axles [9].

DESIGN CONSIDERATIONS

The United States Department of the Army (Army) is planning the construction of a new facility at Fort Carson, Colorado. The Colorado Battle Command Training Center (BCTC) includes a building structure surrounded by a parking area. The parking area is approximately 2,800 m^2.

Design Requirements

The Army had some relativey unique requirements for the parking area:

- It must be possible to erect tents in the parking area. The tents would use large diameter steel spikes that wound need to be driven through the pavement and removed with minimal to no damage to the pavement;
- The pavement is intended to be "semi" permeable with penetrating water either infiltrating into the subgrade or flowing to one of the adjacement storm water management ponds;
- The pavement surface is to consist of 8 cm permeable pavers (openings to provide surface drainage and location to drive tent spikes) over a bedding layer, aggregate base and moisture conditioned subgrade over the natural subgrade;
- Tracked vehicles must be capable of using the pavement surface without any significant damage;
- The tracked vehicles must be capable of running over a tent spike without any signficiant damage to the pavement; and
- The pavement should be permeable to assist in achieving the Leadership in Energy and Environmental Design (LEED) goals of the Department of Defense (DoD).

Subgrade Conditons

The local subgrade soil for the site is composed of a low plasticity clay with a low soaked California Bearing Ratio (CBR). Geotechnical testing determined the CBR of the clay to be in the order of 2 (resilient modulus of about 25 MPa). This material is very fine and has a low permeability. Permeability testing completed for the geotechnical report indicated a percolation rate of some 15 mm per hour but this is expected to be substantially lower when compacted under the pavement structure.

Traffic

Traffic information provided includes:

27,000 kg Hermmit Wheeled Vehicle (20/day @ 65 days/year)
23,000 kg Bradley Tracked Vehicle (20/day @ 65 days/year)

The vehicle configurations are shown in Figure 1.

Figure 1a. Hermmit Vehicle

Figure 1b. M2A2 Bradley

While the loading configuration of the wheels of the Hermmit vehicle is based on four axles, the size of the tires reduces the pressure on the pavement. This is similar for the tracks of the M2A2 Bradley. Assuming a 15 year initial pavement design life and the equivalent contact pressure of the vehicle wheels/tracks, this would equate to some 178,000 equivalent single axle loads (ESALs) on the pavement.

PAVEMENT DESIGN

Pavement designs were completed for both conventional dense graded aggregates and for open graded aggregates (permeable pavement).

Dense Graded Aggregate Pavement Design

The standard dense grade aggregate pavement design was completed using the procedure outlined in the American Society for Civil Engineers (ASCE) Structural Design of Interlocking Concrete Pavement for Municipal Streets and Roadways (ASCE 58-10) [10]. This Standard Guideline applies to paved areas subject to applicable axle loads and trafficked up to 10 million 80 kN ESALs. It also provides preparatory information for design, key design elements, design tables for pavement equivalent structural design, construction considerations, applicable standards, definitions and best practices.

The design parameters are as follows:

W = 178,000 for a design life of 20 years
Z_R = -0.674 for R = 75 percent
S_0 = 0.45
a_i = structural layer coefficients:
  concrete paver and bedding sand = 0.44
  untreated dense graded base = 0.14 (meets requirements for Colorado Department of Transportation (CDOT) Class 5 or 6 base materials)
p_i = 4.2
p_t = 2.5

The expected subgrade material is low plasticity clay with fair to poor drainage (expected due to permeable nature of the pavement). The upper 12 inches of subgrade is to be scarified and moisture treated on-site. This subgrade material corresponds to a Category 7 material as outlined in Table 4.2 of the standard.

The pavement design from Table 4.3 of the standard would be:

105 mm of paver and bedding sand (8 cm pavers + 25 mm of bedding sand)
100 mm of granular base
425 mm of granular subbase

It is proposed to provide a single layer of crushed concrete base instead of a granular base and subbase. Assuming that the CDOT Class 5/6 aggregate has a structural layer coefficient of 0.14, the above base/subbase layer would be equivalent to 375 mm of Class 5/6. Therefore, the final dense graded aggregate pavement structure would be as follows:

8 cm paver
` 25 mm bedding sand
375 mm of crushed concrete meeting CDOT Class 5/6 aggregate requirements

Permeable Pavement Design Procedure

The second design was for a permeable pavement. The permeable pavement was design in accordance with the ICPI procedures as outlined in their Permeable Interlocking Concrete Pavements manual [7] and associated Permeable Design Pro software [8].

The Permeable Design Pro software integrates hydrological and structural solutions into one application using the ICPI design criteria [7] and related sources such as the book, Porous Pavements [11]. A flowchart for the design process is shown in Figure 2.

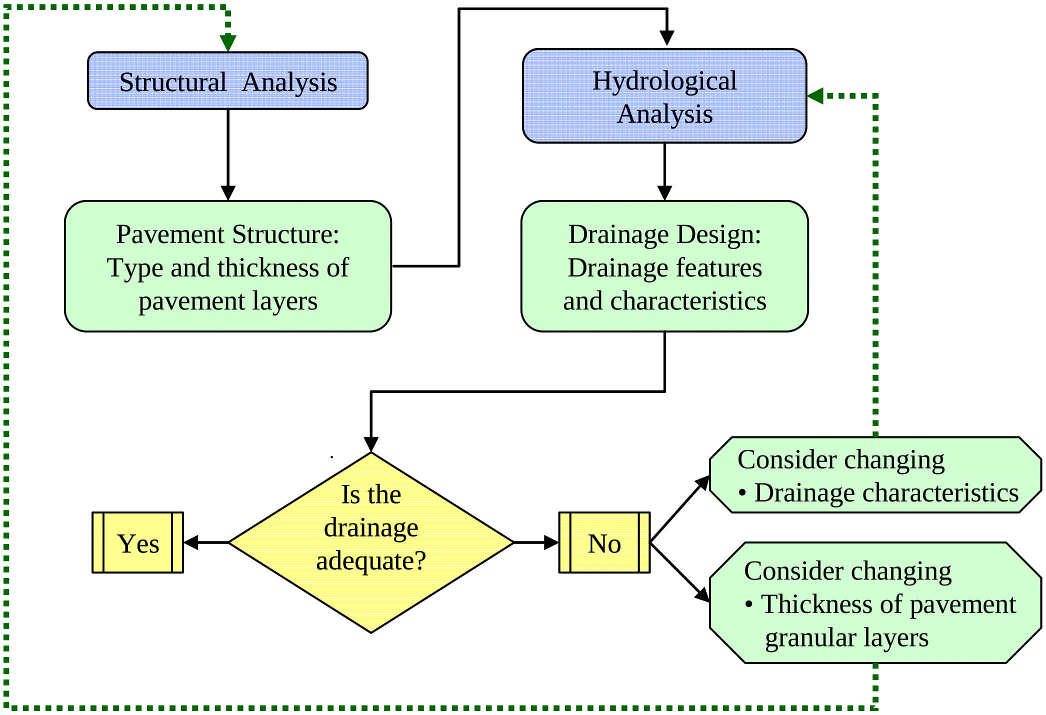

Figure 2: Structural and hydrological design flowchart.

To assess the structural capacity of a pavement, the software uses traffic information, material information, reliability, and serviceability levels. The software application utilizes the American Association of State Highway and Transportation Officials (AASHTO) 93 [6] structural design equation. The design inputs are used to produce a required Structural Number (SN) for a given structure. To determine the thickness of the required layers, the various pavement layer thicknesses and structural layer coefficients are assessed and totalled to determine if they meet the design structural number. To prevent over designing the structure, the SN is set to be equal to the design structural number. For the design of permeable pavements, the structural layer coefficients are specified by the user. Since the layer thickness for the paving layer is specified only the granular material thickness is required to be designed.

The hydrological analysis that has been incorporated into the design procedure assesses if the rainfall can be stored and released by the pavement structure provided. The quantity of water in the pavement system is described as a water balance. The software application manages the volume of water in the pavement system as:

$$Water\ Volume(Time) = Initial\ Water\ Level + \int_{o}^{Time} Inflow(Time) - Outflow(Time)$$

The analysis procedure uses small time steps to estimate the expected water inflow from direct precipitation onto the design surface and runoff contributed by the adjacent catchment areas. The outflow is also estimated in terms of runoff, groundwater recharge, and stormwater drainage during each time step. The combined process allows the water level in the pavement system to be estimated at any time during the storm, while draining and after the rainfall has stopped. A flowchart for the hydrological analysis is shown in Figure 3.

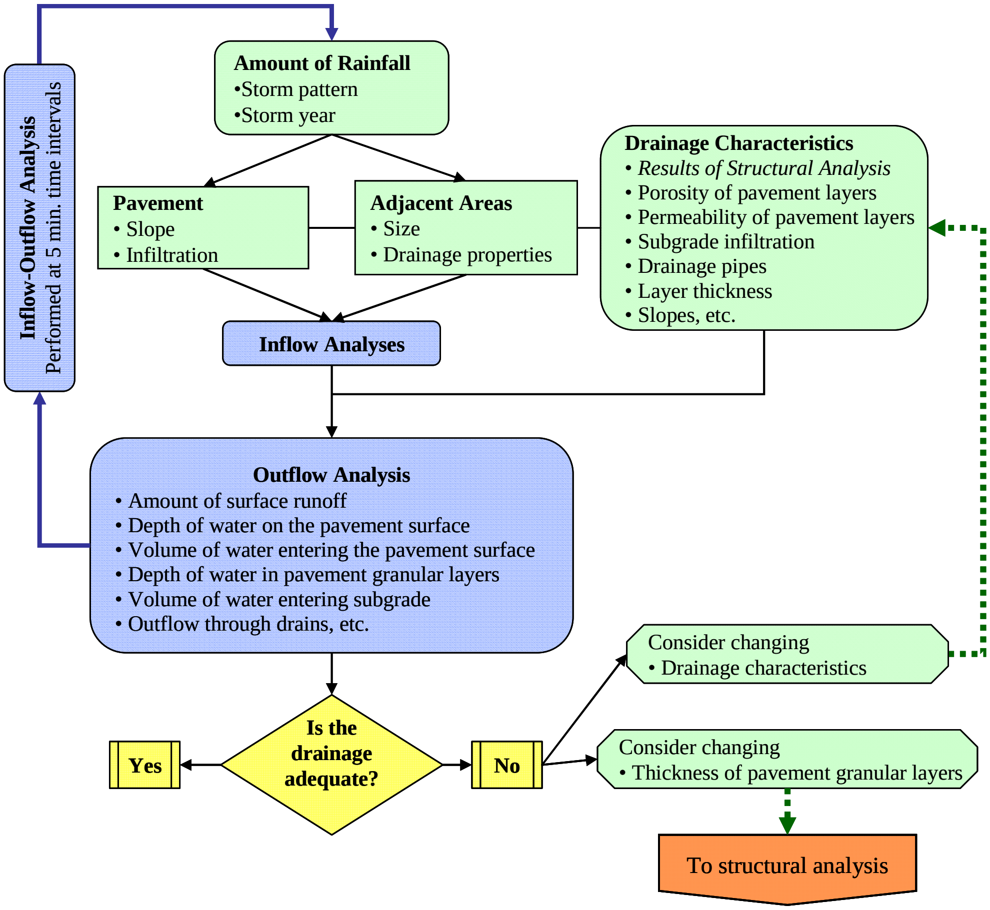

Figure 3. Hydrological design process.

The water entering the pavement comes from either precipitation or from the contributing area. During various storm events, water will fall onto the pavement surface, and adjacent catchment areas. The water landing on the pavement will then be either absorbed into the open graded base material of the structure or run off the surface of the pavement. The water from adjacent catchment areas will behave in similar manner with water returning to the groundwater or running off the catchment area and onto the pavement surface. The following equation is used to estimate runoff [12]:

$$Q = \frac{\left(P - 0.2 \cdot \left(\frac{100}{CN} - 10\right)\right)^2}{\left(P - 0.8 \cdot \left(\frac{100}{CN} - 10\right)\right)}$$

Q: Direct Runoff (in)
P: Rainfall (in)
CN: Curve Number

Calculating the runoff for the catchment area and the contributing area allows the inflow onto the surface of the pavement to be estimated. The total runoff onto the pavement surface is calculated as the sum of the runoff from all adjacent catchment areas. The runoff calculation above is then used to estimate the percentage of water at the surface of the pavement that filters into the open graded granular materials.

In addition to the formula above which is based on the storage capacity of the pavement system, research by Borgwardt [13] in Germany has indicated that there is also a maximum rate of flow of water through the surface joints into the pavement system. Over time, depending on site conditions, the surface joints and granular material can become clogged and reduce this surface inflow by up to 85 percent. The maximum surface inflow rate is used in conjunction with the runoff rate to determine how much water can enter the system.

Water infiltration is calculated in a series of regular time steps where the precipitation is converted to volume of water inflow during each interval. Due to the additional distance that the water has to travel from the catchment areas to the pavement, an additional time lag is anticipated, which will affect the distribution of the water inflow. The time lag anticipated is calculated as:

$$T_t = \frac{0.007 \cdot (n \cdot L)^{0.8}}{P^{0.5} \cdot s^{0.4}}$$

T_t: Travel time (hours)
n: Manning's roughness number
L: Length of travel distance (ft)
P: Precipitation (in)
S: Slope of hydraulic grade line (%)

Throughout the software analysis period, water leaves the system while simultaneously entering the system. The main paths for outflow drainage include groundwater recharge (infiltration into the soil), stormwater drainage system, i.e. piping, and surface runoff. All of the drainage options are not necessarily available for all pavement sections. Depending on the options selected by the user in the pavement geometry and analysis settings, the water will be allowed to leave the pavement structure in any combination of ways.

Groundwater recharge is a constant method of drainage in pavement sections. The water is allowed to percolate through the subgrade into the natural water table. The amount of water entering the subgrade is determined by the subgrade hydraulic conductivity. The flow rate of water is based on Darcy's Law assuming saturated conditions and gravity fed hydraulic gradient. The subgrade infiltration reduction factor, k, is used in this calculation to account for less than saturated conditions and potential clogging due to movement of fine particles into the subgrade. The factor is expected to have a typical value of 0.5.

$$Q_{Groundwater} = k_{Subgrade} \cdot \frac{Depth\ of\ Water\ in\ Pavement}{Thickness\ of\ Pavement} \cdot Subgrade\ Infiltration\ Factor$$

$Q_{Groundwater}$:	Flow rate of water into groundwater recharge (m/day)
$k_{Subgrade}$:	Hydraulic conductivity of the subgrade material (m/day)

Due to the changing depth of water in the pavement materials, the water depth in the pavement is calculated for every time step. As the depth increases, the static pressure is expected to increase which will directly affect the rate of drainage.

It is common for permeable pavement systems to be connected to stormwater systems. Through the use of subsurface drains, excess water within a pavement system can be removed and drained into stormwater drains or other hydraulic features. The stormwater systems in most traditional pavement systems have the drains at the bottom of the pavement structure to ensure that the water is removed complete from the system. However, in many cases the drains in PICP systems are place in the middle of the section to encourage lesser storms to drain into the ground rather than into stormwater systems.

The structural and hydrological design of permeable interlocking concrete pavements has many advanced inputs and characteristics. To assist the designer in evaluating a PICP design, a variety of design details and graphics are produced. The software also provides a printable report that summarized the design inputs and the results. The hydrology of the site and the accumulation of water in the system is a dynamic process throughout the various storms. Graphs are used to assist the designer in understanding water inflow and exit from the pavement system at various time intervals during and after the storm. The graphs represent:

- Precipitation – The depth of rain to fall during the given analysis interval.
- Inflow – The volume of water to enter into the pavement system during any time interval.
- Surface Runoff – The volume of water that will not enter the pavement system and drain over the surface of the pavement into a downstream field, pond, or other stormwater infrastructure.
- Surface Water Depth – The depth of standing water that has pooled on the surface of the PICP because the base and subbase materials are full saturated.
- Depth of Water in Base – The saturated water level in the base material. The shaded area at the surface of the base material indicates the water level at which the design goal has been exceeded.
- Pipe Drainage – The volume of water that is removed from the granular materials through pipe drainage.
  Deep Percolation – The volume of water that exits the pavement into the subgrade.

Open Graded Aggregate Pavement Design

Based on the procedure outlined above, a permeable pavement design was completed for the Battle Command Center parking area. The details of the design are provided below:

Site Information

Pavement Area	2,787 m²
Catchment Area	2,787 m² (Avg CN=48.97)

Layer Information

Paving Layer	**Concrete Pavers + Sand Joint and Bedding**	
	Structural Coefficient	0.3
	Structural Number	38 mm
	Thickness	130 mm
Base Material	**ASTM No 57 Stone**	
	Structural Coefficient	0.09
	Structural Number	9.1 mm
	Thickness	100 mm
	Porosity	0.347
	Void Ratio	0.53
	Permeability	0.019 m/s
Subbase Material	**ASTM No 2 Stone**	
	Structural Coefficient	0.06
	Structural Number	39.6 mm
	Thickness	660 mm
	Porosity	0.347
	Void Ratio	0.53
	Permeability	0.397 m/s
Subgrade Material	**Silty Clay**	
	Subgrade Strength	25 MPa
	Porosity	0.384
	Void Ratio	0.62
	Permeability	8.619 E-10 m/s

Structural Design Information

Average Annual Daily Traffic	1,000
Design ESALs	178,000
Design Structural Number	86.0
Pavement Structural Number	86.9
Structurally Adequate	Yes

Hydrological Design Information

Location	Colorado Springs, CO
Storm Type	II

Storm Return Period (Years)	24-hour Rainfall Intensity mm	Satisfies Infiltration Capacity	Satisfies Storage Goal	Satisfies Storage Capacity
2	54	Yes	Yes	Yes
5	70	Yes	Yes	Yes
10	81	Yes	Yes	Yes
25	96	Yes	Yes	Yes
50	108	Yes	Yes	Yes
100	120	Yes	Yes	Yes

Storage goal represents 85 percent of maximum water storage capacity

The design is governed by the structural capacity of the pavement. The Colorado Springs is on the eastern side of the Rocky Mountains and as such the climate type is arid desert. The table above indicates that the design thickness of the open graded granular subbase is sufficient to accommodate a 100 year design storm. It is emphasized that sand is being used in the joints and for bedding of the paving stones. While this reduces the permeability of the pavement surface, it provides for additional friction and thus increases the structural capacity of the pavement. Since the pavement design is governed by the structural capacity rather than permeability, this was seen as a logical trade-off.

PROOF OF CONCEPT

As there has been little experience with the use of permeable pavements and tracked vehicles, the Army Corps of Engineers elected to prove the concept for the pavement by constructing a test section. The purpose of the test section was to determine if the pavement could accommodate tracked vehicles, if tent spikes could be driven into the pavement and removed without damaging the pavement and if there would be any damage to the pavement if the spikes were driven over by the tracked vehicles.

The test section was located on the base, close to the location where the Battle Command Center would be constructed. A test pad was constructed in an area of gravel roadway that was already subjected to truck and tank traffic. The existing granular surface was excavated to a depth of 300 mm and a new dense graded base was constructed followed by the placement of 25 mm of bedding sand and 8 cm pavers. Edge restraint was provided by a concrete curb, 150 mm in width by 300 mm in depth.

Approximately 2 weeks after construction, a test was completed by driving an M1A1 Abrams tank over the test section. A photograph of the tank on the test section is shown in Figure 4 and a close-up of the location where a tent spike was traversed by the tank is shown in Figure 5.

The test using the tank was a complete success. There was no significant damage to the pavement structure during the tank operations. In addition, the rapid repair capability of the pavement was demonstrated by breaking one of the pavers with a sledge hammer and replacing it with a new unit.

Figure 4. M1A1 Abrams tank on the permeable pavement test section.

Figure 5. Close-up of tent spike location after being run over by the tank.

CONCLUSIONS

In conclusion, this project clearly demonstrated that both a dense graded and open graded permeable pavement could be designed to accommodate very heavy, tracked vehicles including an M1A2 Abrams tank. The paving stones themselves were able to resist the loading and turning movements of the tank with very little damage. The use of permeable pavers permitted the U.S. Army to utilize the pavement for erecting tents, driving tent spikes and removing them with very little impact on the pavement. In addition to being able to accomplish the mission of the Army, the pavement section will contribute to the sustainability goals of the DoD but assisting to infiltrate and clean rainwater at the site.

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