Review of Permeable Pavement Systems and Designs

Mathew Lipman[1] [Dr. Fazil T. Najafi[2]]

Abstract -This paper aims to cover several of these studies to interpret their results and provide insight into future studies. The studies covered in this paper relate towards the application of permeable pavements for parking lots, highways and other roadways to expedite rainwater run off. Some also looked at ways to reduce noise of tires on the roads and increase water quality. Permeable pavement can also cool down the streets and surrounding air due to the high heat capacity of the absorbed water. Research has also been conducted to determine the limitations of installing permeable pavement due to ground conditions or even if it can be installed over existing roadways. The permeable pavement systems are not limited to roadways either; studies are examining if they would also be suitable for airport runways. This review will examine the benefits and locations where permeable pavements can be implemented.

Introduction

Permeable pavement is a relatively new technology, however, despite its relative infancy several studies have critically evaluated various possible applications for this system. Its development started out in the mid 1940's as simple concrete turfblocks to address storm water flooding in the larger cities of the United States. In the 1970's improvements in the process of synthesizing plastics became more cost effective, plastic versions of the turfblocks started being produced. This was considered the beginning of the permeable pavement movement. John Paine, a civil engineer from Florida, developed a formula for Portland Cement Pervious Pavement, which launched Florida as a leader in permeable pavement designs. *(1)* Although permeable pavement systems just started out as a way to drain and manage storm water, it has subsequently been shown that with these systems produce storm water with fewer dissolved pollutants than the storm runoff from traditional impermeable pavement. This paper looks at research conducted by several groups to show the cleansing effects, safety benefits, and other applications of permeable pavement in different locations.

1. Parking lots

Parking lots are an obvious model to test and implement permeable pavement designs. This is because of the large quantities of pavement used to construct parking lots. Parking lots can also have negative effects of the environment due to their size. Additionally parking lots experience less traffic than roadways so the pavement lasts longer which eliminates the need for frequent repaving.

The majority of studies related to permeable pavements being installed in parking lots attempt to mitigate the negative impact that impervious parking lots have on the environment. This is because many parking lots are located in residential areas where storm water runoff and retention ponds are common. Before the parking lots were built rainwater was able to percolate through the soil before entering retention ponds or other ground water supplies. This process is a form of natural filtration in which chemicals and particles dissolved in the rainwater runoff are removed through the soil. *(2)* If this process is interrupted by impervious pavement the rainwater runoff remains contaminated when it enters surrounding bodies of water, which can be detrimental to the ecosystem.

A study conducted by Brattebo and Booth of the University of Washington attempted to determine the environmental effects of parking lot construction. They found that unusually high out flows of water during rainstorms was caused by the inability for water to be absorbed directly in to the ground. This caused severe bank

Mathew Lipman

Undergraduate at the University of Florida studying civil engineering; has taught courses on the Introduction to Engineering, current member of the Engineers Without Boarders UF Chapter.

Dr. Fazil Najafi

Professor at the University of Florida for civil engineering

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1. University of Florida, Department of Civil and Coastal Engineering ,365 Weil Hall, PO Box 116580 Gainesville, Florida 32611, mlipman@ufl.edu

2. University of Florida, Department of Civil and Coastal Engineering, 365 Weil Hall, PO Box 116580 Gainesville, Florida 32611, fnaja@ce.ufl.edu

erosion on the edges of surrounding bodies of water. *(3)* They installed permeable pavement designs in six different locations. Their results can be seen in Figure 1 which shows that rainwater could be absorbed directly into the ground through the permeable pavement with little to no run off even with the heaviest of storms. The only times runoff was detectable from the permeable pavement was at hours four, six, eleven, fourteen and seventeen. As seen from the graph these quantities were miniscule, opposed to the asphalt surface in which the run off almost perfectly coincides with rain intensity *(3)*.

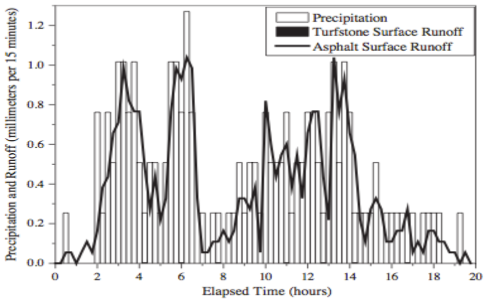


FIGURE 1 Comparison of precipitation rates and surface runoff from the permeable pavement (turfstone) and the asphalt surface.

Not only did the permeable pavement significantly reduce the run off of storm water but it also drastically improved the water quality of absorbed water compared to the run off water from the impervious pavement designs. Paired t-tests on the collected data were used to compare the quality of the water from the pervious surfaces with the asphalt runoff. It was found that before the permeable pavement implementation toxic levels of copper and zinc were found in 97% of all the run off samples, but after the installation of permeable pavements the concentrations dropped well bellow toxic levels and in some cases were not detectable at all *(3)*. The durability of their systems were impressive, even after six years of the parking lot being in use, visual inspection of the permeable pavement showed little wear and tear, none of which compromised structural integrity of the systems *(3)*. The mild damage that did occur was from the rear wheels of cars sitting in the same location, which caused the plastic matrix grid to partially lift out of the soil *(3)*. The plastic grid system is often preferred over a concrete grid due to the costs associated with each. Since the plastic grids can be cut easily to fit in irregularly shaped locations without any special modifications they are cheaper to install than concrete systems require roughly one-third more time for installation due to weight and rigidity of the concrete *(3)*.

Another study evaluated low impact parking lot designs with similar results. It was determined that parking lot designs with swales with a permeable pavement helped reduce the pollutant levels in rainwater runoff. Pollutant concentrations were at least 50% less than the concentrations from impervious pavement with no swales. *(4)* This was the case for the majority of constituents tested except for nitrogen, which remained unchanged as seen in Table 1 *(4)*.

TABLE 1 Yearly Constituent Loads and Percent Efficiency Calculations for Each Pavement Type

	Asphalt, No Swale		Asphalt, with Swale				Cement, with Swale				Pervious, with Swale			
Constituents	F1 (kg/ha-year)	F2 (kg/ha-year)	F7 (kg/ha-year)	F7 (%)	F8 (kg/ha-year)	F8 (%)	F3 (kg/ha-year)	F3 (%)	F4 (kg/ha-year)	F4 (%)	F5 (kg/ha-year)	F5 (%)	F6 (kg/ha-year)	F6 (%)
Ammonia	0.57	0.43	0.11	80	0.24	45	0.08	86	0.12	73	0.11	80	0.06	85
Nitrate	0.72	0.61	0.19	74	0.34	44	0.26	64	0.36	41	0.15	79	0.21	66
Total nitrogen	1.86	1.58	0.78	58	1.44	9	0.79	58	1.33	16	0.53	71	0.92	42
Ortho phosphorus	0.15	0.19	0.15	−1	0.54	−180	0.31	−105	0.54	−180	0.06	61	0.34	−74
Total phosphorus	0.28	0.34	0.21	26	0.66	−94	0.37	−32	0.55	−62	0.07	76	0.33	3
Suspended solids	52.28	58.61	8.68	83	31.79	46	4.47	91	12.76	78	4.26	92	5.11	91
Copper	0.042	0.033	0.008	81	0.025	23	0.008	81	0.009	72	0.003	94	0.006	81
Iron	1.805	1.386	0.227	87	0.676	52	0.156	91	0.228	84	0.114	94	0.107	92
Lead	0.018	0.017	0.002	87	0.007	59	0.003	83	0.004	78	0.001	93	0.003	85
Manganese	0.042	0.041	0.007	83	0.024	40	0.004	90	0.013	68	0.003	93	0.003	92
Zinc	0.174	0.147	0.037	79	0.079	46	0.042	76	0.056	62	0.020	89	0.036	75

Note: Percent (%) represents pollution reduction achieved compared to basins without swales (F1 and F2). Negative numbers indicate more phosphorus loads were exported from some basins with swales.

They concluded that swales, which are depressions in the land encompassing the edges of parking lots, improves water flow and helps remove pollutants. They felt that the combination of swales along with permeable pavement helps create the cleanest runoff. *(4)*

The majority of the studies conducted were preformed on a soil base layer that was either mostly sandy or gritty; not much attention was put in to clay soil. In fact the US Environmental Protection Agency recommends that maximum concentration of clay for use with permeable pavement should be less than 30%. *(5)* This recommendation, would in effect, reduce the number of places where permeable pavement could be utilized. A study conducted by Michigan State University tested this claim. Their findings determined that the EPA's recommendation was incorrect. Their study consisted of the construction of a permeable pavement system, which can be seen in Figure 2, of a surface layer of sand in a plastic grid matrix over a gravel base with drainage pipes running beneath it all *(5)*.

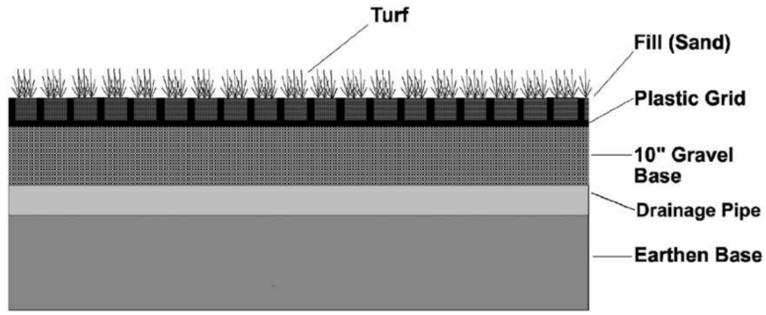


FIGURE 2 Schematic diagram of a cross-section through the porous pavement parking lot.

During their five year study the porous parking lot produced little to no run off compared to the control asphalt lots. When runoff did occur, the onset was rather slow and gradual; this was the opposite of what was found in the paved lots, which can easily be seen in Figure 3 *(5)*. The slower onset causes less erosion to the surrounding land, which is a very good thing when it comes to the landslide potential for clay soils.

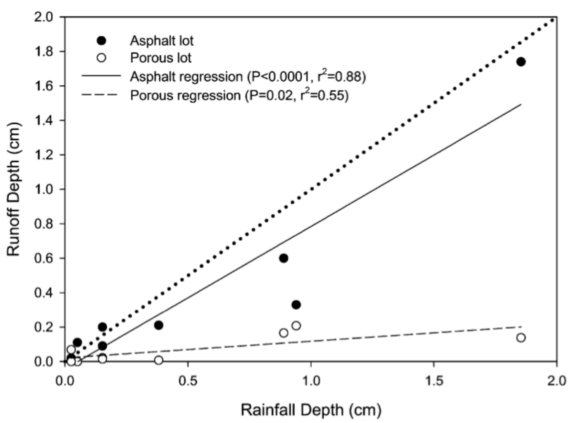
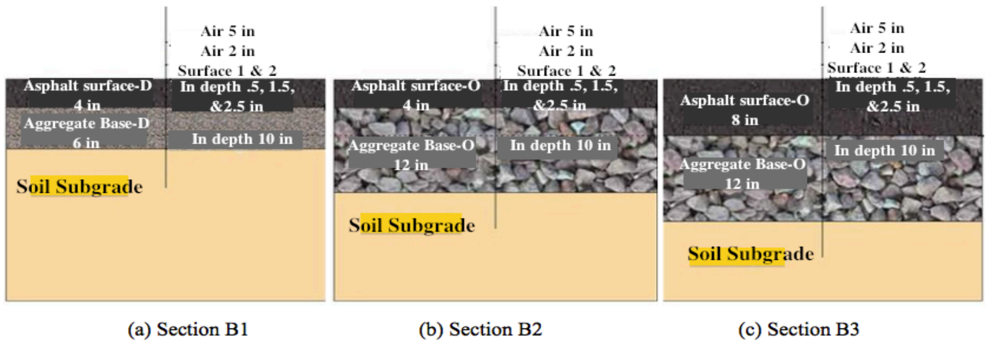


FIGURE 3 The asphalt lot produced significantly more surface runoff than the porous lot. The dotted line represents a 1:1 ratio between runoff and rainfall depth.

Also, when pollutants were able to be detected, the event mean concentration for zinc, calcium, silica and total phosphorous were 17-80% higher than the asphalt parking lots *(6)*.

In addition to improving the quality of ground water, permeable pavement can also improve the quality of the surrounding air. A study conducted at the University of California Pavement Research Center looked at two different permeable pavement designs with temperature probes at different levels, depicted in Figure 4, to determine if there were any cooling effects *(7)*.



Note: D=dense-graded, O=open-graded. 1 in = 25.4 mm.

FIGURE 4 Cross sections and sensor locations for test section B1 – B3.

They found that using the absorbed water, permeable pavement can actually cool down the surrounding air temperature *(7)*. This is due to the fact that it takes a lot of heat energy to warm up water so the water in the streets stays cooler which in turn makes the surrounding air cooler as well. However, this finding is only applicable in situations where the pavement is currently wet. If the pavement is dry the reverse effect occurs and the surrounding air is actually warmer than if the pavement were impermeable *(7)*. This phenomenon can be seen in Figure 5 where under dry conditions the max temperature reached of the permeable pavement is higher than when the pavement is wet *(7)*.

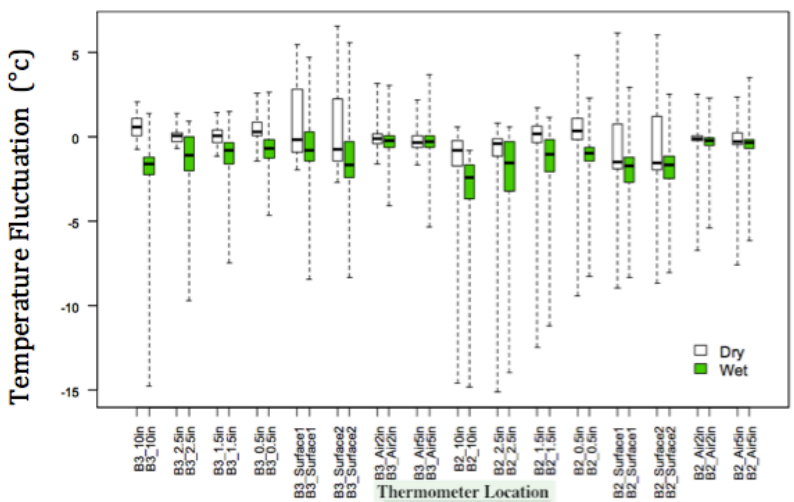


FIGURE 5 Overall cooling effects of permeable pavements (B2 and B3) compared to conventional impermeable pavement (B1) under dry and wet conditions.

This type of warming effect can be overcome by the use of irrigation systems to keep the pavement damp or by constructing it to retain water for longer periods of time. Based on these findings one could conclude that the construction of parking lots utilizing permeable pavement design seems to be beneficial to the surrounding environment in terms of reducing pollution as well as decreased erosion associated with rapid storm runoff.

2. Highways

The results of integrating permeable pavement into the highway system are potentially more complicated than parking lots. This is due to the fact that cars travel on highways at much higher speeds. This means that any negative effects caused by permeable pavement could present a life-threatening situation. Various studies attempted to understand if there are any safety concerns associated with permeable pavement on highways. Also, they attempted to determine if the same filtration effect that was found with parking lots applies to highways.

A study from the Center of Research in Water Resources looked at the amount of pollutants in storm runoff from permeable highways versus impermeable highways. A key point of this study is that they looked at permeable pavement that was applied directly over the existing roadway. This method of converting old impermeable highways into permeable highways would be less expensive than constructing a whole new highway. Because the surface pavement is open graded this allowed for the rainwater to pass directly through the pavement and not pool on the surface like traditional asphalt highways. The lack of water pooling caused significantly less spray by passing vehicles, which increases visibility for other motorists, reduces the risk of hydroplaning and also actually improves the water quality *(8)*.

It was found that the storm water collected from the porous sections of the highway were cleaner than that of traditional highway runoff water. As can be seen in Table 2, the water samples from the porous pavement showed significantly lower concentrations of total phosphorus, total lead, copper, and zinc, however there was little change in levels of nitrates, nitrites or other dissolved constituents *(9)*.

TABLE 2 Event mean concentrations for Conventional Asphalt and permeable friction course

Constituent	Conventionalasphalt	PFC	Reduction%	p -value
TSS (mg/L)	117.80	8.80	93	0.016
TKN (mg/L)	1.13	1.09	3	0.892
NO_3 / NO_2 (mg/L)	0.43	0.41	6	0.917
Total P (mg/L)	0.13	0.08	36	0.056
Dissolved P (mg/L)	0.04	0.08	-100	0.679
Total copper (μg / L)	26.80	12.90	52	0.006
Dissolved copper (μg / L)	5.90	9.84	-66	0.152
Total lead (μg / L)	12.60	1.53	88	0.025
Dissolved lead (μg / L)	< 1.0	< 1.0	NA	NA
Total zinc (μg / L)	167.40	34.68	79	0.003
Dissolved zinc (μg / L)	47.10	27.36	42	0.245
COD (mg/L)	64.00	59.52	7	0.781

The improved water quality from the porous pavement on highways has two potential explanations. One is the same as parking lots where the pores act as a filtration for the water. The other is unique to highways in which the porous pavement reduced the water spray associated with driving at high speeds *(10)*. The authors felt that the reduction in spray means that less water splashes up on to cars' undercarriages where a large amount of chemical pollutants lie *(11)*. The open graded pavement provides motorists with a roadway, which has more friction than regular roadways due to macroscopic imperfections associated with open gradient paving, and has the added benefit of less noise from the tires on the road. It has been found that the use of open graded pavement can reduce noise anywhere from three to six decibels at highway speeds *(12)*.

The cleansing effects of the permeable pavement are not only beneficial to the environment but they also can save the state money. This is due to the fact that in order for the state to have clean water sources it has to spend money to remove the contaminants from traditional asphalt runoff. On average, this costs about $58 to $230 per kilogram of metals removed due to the high price of civil works along highways *(8)*. With this figure in mind it can be seen that even though permeable pavement is more costly than asphalt pavement to install, the reduced amount of runoff filtering required for permeable pavement may save money in the long run.

The authors did find drawbacks associated with porous pavement for highway systems. Over the years the pores tend to get clogged causing less filtration. This, if left untreated, could cause the porous pavement to behave a lot more like traditional impervious pavement. Yet, in the Netherlands it was determined that even after three years the porous pavement still has positive effects on water runoff quality *(8)*. The Dutch have also found a way to combat the issue of permeable pavement becoming impermeable. They have developed aggressive cleansing vehicles, which are a form of super street cleaner equipped with vacuums and high-powered pressure washers.

Even though permeable pavement is able to be cleaned to ensure optimal drainage over the course of its life span, few studies have actually looked at the over all durability of permeable pavement. It can be hypothesized that the over all life span of permeable pavement is less than traditional impervious pavement. This is due to the structure of permeable pavement, the pores allow for the water to flow through which in turn makes more of the pavement's surface area in contact with the water. The water flowing through the pavement naturally weathers it quicker than impermeable designs *(13)*. The air pockets in the pavement also can lead to increased levels of oxidation, which can potentially shorten the life span *(13)*.

Another potential draw back is that the over all cost of permeable pavement is usually higher than traditional asphalt pavement. The cost of one ton of open graded frictional course paving is on average 10 to 80 percent greater than dense graded frictional paving with a life span of only 15 to 100 percent that of dense grade frictional paving *(14)*. However the lifespan of the open graded frictional paving can be increased to about the same as dense graded frictional paving with the addition of modified asphalt. This added life expectancy though raises the cost of open graded frictional paving to about 50 to 80 percent higher than traditional paving *(14)*.

3. Runways

The design and structure of airport runways are one of the most vital parts of airline travel due to the fact that the majority of the airline accidents occur on the runway especially during inclement weather *(15)*. Although these accidents are exceedingly rare in comparison to vehicular accidents, the severity of airline accidents is usually much greater in terms of over all fatality. Therefore researchers are interested in making runways safer during rainstorms. The main factors that contribute to the greater hazards caused by rain on runways are partially due to the design of the runway as well as the vehicles traversing them. Runways are much wider than highways which means there is much more rainwater on the pavement surface. Due to the extreme width of runways it takes longer for the water to run off the sides. Also, runways are often constructed with less irregularities than highways meaning when wet the frictional coefficient drops substantially. Unfortunately, if runways are constructed with greater macro texture for improved friction the irregularities on the runway surface will causes the surface water level to increase *(15)*. The implementation of permeable pavement on to runways may be able to address both of these problems by providing more irregularities on the runway surface as well as draining water from the runway. In the study conducted by Benedetto, the "D3" surface type, which has the largest pores, was found to behave under wet conditions in an almost identical manner as when it was dry.

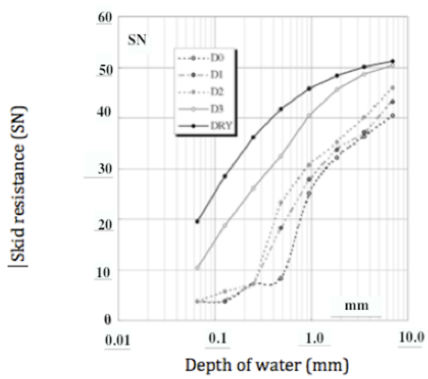


FIGURE 6 Skid resistance for different draining pavements.

Figure 6 shows that the skid resistance (SN) of the runway was reduced slowly as surface water levels increased so the pilots are able to correct for the gradual changes that occur *(15)*. It was found that if runways are paved with porous pavement with exceptionally large pores the skid resistance will not change drastically when wet nor will rainwater pool on the surface *(15)*. Ultimately this has the potential to create a safer runway.

4. Innovations for future research

To date, the application of permeable pavement systems has been limited to roadways for vehicular travel. Ongoing and future research could potentially allow for new and innovative applications such as with airport runways. There is a myriad of different applications where humans' quest for development is hindered by environmental consequences. It is possible that with the use of permeable pavements these events may not be so catastrophic. Landslides are one example. Until recently, landslides were only thought to be associated with high intensity rainstorms on steep inclines. However, recent studies have shown that the threshold of rainfall intensity versus duration for shallow sloped landslides to occur is lower than previous estimates *(16)*. It was found that the rainfall intensity plays a more important role in increasing the chances for landslides to occur due to the sheer quantity of water draining over a short amount of time *(16)*. These conditions can be exasperated by human development, which alters the drainage path of the rainwater, increasing the likelihood of a landslide *(17)*. This is where the permeable pavement design could come in to play. Virtually all the studies conducted on permeable pavement have noted its incredible hydrological properties; because the permeable pavement allows water to pass through it in to the soil it does not significantly alter the drainage path of the rainwater. This means that structures could potentially be built with a permeable foundation so they would have little impact on the surrounding environment. Before all of this can be accomplished though more research has to be put into improving the lifespan as well as decreasing the costs of permeable pavement. Hopefully if these two negative aspects of permeable pavement can be eliminated these systems can be installed in more places around the world.

5.Conclusion

This paper looked at various studies conducted on permeable pavement systems and their current application. These permeable pavement systems are changing the way human development interacts with the natural environment. Its application towards parking lots, highways and even airport runways are all improvements in terms of water quality, water quantity and safety.

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