

## **Evaluating the Hydrological Performance of Permeable Pavements in Flood-Prone Urban Areas of Pakistan**

Atayyab Rabbani Awan<sup>1</sup>, Asjad Javed<sup>2</sup>, Muhammad Shahbaz<sup>3</sup>, Uzair Ali<sup>4</sup>, Muhammad Haseeb Zaheer<sup>5</sup>, Muhammad Anwar Ullah<sup>6</sup>

<sup>1</sup>*Field Engineer, City of Westlake, Ohio, USA*

<sup>2</sup>*Communication and Works Department, Punjab, Pakistan*

<sup>3</sup>*Guangdong Provincial Key Laboratory of Deep Earth Sciences and Geothermal Energy Exploitation and Utilization, Institute of Deep Earth Sciences and Green Energy, College of Civil and Transportation Engineering, Shenzhen University, Shenzhen, China*

<sup>4</sup>*Local Government and Rural Development Department, Khyber Pakhtunkhwa, Pakistan*

<sup>5</sup>*University of Science and Technology (UST), Daejeon, Republic of Korea*

<sup>6</sup>*Balochistan University of Engineering and Technology, Khuzdar, Pakistan*  
*Email: atayyab1661@gmail.com*

**Abstract:** The field of Pavement Engineering has experienced the introduction of permeable pavements. Permeable pavements can effectively diminish runoff during heavy rain by facilitating water infiltration through the surface and into the groundwater table. These pavements can recharge groundwater while supporting moderate loads, thereby alleviating the negative impacts of heavy Rainfall during monsoon seasons, which can obstruct business activities, particularly in urban environments. Urban regions in Pakistan are becoming more susceptible to flooding, especially in low-lying areas where conventional impermeable pavements worsen the situation. This study examines the efficacy of permeable pavements as a sustainable approach to alleviate flooding in these regions. The structural and hydrological designs of permeable pavements, specifically pervious concrete, will be analyzed through a modeling approach utilizing 'Pervious Pave' software, by varying the void ratios and thickness of reservoir layers. Information concerning soil infiltration capacity, rainfall intensity, elevation profiles, and the duration necessary for complete water penetration will be employed for comprehensive laboratory analysis. The results indicate that permeable pavements significantly improve water infiltration into the soil, decreasing surface runoff and alleviating the pressure on traditional drainage systems. Through diverse analytical methods, the study illustrates that permeable pavements significantly reduce flooding by facilitating rainwater infiltration into the soil, thereby enhancing groundwater reserves and decreasing surface water buildup. This study offers significant insights for urban planners, engineers, and policymakers, presenting evidence-based recommendations for integrating permeable pavements in flood-prone urban regions of Pakistan. Adopting this environmentally conscious strategy allows urban areas to strengthen their defenses against flooding, foster sustainable water management practices, and cultivate more enjoyable living spaces for their inhabitants.

**Keywords:** Low-lying, sustainable, impermeable, percolate, replenish, flood-prone, eco-friendly.

## 1. Introduction

In recent years, there has been a significant shift towards sustainability and resilience in response to climate change. Structures are being developed that prioritize sustainability, economic viability, resilience against the adverse effects of climate change, and a minimized environmental footprint. The emergence of permeable pavements has become increasingly important within pavement engineering. When rainwater descends upon conventional Pavement such as concrete, it accumulates and subsequently flows over non-porous surfaces, resulting in stormwater runoff. Conversely, permeable Pavement facilitates the gradual infiltration of stormwater, permitting it to seep through and access the soil and groundwater below the surface (Alsobrook, 2020). A range of permeable pavement materials exists, including synthetic grass pavers, porous asphalt, and pervious concrete and interlocking pavers. Precast blocks, typically composed of brick or concrete, serve the purpose of creating interlocking pavers. The arrangement of the blocks allows for the passage of water between them, facilitating its movement to the soil below.

In contrast, grass pavers consist of open-cell structures made from concrete or plastic, featuring turf cultivated in soil-filled cells (Alsobrook, 2020). Porous asphalt and pervious concrete pavements feature voids or pores that facilitate the passage of water through the upper surface into an underlying aggregate reservoir layer. This layer temporarily stores the water before gradually infiltrating the soil beneath.

The objectives of this research investigation are outlined as follows.

- To evaluate the suitability and efficacy of permeable pavements in the city centers of Pakistan. Low-lying areas of urban cities are primarily impacted by high rainfall intensity levels, which adversely affect economic activities.
- To evaluate the infiltration rates, runoff reduction, and water storage capacity of permeable pavements compared to conventional impervious surfaces.
- To evaluate the effectiveness of permeable pavements in alleviating the effects of intense Rainfall and decreasing the likelihood of urban flooding, thus improving the overall stormwater management system.

In 2004, the Westmoreland neighborhood in Portland undertook an innovative project to manage stormwater runoff. Stormwater from North Gay Avenue enters the City's combined sewer system during rainy weather and mixes with sanitary sewage there. The wastewater treatment plant receives part of the combined sewage, with the remainder overflowing into the Willamette River. The neighborhood paved three blocks of streets using permeable Pavement. The pavement blocks have spaces filled with OK rock, enabling water infiltration. Below these blocks, two layers of rock provide a stable foundation, and geotextile fabric layers further decrease the pollutants carried into the soil as water infiltrates. This initiative marked the first use of such permeable paving material on a public street in Portland. This was a primary environmental concern for which the project was initiated. To elaborate, the original street was dug out 8-12 inches below the street grade. The excavation reached its full depth 8-13 inches below the top of the curb. A 2"-minus rock drainage blanket, 6–10 inches deep, was spread over a drainage geotextile fabric laid out on the ground. On top of the drainage blanket rock, a customized concrete curb measuring 12 inches in width and roughly 10 inches in depth was constructed and poured. The paver-block curb lanes and the asphalt middle lane are divided by this modified curb. Over the drainage blanket rock was an additional layer of geotextile cloth. Two 2-inch layers of asphalt were laid down on a 2-inch base of ¾"-minus aggregate to pave the center lane. Over the geotextile fabric in the curb lanes, a 3/8"-minus rock leveling bed was positioned and compacted to a depth of 3 inches. After the permeable pavers were placed on the leveling bed, OK rock was added to the spaces left by the paving blocks and compacted (Portland, Oregon, 2004). Most stormwater seeps through the porous Pavement, into the rock layers beneath the street, and eventually into the earth when permeable pavements are installed. The storm inlets already in place were kept in place to collect any excess runoff. This project was a breakthrough for the entire community. Porous Asphalts are one of the types of permeable pavements designed to allow water to infiltrate and merge with the groundwater. Although the design of porous asphalt may vary depending on application level, desired infiltration, and climatic conditions, this thesis will explain a generic design to help understand its concept. Several layers are designed for structural, hydrologic control, and water quality improvement beneath the porous asphalt (Figure 1). Mixes are typically designed with polymer-modified binders to reduce drain down and resist scuffing (transportation, 2015). In ascending order: a stabilizing course of crushed stone 4 "-8"; a filter course of poorly graded sand 8 "-12"; a filter blanket 3", which acts as a separation bed between the filter course

and the reservoir layer; and at least 4" thick reservoir course of crushed stone. If the subsurface is suitable, the pea gravel layer may also be thickened and used as the reservoir course (Briggs et al., 2016). This substitute makes the construction of the base easier. The purpose of fine gradation of filter courses is to improve water quality by enhancing filtration and delaying infiltration. The uniformly graded crushed stone reservoir course's high air void content maximizes the amount of filtered water stored, giving water more time to seep into the uncompacted subgrade layer below between storms. A filter blanket is placed between them to prevent the downward migration of filter course material. Geotextile should not be used on the system's bottom unless necessary for structural reasons (Briggs et al., 2016). Instead, it should only be utilized to stabilize the porous asphalt system excavation's sloping sides.

- The pervious concrete layer comprises an open-graded concrete mixture that usually ranges from 4-6 inches deep. Void content may range from 15-20% (Shinde & Valunekar, 2015).
- The aggregate base course consists of clean and durable crushed aggregate with a void content of 35-40%. The aggregate sub-base layer should be a minimum of 10 inches deep and designed with a drawdown time of 48 hours.
- Geotextile fabric is placed between the sub-base and the sub-grade layer. The filter fabric provides a separation to stop the movement of fine soil particles into the reservoir layer (Shinde & Valunekar, 2015).
- Subgrade layer (infinite thickness).

## 2. Materials and Methodology

### Identification of Low-Lying Zones of Rawalpindi vis-à-vis Significance of Permeable Pavements

The project emphasizes measures to mitigate urban flooding in low-lying areas, necessitating the initial identification of these regions. The Arc GIS Pro software was utilized effectively in this context. Initially, an analysis of localized depression was conducted. Flow direction analysis was also conducted to examine the water direction of the ground relief. This also confirmed the analysis of localized depression. This process identified low-lying regions, and their elevation profiles were extracted from Google Earth to quantify the elevations and depressions.

#### Localized Depression Analysis

Localized depression analysis entails identifying and evaluating specific low-lying areas susceptible to water accumulation within a region. This analysis identifies regions susceptible to flooding and guides the development of specific stormwater management strategies.

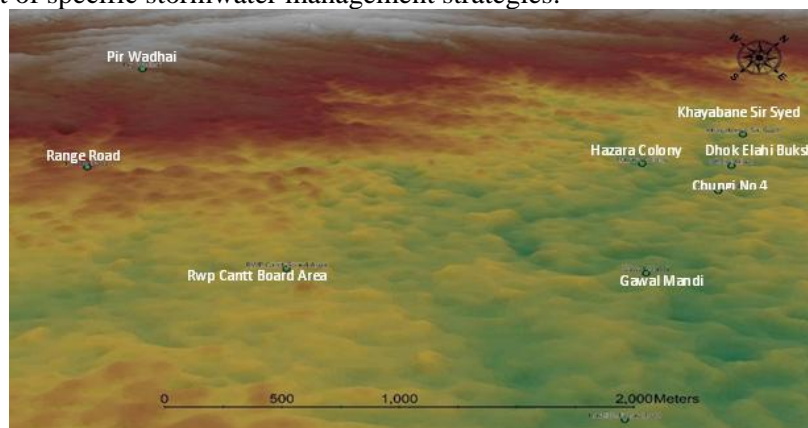


Figure 5: Localized Depression Analysis depicting the low-lying zone of Rawalpindi

Figure 2 illustrates some regions in Rawalpindi designated as low-lying areas based on a localized depression study conducted using Arc GIS Pro software. The locations encompass the Rawalpindi Cantonment Board area, Range Road, Khayaban-e-Sir Syed, Dhok Dallah, Chungi No 4, Hazara Colony, and Gawal Mandi. The green color represents low-lying places with comparatively lower elevations than their surroundings. Consequently, the likelihood of urban flooding due to intense monsoon rainfall is elevated in these regions. Correspondingly, regions shown in yellow are also low, albeit comparatively higher than those in green.

Flow Direction vis-à-vis Drainage Network

The flow direction tool delineates locations towards which different bodies of water converge. As these places are situated in depressions, causing water to flow towards and accumulate in them, this tool will assist in validating the conducted study.

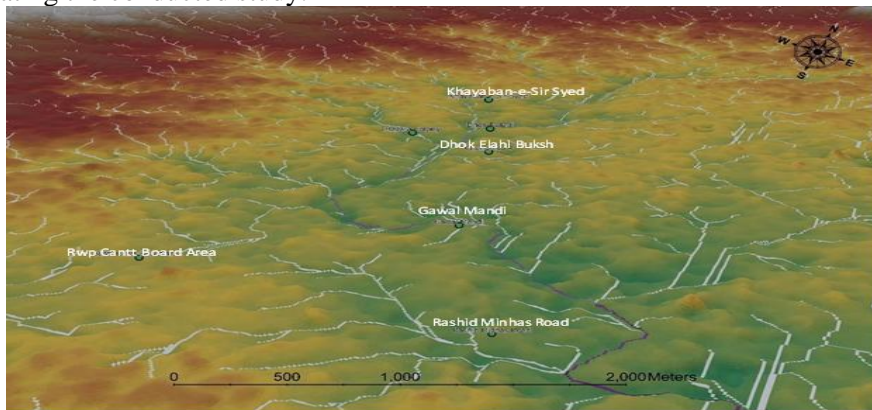


Figure 6: Flow direction analysis depicting the direction of surface runoff  
 Figure 6 illustrates the flow direction, indicating the trajectory of surface runoff towards lower elevation regions. These regions correspond to those depicted in Figure 5.

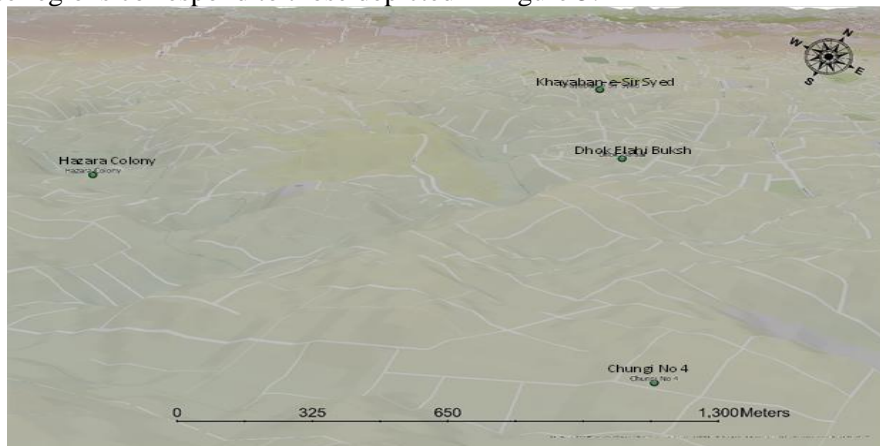


Figure 7: Closer view of areas identified as low-lying zones  
 Figure 7 illustrates low-lying regions with an enlarged perspective. Despite the absence of actual ground undulations, a 'vertical exaggeration factor' of '5' was employed to enhance the visibility of the low-lying areas. The above research indicates that implementing permeable pavements in lower elevation places will substantially decrease surface runoff from precipitation, mitigating the danger of urban floods.

Analysis from Elevation Profiles

The height profiles of Chungi No. 4, Dhok Elahi Bukhsh, Gawal Mandi, and Hazara Colony have been acquired using the Google Earth elevation profiling tool.



Figure 8: Elevation Profile of road running in general area Chungi No 4



Figure 9: Elevation Profile of road running in general area Dhok Elahi Bukhsh

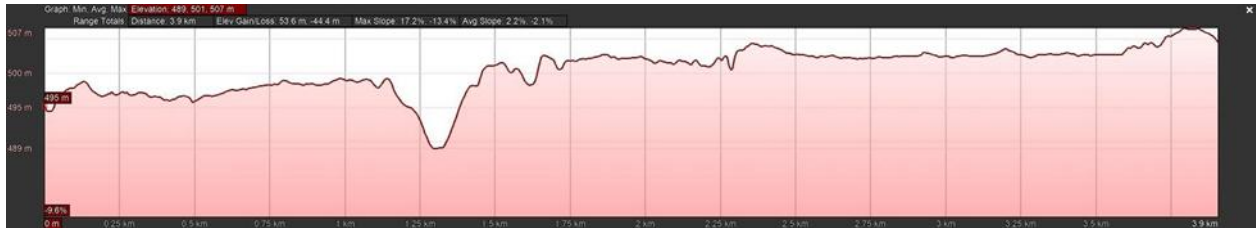


Figure 10: Elevation Profile of road running in general area Gawalmandi



Figure 11: Elevation Profile of road running in general area Hazara Colony

Table 1: Summary of Elevation Profiles

Location	Linear distance taken for analysis (km)	Min Elevation (ft.)	Max Elevation (ft.)	Elevation Gain / Loss (ft.)	Max Slope (%)
Hazara Colony	5.8	1639	1682	208 / -211	14.2% / -10.6%
Gawal Mandi	5.5	1604	1662	176 / -146	17.2% / -13.4%
Dhok Elahi Bukhsh	9.2	1625	1652	253 / -271	6.7% / -6.2%
Chungi No. 4	4.3	1623	1652	78.8 / -79.7	7.8% / -7.9%

Analysis of the low-lying areas of Rawalpindi, conducted using ARC GIS in conjunction with elevation profiles, indicates that the implementation of permeable pavements in this region could mitigate the risk of urban flooding and substantially alleviate the burden on drainage infrastructure, as these pavements facilitate water infiltration and groundwater recharge.

Maximum Rainfalls in Major Urban Cities of Pakistan

The data presented in Table 2 has been sourced from the Pakistan Meteorological Department's website. Rawalpindi, located in the province of Punjab, registers the most significant 24-hour Rainfall at 78.3 inches. This precipitation will serve as a critical parameter in this research, as it will employ Pervious Pav software to ascertain the thickness of the reservoir layer.

Table 2: Historical maximum rainfalls of major cities recorded in 24 hours (Pakistan Meteorological Department, 2019).

S/No	Province	City	Maximum Rainfall in 24 hours (in)
1	Punjab	Lahore	57.9
2		Rawalpindi	78.3
3		Islamabad	24.0
4		Bahawalpur	50.8
5		Jhelum	66.3
6		Sialkot	51.8
7	KPK	Peshawar	60.0
8		DI Khan	32.5
9	Sindh	Karachi	55.6
10		Hyderabad	33.7
11	Baluchistan	Quetta (Samungli)	30.0
12		Quetta (Sheikh Manda)	28.0
13	AJK	Muzaffarabad Airport	97.8
14		Gilgit	20.0
15		Skardu	28.0

## Application of 'Previous Pave' Software

### Purpose

Previous Pave is a software solution created by the American Concrete Pavement Association (ACPA) that delivers results for pervious concrete pavements' structural and hydrological specifications. The objective of employing this software was to ascertain the thickness of the pervious concrete and reservoir layer, which will subsequently undergo laboratory testing for infiltration capacity. Evaluating this capacity for the design of storm precipitation in Rawalpindi will yield valuable insights for assessing the effectiveness of these pavements. Given the absence of a standardized method for assessing the thickness of permeable pavements, this software was essential for the research.

### Specifications of the software

A design period of 20 years has been established for this research. The specified range for collectors or arterial streets is between 75% and 95%. Consequently, a reliability level of 95% has been chosen.

For load spectra, 'Collector' has been chosen as it meets the reliability standard of 95% applicable to collector roads. Additionally, a default ADTT of 50 has been established for collector roads. Consequently, it has been chosen with a growth percentage of 4%. The traffic on the design lane has been established at a rate of 100%.

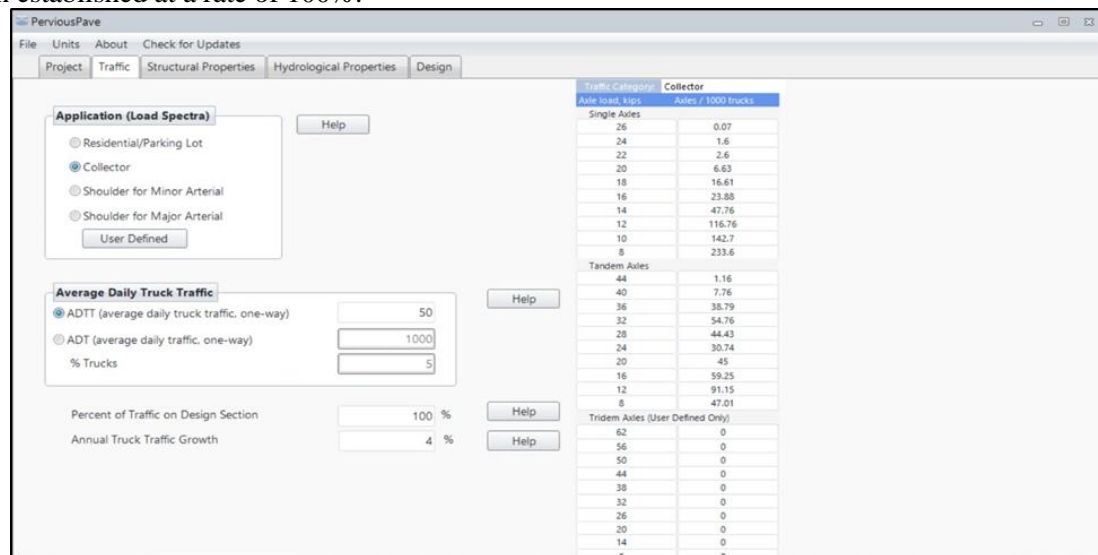


Figure 13: Traffic Tab of Pervious Pave Software

The subsequent details pertain to the structural and hydrological properties, as well as the design of the software.

The resilient modulus of subgrade (MRSG) has been established at 3500 psi, corresponding to the lower limit specified for the Class 'C' soil type range, between 3500 and 4275 psi.

The composite modulus of the subgrade was determined using software, and one reservoir layer was selected. The expected thickness is established at 8 inches, and the resilient modulus of the subgrade is determined to be 25,000 psi, representing the default average value. The compressive Strength (fc') of 3000 psi corresponds to a 28-day flexural strength range for concrete of 400-550 psi. Consequently, the selected MR is 550 psi for an average fc' of 3000 psi, and the software automatically calculates the modulus of elasticity (E).

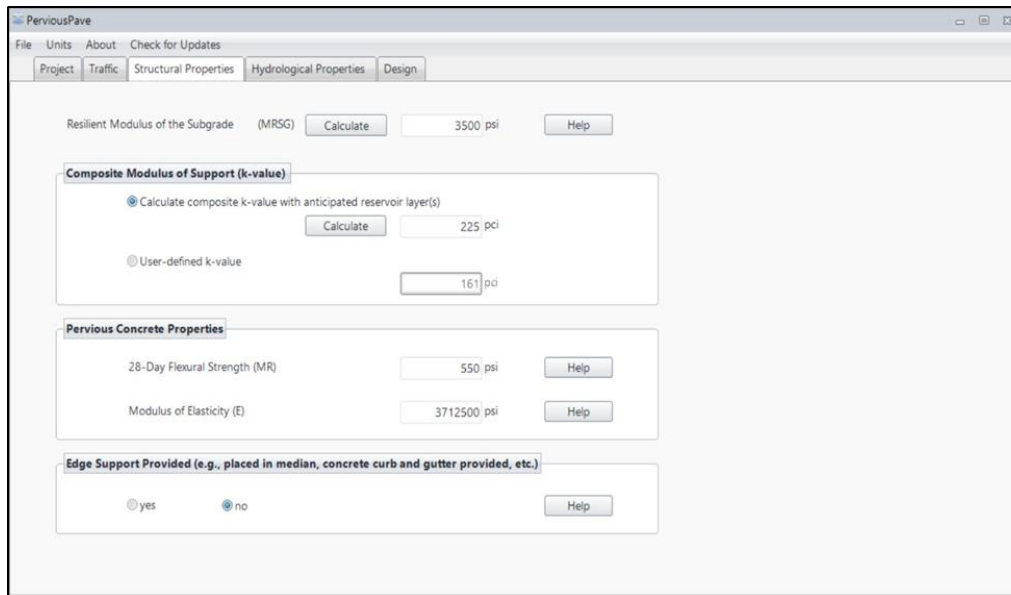


Figure 14: Structural Properties Tab of Pervious Pave Software

Assuming the construction of a 5 km long strip of road as pervious concrete Pavement with a width of 3.5 m, the area of pervious concrete in square feet is calculated as  $5 \times 1000 \times 3.5 \times 3.2812 = 188,386 \text{ ft}^2$ . The area that is not permeable and requires drainage is indeterminate; thus, it can be estimated as 1.5 times the area of the permeable concrete, specifically  $1.5 \times 188,386 = 282,580 \text{ ft}^2$ .

The infiltration rate of soil in the Potohar Plateau region, including Rawalpindi, is around 0.5 to 1 inch per hour (Malik, Ashraf, Bahzad, and Aslam, 2019). Consequently, the lesser value of 0.5 inch/hr. has been chosen. The vacancy percentages of pervious concrete and reservoir layer materials are 15% and 40%, respectively. These values are presumed since they have been tested to be optimal for efficient drainage of surface runoff. The design storm precipitation is 78.03 inches, the most significant historical Rainfall recorded in Rawalpindi, as shown in Table 2. The maximum retention duration of water in the permeable part is established at 24 hours.

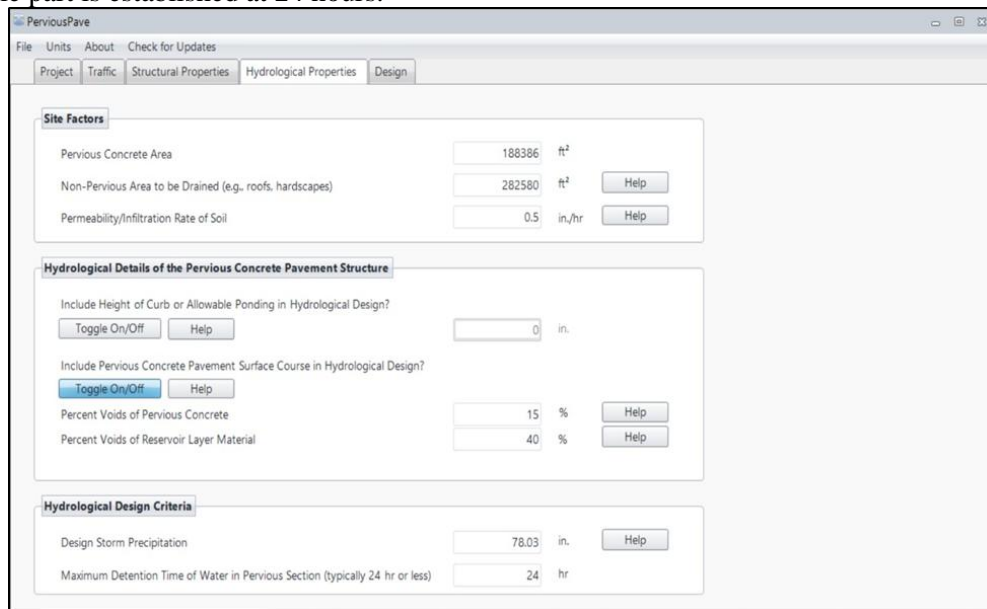


Figure 15: Hydrological Properties Tab of Pervious Pave Software

The structural study conducted using the program indicates that the necessary thickness of pervious concrete is 6.5 inches.

The hydrological analysis indicates that the water-treated volume is 78,494.3 cubic feet. The necessary thickness of the reservoir layer to handle this water efficiently within the designated detention period is determined to be 10.06 or 11 inches.

The thickness of the reservoir layer typically ranges from 6 to 12 inches, contingent upon the aforementioned considerations. Since 11 inches falls within this range, there is no necessity to augment

the area of pervious concrete or the proportion of voids in the reservoir layer.

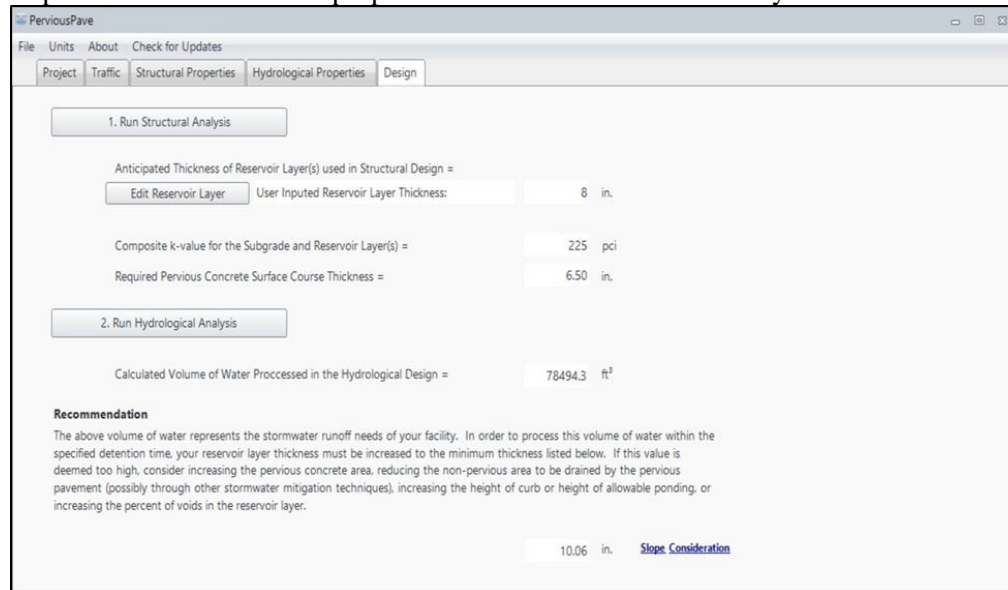


Figure 16: Design Tab of Pervious Pave Software

### Methodology for Structural Design

The AASHTO road test in the late 1950s in Ottawa, Illinois, exclusively utilized conventional concrete and asphalt. No permeable pavements were installed. Consequently, employing this approach to build pervious concrete may yield imprecise results. To effectively utilize this approach and set its inputs for the construction of pervious concrete, comprehensive testing of flexural Strength, compressive Strength, elastic modulus, and Poisson's ratio is essential. This study excludes the examination of such factors. The test values acquired from ASTM standards testing conducted at the University of Arkansas, Fayetteville, will be utilized. The 28-day compressive Strength of a coarse-graded pervious mix was around 1400 psi (Smith, 2019). Flexural Strength ranged from 150 to 550 psi (Pervious Concrete Pavement, 2011).

### Selection of Gradation

The National Ready Mixed Concrete Association's Guideline for Proportioning Pervious Concrete Mixtures recommends using AASHTO No. 67 for pervious concrete mixes (NRMCA, 2020). The gradation was modified to include only aggregate sizes that would be retained on the No. 4 sieve and larger. The sizes encompass aggregates retained on 1/2", 3/8", and No. 4 sieve. The passing percentages for these sizes were 67%, 33%, and 0% (Smith, 2019).

### Water/Cement (W/C) Ratio against Percentages of Fly Ash

Tests ASTM C305-14 and ASTM C1437-15 were conducted at the University of Arkansas. ASTM C305-14 was utilized to manufacture several paste batches with differing water-to-cement ratios. ASTM C1437-15 then evaluated the consistencies. The water-to-cement (W/C) ratios for 0%, 15%, and 30% fly ash were determined to be 0.41, 0.38, and 0.375, respectively.

### Compressive Strength ( $f'c$ )

Compressive Strengths for 7, 14, 21, and 28 days are given in the following table.

Table 3: Values of Compressive Strengths against % FA

% Fly Ash (FA)	7-day $f'c$ (psi)	14-day $f'c$ (psi)	21-day $f'c$ (psi)	28-day $f'c$ (psi)
0%	1900	1465	1450	1440
15%	1400	1550	1500	1440
30%	1120	1390	1400	1440

### Flexural Strength

$PL$

$R = \frac{P}{b}$

$bd^2$

$b$ =Width of specimen at fracture (in);  $d$ =Depth of specimen at fracture (in).

The flexural Strength after 28 days for 0% FA, 15% FA, and 30% FA was found to be 229 psi, 228 psi, and 249 psi, respectively.

$R$ =Modulus of Rupture (psi);  $P$ =Load applied by testing machine;  $L$ =Length of span (in);

### Determination of Slab Thickness

The empirical equation derived from the AASHTO road test will be used to determine slab thickness.

$$\log_{10}(W_{18}) = Z_R S_O + 7.35 \log_{10}(D + 1) - 0.06 + \frac{1.624 \times 10^7}{1 + (D + 1)^{8.46}} + (4.22 - 0.32 p_t) \log_{10} \left( \frac{S'_c C_d (D^{0.75} - 1.132)}{215.63 J (D^{0.75} - \frac{18.42}{E_c^{0.25}})} \right) \left( \frac{1}{k} \right)$$

Where,

$W_{18}$  = estimated amount of 18,000 lb. equivalent single-axle loads (ESALs)

$Z_R$  = standard normal deviate; relates to the design's reliability

$S_O$  = combined standard error of traffic & performance prediction; design's reliability  $\Delta PSI$  = difference of  $p_t$ , initial serviceability index &  $p_t$ , terminal serviceability index

$S'_c$  = modulus of rupture of concrete, which relates to flexural Strength (psi)

$C_d$  = drainage coefficient

$J$  = load transfer coefficient, which relates to the efficiency of load transfer

$E_c$  = elastic modulus of concrete (psi)

$k$  = modulus of subgrade reaction (PCI)

Design Traffic Loads ( $W_{18}$ )

Permeable pavements are not usually applicable for highways, so traffic loads for urban streets will be used.

Table 4: Traffic Loads for Design

Minimum ESALs	Average ESALs	Maximum ESALs
$5 \times 10^5$	$1 \times 10^6$	$1.5 \times 10^6$

Reliability ( $Z_r$ ,  $S_o$ )

The value of standard normal deviation, i.e., -0.674, against the reliability of 75%, is taken based on the average values from the AASHTO 93 guide (Christopher, Schwartz, & Boudreau, 2010).

The Arkansas Department of Transportation roadway design guide uses a standard deviation of 0.35 (Arkansas, 2020).

Design Change in Pavement Serviceability Index ( $\Delta PSI$ )

Taking  $p_t = 4.5$  and  $p_o = 2.5$  (Arkansas, 2020)  $\Delta PSI = 4.5 - 2.5 = 2$

Concrete Modulus of Rupture ( $S'_c$ )

A value of 230 psi was selected for concrete flexural Strength since all the tests had similar results.

Below is the most used relation to find concrete flexural Strength.

$$S'_c = (f'_c)^\beta$$

Where  $\alpha$  and  $\beta$  are coefficients obtained from laboratory testing performed at the University of Arkansas.

Their values are 6.15 and 0.5, respectively, from  $S'_c$  of 230 psi and  $f'_c$  of 1400 psi

#### 3.4.10 Drainage Coefficient ( $C_d$ )

The value taken is 1.0 in this case, as all the water on permeable pavements will drain.

Load Transfer Coefficient ( $J$ )

In permeable pavements, there are no load transfer devices (dowel bars and tie bars). A value of 4.0 is taken, within the range of AASHTO's 1993 guide on load transfer coefficients for plain jointed tied PCC with no load transfer devices (Christopher, Schwartz, & Boudreau, 2010).

Elastic Modulus of Concrete ( $E_c$ )

Tests performed at the University of Arkansas did not provide reliable results, so the commonly used empirical relation between  $E_c$  and  $f'_c$  given below will be used.

$$E_c = 57000(f'_c)^{0.5}$$

With  $f'_c = 1400$  psi,  $E_c = 2132745$  psi

Modulus of Subgrade Reaction ( $k$ )

AASHTO's 1993 guide was used to determine  $k$ . A base (open-graded stone reservoir layer) thickness of 18" is taken to drain water into the subgrade gradually. Sub-base elastic modulus of 15,000 psi is taken from the lower limit for the 'Unbound Granular Materials' range, i.e., 15000 to 45000 psi.; The median value available on the chart for the roadbed resilient modulus of 7000 psi is taken. The following chart will use the above values to determine the subgrade reaction ' $k$ ' modulus as 490 PCI, as red arrows indicate.

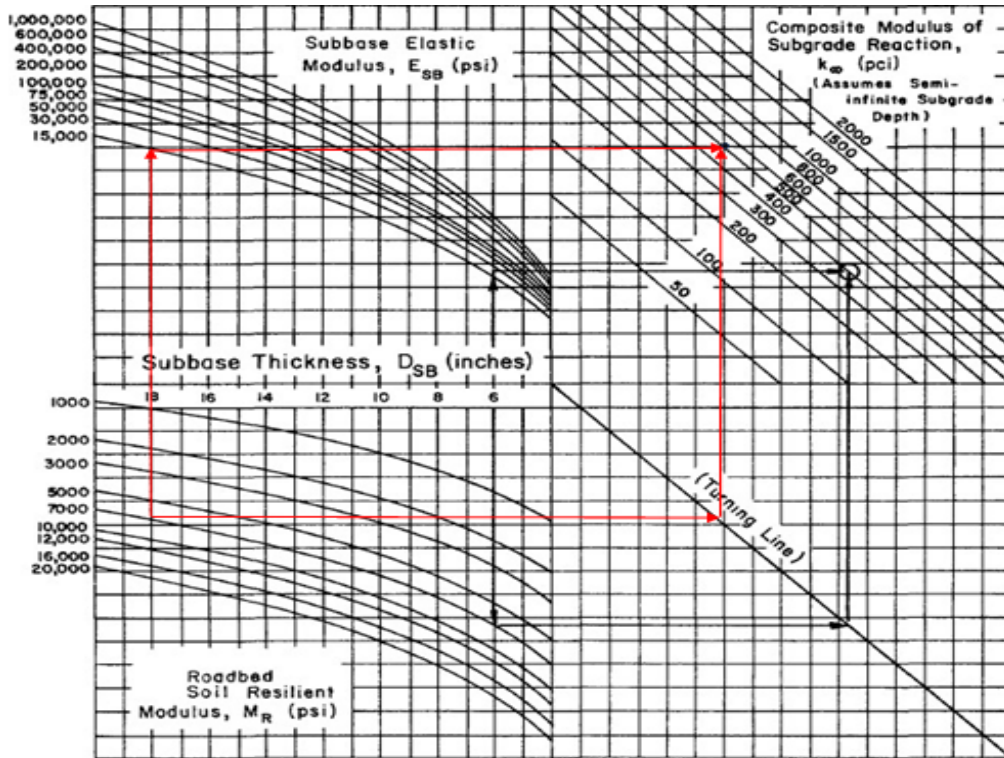


Figure 17: Chart for Determining Modulus of Subgrade Reaction ' $k$ '

Summary of Design Inputs

Design Input Parameter	Value	Source
$W_{18}$	$5 \times 10^5, 1 \times 10^6, 1.5 \times 10^6$ ESALs	Assumed values for urban streets
$R$	75%	AASHTO 1993 Guide
$S_O$	0.35	ARDOT Guidelines
$\Delta PSI$	2	ARDOT Guidelines
$S'C$	230 psi	University of Arkansas, Lab Test
$C_d$	1.0	ARDOT Guidelines
$J$	4.0	AASHTO 1993 Guide
$E_c$	2132745 psi	University of Arkansas, Lab Test
$k$	490 PCI	AASHTO 1993 Guide

Resulting Pervious Concrete Surface Thickness

Design ESALs	Pavement Thickness obtained from Equation 5	Design Pervious Concrete Thickness
$5 \times 10^5$	10.24 in	10.5 in
$1 \times 10^6$	11.53 in	12 in
$1.5 \times 10^6$	12.33 in	12.5 in

Summary

This section includes identifying low-lying areas and maximum Rainfall and a detailed description of the functionalities and features of pervious pave software. It concludes by discussing various aspects of structural design, including flexural Strength, traffic load, and reliability.

### 3. Results and Discussion

#### Falling Head Test

Subsequent hydraulic conductivity values were derived from falling head tests conducted in the laboratory. The findings were initially presented in 'cm/sec' but changed to 'in/hour' in the same table for the reader's convenience, allowing for straightforward comparison with the design storm precipitation of 78.03 inches.

Table 6: Hydraulic Conductivity values obtained from Falling Head Test

Samples						
Serial	S1		S2		S3	
	cm/sec	in/hour	cm/sec	in/hour	cm/sec	in/hour
1	0.13	184.25	0.13	184.25	0.14	198.42
2	0.14	198.42	0.14	198.42	0.13	184.25
3	0.13	184.25	0.13	184.25	0.15	212.69
4	0.13	184.25	0.11	155.90	0.13	184.25
5	0.15	212.59	0.13	184.25	0.14	198.42
Average Value	0.136	192.75	0.128	181.41	0.138	195.61

0.11 cm/s or 155.90 in/hr, indicated in red cells, represents the minimum hydraulic conductivity value, whilst 0.15 cm/s or 212.59 in/hr, indicated in yellow cells, is the lowest hydraulic conductivity value recorded among all sample data. The hydraulic conductivity values derived from the falling head tests were uniform across all three concrete mixtures. This result indicates that the differences in coarse aggregate gradation utilized in this investigation do not substantially affect the drainage characteristics of the pervious concrete. The hydraulic conductivity values obtained from this permeability test ranged from 0.13 to 0.15 cm/s. These results align with the range often documented for pervious concrete mixtures in the literature. Numerous writers examining this characteristic in pervious concrete have reported values between 0.01 and 1.5 cm/s (Schaefer, Wang, Suleiman, & Keavern, 2006). The findings of the falling head test significantly differ from those of the constant head test, as shown in the literature, with the former producing greater hydraulic conductivity values. This gap may be ascribed to variations in equipment technology. The falling head test encased the samples in plastic film to mitigate or inhibit lateral water movement. In contrast to the configuration of the constant head permeameter, the falling head test did not include the application of external pressure to the cores. The absence of external pressure may have caused considerable water loss from the specimens' sides, leading to elevated hydraulic conductivity values (Montes & Haselbach, 2006).

#### Discussions

Table 6 illustrates that the cells marked in red represent the minimum hydraulic conductivity value across all sample data, precisely 0.11 cm/s or 158.4 in/hr. The minimum figure observed during the experiment remains significantly higher than the design storm precipitation, roughly double, namely 78.03 inches recorded over a 24-hour rainfall period. The minimum value has been chosen to ensure the most secure outcome for comparison.

The design storm precipitation of 78.03 inches occurred over a specified duration, maybe a few hours, although the rainfall gauge recorded the measurement after 24 hours. In the absence of specific data on the duration of the design storm precipitation, it was assumed for research purposes that the Rainfall occurred over 1 hour at a rate of 78.03 in/hr, with clear weather prevailing for the subsequent 23 hours. This premise had significance for two reasons. Firstly, it ensures our safety by supposing a one-hour downpour indicates an exceptionally high precipitation intensity. Pavements engineered to withstand this rainfall intensity will be secure against any level of precipitation. Secondly, comparing the hydraulic conductivity values with the design precipitation is facilitated because the experimental values are likewise expressed in 'inches/hour.'

Considering the aforementioned, since the lowest measured hydraulic conductivity value of 155.90 in/hr significantly exceeds the design storm precipitation of 78.03 in/hr., it can be conclusively determined that the pervious concrete Pavement, adhering to the gradation and specifications outlined in Tables 4 and 5, with thicknesses calculated in Section 3.4.15, is suitable for deployment in any region of Rawalpindi, by the projected traffic ESALs specified.

#### 4. Conclusions

Following the extensive study and analysis conducted throughout our project on the efficacy of permeable pavements in alleviating floods in low-lying urban areas of Pakistan, the results reached are presented below:

- Applying flow direction and localized depression tools inside Geographic Information System (GIS) software and elevation profiles from Google Earth was crucial for precisely locating low-lying, flood-prone locations in urban environments. The detected locations corresponded with those previously recognized by the District Administration (Islamabad), corroborating the findings.
- Using the Pervious Pave program and the AASHTO technique for calculating the thickness of pervious concrete pavements yielded consistent outcomes, affirming the reliability of these design methodologies in real-world applications.
- While determining pavement thickness utilizing AASHTO's equation for stiff pavements, specific values were either assumed or derived from various recommendations. The laboratory results demonstrated the efficacy of these pavements, indicating that the AASHTO technique could be applied to previous concrete pavements under specific assumptions.
- Although gradation does not substantially affect drainage properties, the appropriate water/cement ratio and aggregate/cement ratio are essential for attaining the desired permeability and structural integrity. This highlights the necessity for rigorous quality control in material selection and pavement construction.
- Permeable pavements are exceptionally efficient in managing severe rainfall events in urban settings, as demonstrated by experimental data indicating that a 10-inch thick pervious concrete pavement can accommodate up to 158.4 inches of Rainfall, significantly surpassing the highest recorded 24-hour Rainfall in the region (78.3 inches).

#### References

1. (2004). Retrieved from Portland Oregon: <https://www.portlandoregon.gov/bes/article/77074>
2. (2019) Retrieved from Pakistan Meteorological Department: <https://ffd.pmd.gov.pk/rainfall-data>
3. Alsobrook, A. D. (2020). Guidelines for Permeable Pavement. Retrieved from [www.princegeorgescountymd.gov](http://www.princegeorgescountymd.gov): [https://www.princegeorgescountymd.gov/sites/default/files/media-document/dcv32200\\_guidelines\\_permeable-pavement\\_updated-042120.pdf](https://www.princegeorgescountymd.gov/sites/default/files/media-document/dcv32200_guidelines_permeable-pavement_updated-042120.pdf)
4. Arkansas, T. D. (2020). ROADWAY DESIGN PLAN DEVELOPMENT GUIDELINES. Retrieved from [ardot.gov](http://ardot.gov): <https://www.ardot.gov/wp-content/uploads/2020/11/Roadway-Design-Plan-Development-Guidelines-1.pdf>
5. Bekele, A. (2011). Implementation of the AASHTO pavement design procedures into MULTI-PAVE.
6. Briggs, J. F., Roseen, R. M., Ballesterro, T. P., Pochily, J., Swenson, G., Houle, J. J., & Puls, T. A. (2016). UNHSC Design Specifications for Porous Asphalt Pavement and Infiltration Beds. Durham, New Hampshire: University of New Hampshire Stormwater Center (UNHSC).
7. Christopher, B. R., Schwartz, C. W., & Boudreau, R. L. (2010). Geotechnical aspects of pavements. Reference manual. US Department of Transportation, Federal Highway Administration.
8. Kia, A., Delens, J. M., Wong, H. S., & Cheeseman, C. R. (2021). Case Studies in Construction Materials 15. Structural and hydrological design of permeable concrete pavements, e00564.
9. Malik, M., Ashraf, A. M., Bahzad, A., & Aslam. (2019). Retrieved from Pakistan Council of Research in Water Resources: <https://pcrwr.gov.pk/wp-content/uploads/2020/Water-Management-Reports/Soil%20physical%20and%20hydraulic%20properties.pdf>
10. Montes, F., & Haselbach, L. (2006). Measuring Hydraulic Conductivity in Pervious Concrete. Environmental Engineering Science V. 23, p. 960-969. Retrieved from Penn State University: <https://pure.psu.edu/en/publications/measuring-hydraulic-conductivity-in-pervious-concrete>
11. Niu, Z. G. (2016). Stormwater infiltration and surface runoff pollution reduction performance of permeable pavement layer. Environmental Science and Pollution Research, 23, 2576-2587.
12. NRMCA. (2020). PIP 4 – Guide to Pervious Concrete Mix Design. Retrieved from NRMCA: <https://www.nrmca.org/wp-content/uploads/2020/04/PiP4.pdf>
13. Pervious Concrete Pavement. (2011). Retrieved from <https://www.perviouspavement.org/>
14. SCHAEFER, V., WANG, K., SULEIMAN, M., & KEVERN, J. (2006). Retrieved from Pervious Pavement: <https://www.perviouspavement.org/downloads/Iowa.pdf>
15. Schaefer, V., Wang, K., Suleiman, M., & Kevern, J. (2006). Mix Design Development for Pervious Concrete in Cold Weather Climates. Iowa: Iowa State University, 2006. .

16. Shinde, G. U., & Valunekar, S. S. (2015). Cost and time control in stormwater management using pervious concrete 3(2). *International Journal for Scientific Research & Development*, 1947-1949.
17. Smith, A. (2019). *Structural Design Guidelines for Pervious Concrete Pavements*.
18. Tennis, P. D., Leming, M. L., & Akers, D. J. (2004). *Pervious concrete pavements (Vol. 8)*. Skokie, IL: Portland Cement Association.
19. TRANSPORTATION, U. D. (2015, April). *Porous Asphalt Pavements with Stone Reservoirs*. Retrieved from [www.fhwa.dot.gov](http://www.fhwa.dot.gov):  
<https://www.fhwa.dot.gov/pavement/asphalt/pubs/hif15009.pdf>
20. Woods-Ballard, B., Kellagher, R., Martin, P., Jefferies, C., Bray, R., & Shaffer, P. (2007). *The SUDS manual (Vol. 697)*. London: Ciria.