ASSESSING THE EFFECTIVENESS OF PERMEABLE PAVEMENTS IN MITIGATING FLOODING IN LOW LYING ZONES IN URBAN AREAS OF PAKISTAN

FINAL YEAR PROJECT UG 2024

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No part of this thesis has been submitted anywhere else for any other degree. This thesis is submitted to the Transportation and Geotech Department of Military College of Engineering, Risalpur in partial fulfillment of the requirements for the degree of Bachelor of Engineering in Field of Civil Engineering.

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We hereby declare that the thesis entitled "ASSESSING THE EFFECTIVENESS OF PERMEABLE PAVEMENTS IN MITIGATING FLOODING IN LOW LYING ZONES IN URBAN AREAS OF PAKISTAN" submitted by us, is based on the study and work done solely by us. All references to work done by any other person, institution, or source have been duly cited. We further clarify that this thesis has not been published or submitted for publication anywhere else.

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TABLE OF CONTENTS

ABSTRACT 4
CHAPTER 1 5
INTRODUCTION 5
1.1 Background Study 5
1.2 Problem Statement 5
1.3 Objectives 6
1.4 Organization of the Report 6
1.5 Significance 7
1.6 Summary 7
CHAPTER 2 8
LITERATURE REVIEW 8
2.1 Overview 8
2.2 Case Study of Portland 8
2.3 Cross-Sectional Details of Porous Asphalt 9
2.4 Cross-Sectional Details of Pervious Concrete 11
2.5 Hydrological Factors Involved in Design of Permeable Pavements 12
2.5.1 Infiltration Considerations 12
2.5.2 Intensity of Rainfall 12
2.5.3 Runoff Calculations 12
2.5.4 Storage Depth 13
2.6 Summary 13
CHAPTER 3 15
MATERIALS AND METHODOLOGY 15
3.1 Identification of Low-Lying Zones of Rawalpindi vis-à-vis Significance of Permeable Pavements 15
3.1.1 Background 15
3.1.1 Localized Depression Analysis 15
3.1.3 Analysis from Elevation Profiles 18
3.2 Maximum Rainfalls in Major Urban Cities of Pakistan 19
3.3 Application of 'Pervious Pave' Software 20
3.3.1 Purpose 20
3.3.2 Project Tab 20

3.3.3 Traffic Tab ... 21
3.3.4 Structural Properties Tab ... 22
3.3.5 Hydrological Properties Tab ... 22
3.3.6 Design Tab ... 23
3.4 Methodology for Structural Design ... 24
3.4.2 Water/Cement (W/C) Ratio Against Percentages of Fly Ash ... 25
3.4.3 Compressive Strength (f'c) ... 25
3.4.4 Flexural Strength ... 25
3.4.5 Determination of Slab Thickness ... 25
3.4.6 Design Traffic Loads (W_{18}) ... 26
3.4.7 Reliability (Z_r, S_o) ... 26
3.4.8 Design Change in Pavement Serviceability Index (ΔPSI) ... 27
3.4.9 Concrete Modulus of Rupture (S'_c) ... 27
3.4.10 Drainage Coefficient (C_d) ... 27
3.4.11 Load Transfer Coefficient (J) ... 27
3.4.12 Elastic Modulus of Concrete (Ec) ... 27
3.4.14 Summary of Design Inputs ... 28
3.4.15 Resulting Pervious Concrete Surface Thickness ... 29
3.5 Summary ... 29
CHAPTER 4 ... 30
EXPERIMENTATION ... 30
4.1 Experimental Setup ... 30
4.1.1 Sample preparation ... 30
4.1.2 Falling Head Permeability Test ... 32
CHAPTER 5 ... 33
RESULTS AND DISCUSSION ... 34
5.1 Falling Head Test ... 34
5.2 Discussions ... 35
CHAPTER 6 ... 36
CONCLUSIONS ... 36
REFERENCES ... 37

TABLE OF FIGURES

Figure 1: X-Section of Porous Asphalt Pavement 9
Figure 2: Typical Cross-Section of Porous Asphalt 10
Figure 3: Typical X-Section of Pervious Concrete 11
Figure 4: X-section of Pervious Concrete shown in separate layers 11
Figure 5: Localized Depression Analysis depicting low-lying zone of Rawalpindi 15
Figure 6: Flow direction analysis depicting direction of surface runoff 16
Figure 7: Closer view of areas identified as low-lying zones 17
Figure 8: Elevation Profile of road running in general area Chungi No 4 18
Figure 9: Elevation Profile of road running in general area Dhok Elahi Bukhsh 18
Figure 10: Elevation Profile of road running in general area Gawalmandi 18
Figure 11: Elevation Profile of road running in general area Hazara Colony 18
Figure 12 Project Tab of Pervious Pave Software 21
Figure 13: Traffic Tab of Pervious Pave Software 21
Figure 14: Structural Properties Tab of Pervious Pave Software 22
Figure 15: Hydrological Properties Tab of Pervious Pave Software 23
Figure 16: Design Tab of Pervious Pave Software 24
Figure 17: Chart for Determining Modulus of Subgrade Reaction 'k' 28
Figure 18: Pervious Concrete Sample (32 cm x 22.5 cm x 25.4 cm) 31
Figure 19: Setting the Falling Head Permeability apparatus (left). Increasing water column height to 35 cm after closing the valve (right) 32
Figure 20: Setting up of apparatus (left). Pervious concrete sample over which apparatus has been placed (right). 33

ABSTRACT

Pavement Engineering has seen a penetration of the concept of permeable pavements. Permeable pavements have the capability to reduce the runoff from intense rainfalls by allowing the water to penetrate the pavement and subsequently enter the ground water table. In this way, these pavements can recharge the ground water while sustaining moderate loads, hence mitigating the adverse effects of intense rainfalls in monsoon seasons which contribute in the hindrance of business activities especially in urban areas.

Urban areas in Pakistan are increasingly vulnerable to flooding, particularly in low-lying zones where traditional impermeable pavements exacerbate the problem. This study investigates the effectiveness of permeable pavements as a sustainable solution to mitigate flooding in these areas. By changing the void ratios and thickness of reservoir layers, structural and hydrological designs of permeable pavements particularly the pervious concrete, will be analyzed through modeling approach using '*Pervious Pave*' software. Data relating to soil infiltration capacity, rainfall intensity, elevation profiles and time required to allow the water to completely penetrate, will be utilized for thorough laboratory testing.

The findings reveal that permeable pavements significantly enhance water infiltration into the ground, reducing surface runoff and lessening the burden on conventional drainage systems. Through various types of analysis, the study demonstrates that permeable pavements effectively mitigate flooding by allowing rainwater to percolate into the soil, thus replenishing groundwater resources and minimizing surface water accumulation.

This study contributes valuable insights for urban planners, engineers, and policymakers, providing evidence-based recommendations to incorporate permeable pavements in flood-prone urban areas of Pakistan. By embracing this eco-friendly approach, cities can enhance their resilience against flooding, promote sustainable water management, and create more livable environments for their residents.

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

CHAPTER 1

INTRODUCTION

1.1 Background Study

During recent years, the world has seen a paradigm shift towards sustainability and resilience in the face of climate change. Structures are being designed which are sustainable, economically viable, are resilient towards damaging effects of climate change and have reduced environmental impact. In the field of pavement engineering, the introduction of permeable pavements has gained considerable significance.

When rainwater falls onto traditional pavement like concrete, it gathers and subsequently moves over impermeable surfaces as stormwater runoff. In contrast, permeable pavement enables the gradual infiltration of stormwater, allowing it to seep through and reach the soil and groundwater beneath the surface (Alsobrook, 2020).

There are several varieties of permeable pavement materials, such as synthetic grass pavers, porous asphalt, pervious concrete, and interlocking pavers. Precast blocks, usually made of brick or concrete, are used to make interlocking pavers. The blocks are positioned such that water can pass between them and reach the soil underneath. Conversely, grass pavers are open-cell pavers composed of concrete or plastic that have turf planted in soil-filled cells (Alsobrook, 2020).

Both porous asphalt and pervious concrete pavements contain voids or pores that let water seep through the top surface and into an aggregate reservoir layer below., where it can be stored temporarily before gradually infiltrating into the soil below.

1.2 Problem Statement

Urban areas in Pakistan are facing increasing challenges related to increased runoff from intense rainfalls occurring as a result of climate change, lack of stormwater management, groundwater depletion, and deteriorating water quality due to rapid urbanization and inadequate infrastructure. Impervious surfaces, such as traditional pavements, exacerbate these issues by promoting surface runoff and hindering natural water infiltration. The runoff not only damages existing pavement and drainage infrastructure but also puts a temporary stop to business activities, hence affecting the economy. Permeable pavements have emerged as a potential solution to mitigate these problems, but there is a critical lack of comprehensive research and analysis regarding their effectiveness, feasibility, and adaptability within the context of urban environments of Pakistan. The existing knowledge gap necessitates an in-depth investigation into the analysis of the effectiveness of permeable pavements in urban areas of Pakistan.

1.3 Objectives

- To analyze the applicability vis-a-vis effectiveness of installing permeable pavements in urban areas of Pakistan. Focusing on the low-lying areas of urban cities as they are first and most affected by high rainfall intensities, affecting economic activities.
- To analyze the infiltration rates, runoff reduction, and water storage capacity of permeable pavements against traditional impervious surfaces.
- To assess how permeable pavements can mitigate the impact of heavy rainfall and reduce the risk of urban flooding, thereby enhancing the overall stormwater management system.

1.4 Organization of the Report

- Chapter 1 discusses the major concept of permeable pavements, case study of Portland city, typical cross-sectional details, and hydrological factors involved in their designing.
- Chapter 2 builds upon the general outline of the thesis, giving a deeper insight into the literature review conducted to support the thesis.
- Chapter 3 explains the methodology used in the research, firstly identifying low-lying regions from Arc GIS Pro, building their elevation profiles from Google Earth to further validate the analysis, application of Pervious Pave software and lastly, designing pervious concrete by using AASHTO method while utilizing the parameters from various guidelines.
- Chapter 4 will address the experimentation part, in which sample of already designed pavement from software and AASHTO method will be prepared and tested in laboratory to verify its infiltration rate.
- Chapter 5 will discuss results and reasonings.
- Chapter 6 concludes the entire research and outlines the key points of the work.

1.5 Significance of Study

Assessing the effectiveness of permeable pavements in mitigating flooding in low-lying urban zones of Pakistan holds significant value due to multiple factors. Urban centers in Pakistan are particularly vulnerable to flooding, exacerbated by rapid urbanization, climate change, and inefficient drainage systems. Permeable pavements offer a sustainable solution by allowing water to infiltrate the ground, reducing runoff, and enhancing groundwater recharge, which is crucial in water-scarce regions. Moreover, these systems help alleviate environmental issues like the urban heat island effect and water pollution. Economically, they can potentially reduce the considerable costs associated with urban flooding by preventing damage to infrastructure and minimizing economic disruptions. By providing local data on the effectiveness of such green infrastructure, this research can inform urban planning and policy decisions, ensuring that resilience and sustainability are at the forefront of urban development in Pakistan. This is especially pertinent as cities grapple with the dual challenges of development and climate adaptation.

1.6 Summary

The introduction addresses the global trend towards sustainability and resilience amid climate change, highlighting the importance of permeable pavements in managing stormwater runoff. It points out the specific challenges faced by urban areas in Pakistan, including runoff, groundwater depletion, and water quality deterioration, exacerbated by traditional impermeable pavements. The research aims to assess the effectiveness of permeable pavements in mitigating these challenges, particularly in low-lying urban areas, and to analyze their impact on stormwater management.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

The literature review aims to provide a comprehensive understanding of existing research and knowledge related to permeable pavements, stormwater management, and urban flooding, with a focus on relevant studies and findings applicable to the urban areas of Pakistan. It will explore the evolution of permeable pavement technologies, their effectiveness in reducing stormwater runoff and improving water infiltration, and their impact on urban environments. Additionally, the literature review will examine case studies and best practices from other regions or countries facing similar challenges, drawing insights that can inform the implementation and adaptation of permeable pavements in Pakistan. It will critically analyze the strengths and limitations of existing research, identify gaps in knowledge, and establish a foundation for the subsequent methodology and analysis in the research project.

2.2 Case Study of Portland

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 fine rock, enabling water infiltration. Below these blocks, there are two layers of rock providing 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 major environmental concern for which the project was initiated.

To elaborate, the original street was dug out to a depth of 8-12 inches below the street grade. 8-13 inches below the top of the curb, the excavation reached its full depth. A layer of 2"-minus rock drainage blanket, 6–10 inches deep, was spread over a drainage geotextile fabric that had been 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, there 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 leveling bed of 3/8"-minus rock was positioned and compacted to a depth of 3 inches. After the permeable pavers were put in place on the leveling bed, fine rock was added to the spaces left by the paving blocks, and it was then compacted (Portland Oregon, 2004).

Most stormwater seeps through the porous pavement, into the layers of rock beneath the street, and eventually into the earth when permeable pavements are installed. The storm inlets that were already in place were kept in place to collect any excess runoff. This project was a breakthrough for the entire community.

2.3 Cross-Sectional Details of Porous Asphalt

Porous Asphalts are one of the types of permeable pavements designed to allow water to infiltrate and merge with the groundwater. Although, design of porous asphalt may vary depending upon level of application, infiltration desired and climatic conditions but in this thesis, a generic design will be explained to understand its concept.

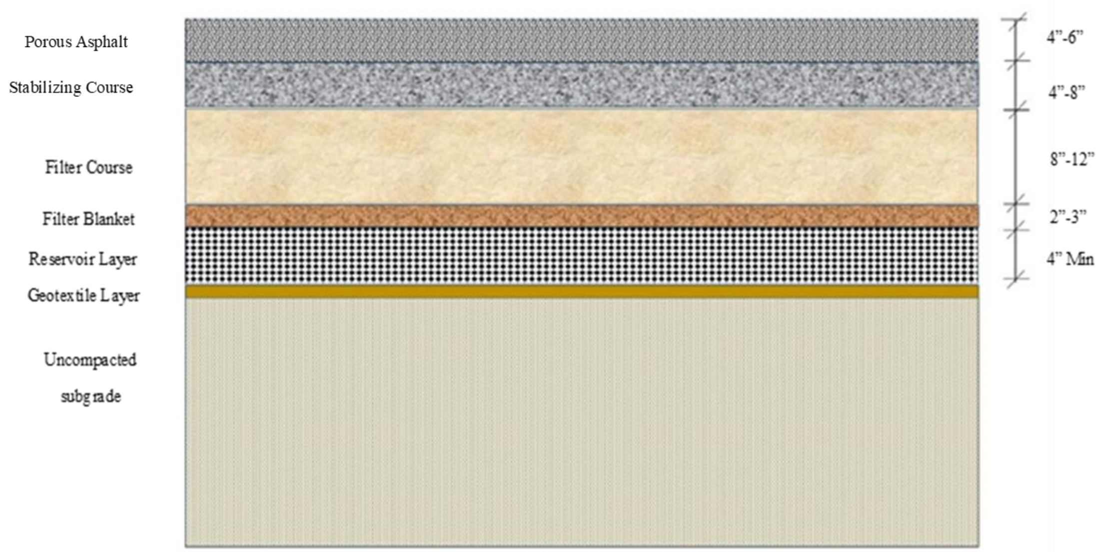

Figure 1: X-Section of Porous Asphalt Pavement

Several layers designed for structural, hydrologic control, and water quality improvement are laid beneath the porous asphalt itself (Figure 1). To reduce drain down and provide resistance to scuffing, mixes are typically designed with polymer-modified binders (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 construction of subbase easier. The purpose of fine gradation of filter course 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 in between storms. To prevent downward of migration filter course material, a filter blanket is placed in between. 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.

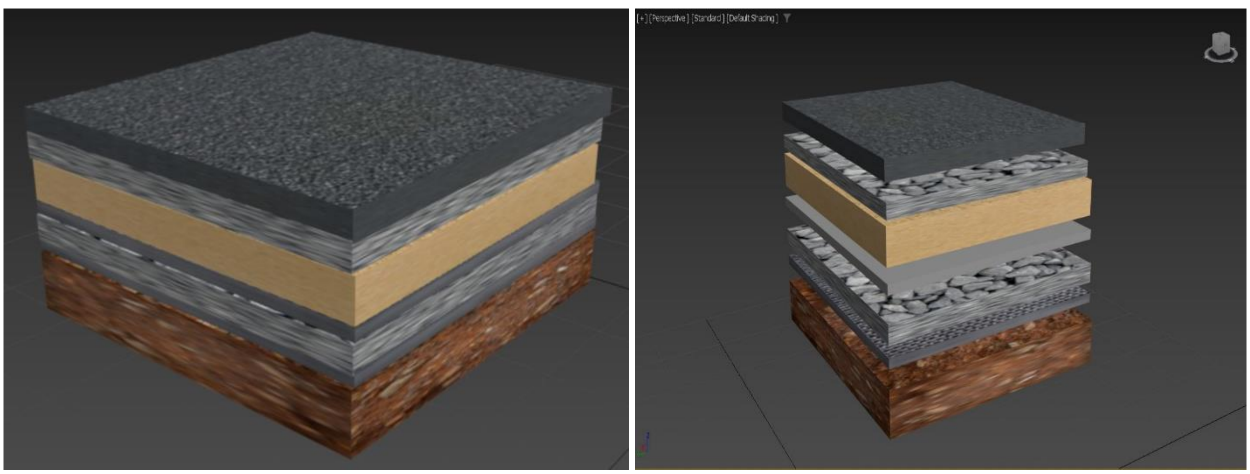

Figure 2: Typical Cross-Section of Porous Asphalt

2.4 Cross-Sectional Details of Pervious Concrete

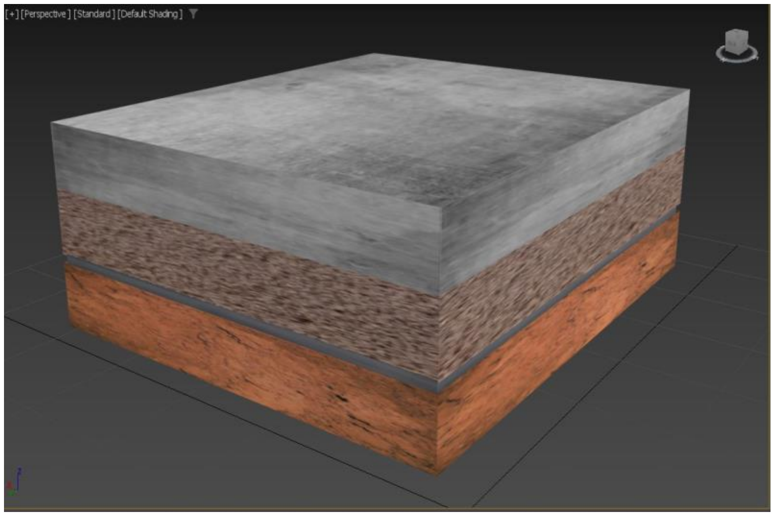

Figure 3: Typical X-Section of Pervious Concrete

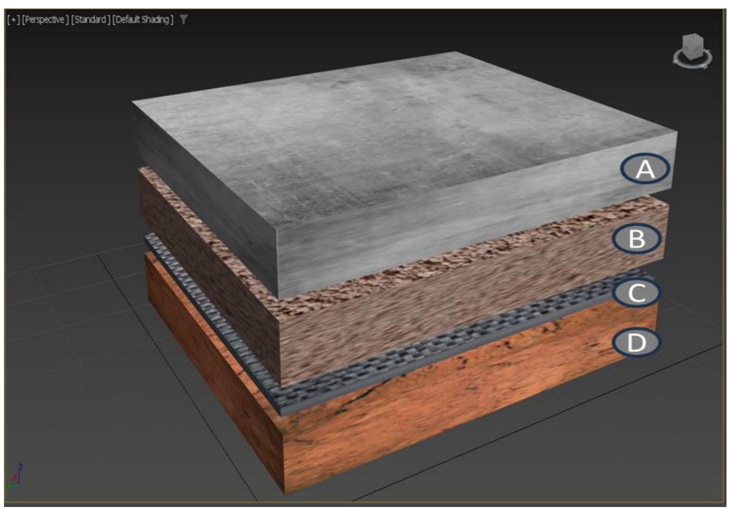

Figure 4: X-section of Pervious Concrete shown in separate layers

Figure 3 and 4 above show typical pervious concrete x-section (created in Autodesk 3ds Max). This is explained in the following paragraphs.

A: Pervious concrete layer consists of an open-graded concrete mixture usually ranges from 4-6 inches deep. Void content may range from 15-20% (Shinde & Valunjkar, 2015).

B: The aggregate base course consists of a clean and durable crushed aggregate with a void content of 35-40%. The aggregate sub-base layer should have a depth of minimum 10 inches. The layer should be designed with a draw down time of 48 hours.

C: Geotextile fabric is placed between sub-base and sub-grade layer. The filter fabric provides a separation to stop the movement of fine soil particles into the reservoir layer (Shinde & Valunjkar, 2015).

D: Subgrade layer (infinite thickness).

2.5 Hydrological Factors Involved in Design of Permeable Pavements

2.5.1 Infiltration Considerations

A major hydrological design consideration is the depth of sub-base. The minimum depth of sub-base should be kept so that maximum depth of water h_{max} does not cause flooding over the surface. Sub-base depth depends upon rainfall intensity (mm/hr or in/hr), peak surface runoff from surrounding sites and permeability characteristics of sub-base and sub-grade (Kia, Delens, Wong, & Cheeseman, 2021). Moreover, h_{max} also depends upon how much infiltration is desired.

If complete infiltration of rainfall is desired (usually the case in permeable pavements), then the following equation will govern.

$$\text{hmax} = D\,\frac{(R * I) - q}{n} \qquad (1)$$

$$t\frac{1}{2} = \frac{n * hmax}{2q} \qquad (2)$$

In equations above, D = duration of rainfall (hr); R = ratio of drained area to infiltration area; i = intensity of rainfall (m/hr); q = coefficient of infiltration determined from percolation test; n = porosity and $t_{1/2}$ is the time taken to discharge 50% of the area in not more than 24 hours.

2.5.2 Intensity of Rainfall

The depth (mm, in), duration (hours) and frequency of critical rainfall events can be obtained from Pakistan Meteorological Department Website. The data is considerably accurate as it is for large catchment areas. Therefore, it serves the purpose of designing permeable pavements.

2.5.3 Runoff Calculations

Permeable pavements must have sufficient storage capacity so that runoff from surrounding impervious surfaces can also be managed. For conventional permeable pavements, the ratio of catchment area to permeable pavement area should not exceed 2 so to avoid excessive clogging from sediments in surface runoff (Woods-Ballard, et al., 2007). Apart from rainfall, runoff from surrounding impervious surfaces is also considered as rainfall and runoff calculated accordingly.

$$V = i * A * D \quad (3)$$

V = runoff volume in (mm^3); i = Rainfall intensity in mm/hr; A = Area of impervious surfaces; D = Duration of design rainfall duration (hr).

2.5.4 Storage Depth

The storage capacity of a pervious concrete pavement is usually tailored to meet specific local rainfall requirements. While the overall amount of rainfall is crucial, it is equally important to consider the soil's infiltration rate.

The overall storage capacity of the pervious concrete system includes the capacities of the pervious concrete pavement and any utilized subbase, along with the amount of water that infiltrates into the soil below. The theoretical storage capacity of the pervious concrete is determined by its effective porosity, representing the portion of the concrete that can be filled with rain during service. To illustrate, a 4-inch thick pavement with 15% porosity, situated over an impervious clay, has the potential to retain up to 0.6 inches of rain before contributing to excess surface runoff (Smith, 2019).

Another significant reservoir for storage is the subbase. When compacted clean stone, such as #67 stone, is used as a subbase, it shows a porosity of 40%. In contrast, a typical aggregate subbase, with higher fine content, will have a lower porosity, usually around 20% (Tennis, Leming, & Akers, 2004). In the given scenario, with 4 inches of pervious concrete having 15% porosity placed on top of 6 inches of clean stone, the nominal storage capacity would amount to 3.0 inches of rain. This is calculated by adding the contributions from the pervious concrete (15% of 4 inches) and the clean stone subbase (40% of 6 inches), resulting in a total storage capacity of 3.0 inches.

2.6 Summary

The summary encapsulates the implementation of permeable pavement in Portland's Westmoreland neighborhood, a pioneering project aimed at managing stormwater runoff and reducing combined sewer overflow into the Willamette River. By paving three blocks with permeable pavement, utilizing layers of rock and geotextile fabric beneath the surface, the project allowed stormwater to infiltrate into the ground, mitigating environmental concerns and demonstrating the effectiveness of permeable pavements in urban settings.

Furthermore, this highlights the key considerations in designing permeable pavements, such as the depth of the sub-base, ratio of catchment area to pavement area. It also underscores the importance of tailored design for specific local rainfall requirements and soil infiltration rates, emphasizing the role of effective porosity in determining the storage capacity of pervious concrete pavements. Overall, the summary underscores the significance of permeable pavements as sustainable solutions for managing stormwater runoff and improving urban water quality, while emphasizing the need for meticulous design and implementation to achieve optimal performance.

CHAPTER 3

MATERIALS AND METHODOLOGY

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

3.1.1 Background

As the project focuses on measures to mitigate urban flooding in low lying areas, it was important to first identify these regions. In this regard, optimum use was made of Arc GIS Pro software. Firstly, localized depression analysis was carried out. Further on, flow direction analysis was also done to analyze the direction of water i.e. the relief of ground. In doing so, it also validated the analysis of localized depression. From this process, low lying regions were identified, and their elevation profiles were obtained from Google Earth to quantify the elevations and depressions.

3.1.2 Localized Depression Analysis

Localized depression analysis involves identifying and assessing specific low-lying areas prone to water accumulation within a region. This analysis helps pinpoint areas vulnerable to flooding and informs the design of targeted stormwater management.

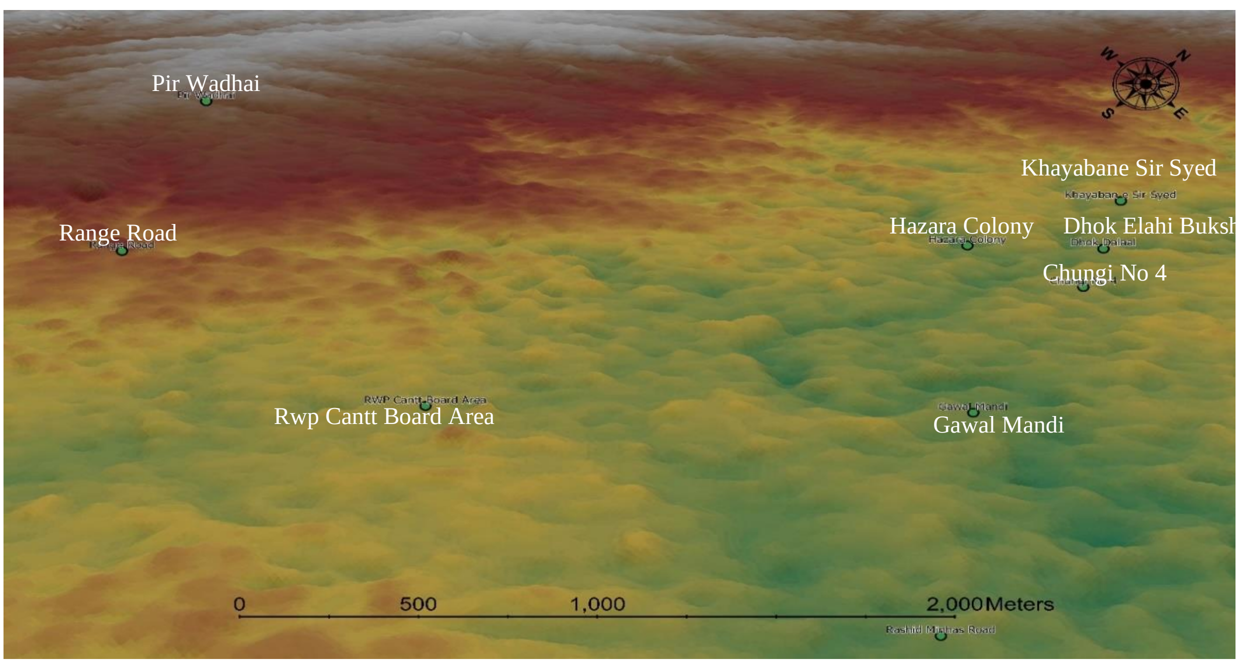

Figure 5: Localized Depression Analysis depicting low-lying zone of Rawalpindi

Figure-2 shows a few areas of Rawalpindi that have been identified as low-lying zones through localized depression analysis carried out in Arc GIS Pro software. These include Rawalpindi Cantonment Board area, Range Road, Khayaban-e-Sir Syed, Dhok Dallal, Chungi No 4, Hazara Colony and Gawal Mandi. Green color depicts low lying areas whose elevation is relatively low as compared to surroundings. Therefore, the risk of urban flooding from high intensity monsoon rainfalls is high in these areas. Similarly, areas in yellow color are low too but relatively higher than the green ones.

3.1.2 Flow Direction vis-à-vis Drainage Network

Flow direction tool identifies such areas towards which various bodies of water flow. Since such areas are those which lie in depression, because of which water flows towards them and accumulates, this tool will help validate the analysis carried out previously from localized depression.

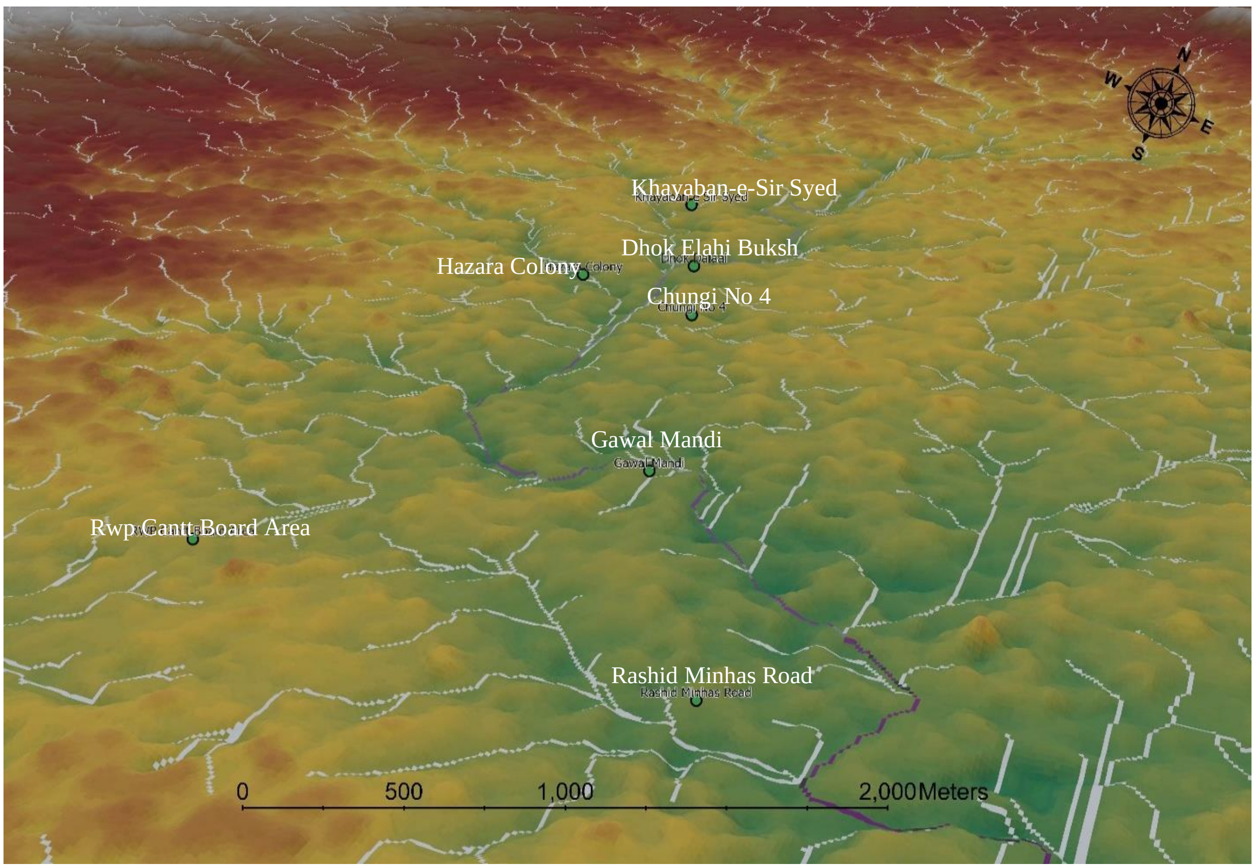

Figure 6: Flow direction analysis depicting direction of surface runoff

Figure-6 shows flow direction, which means direction of surface runoff flowing towards lower elevation areas. These areas are the same as shown in Figure-5. Therefore, Figure-6 supports the analysis of Figure-5.

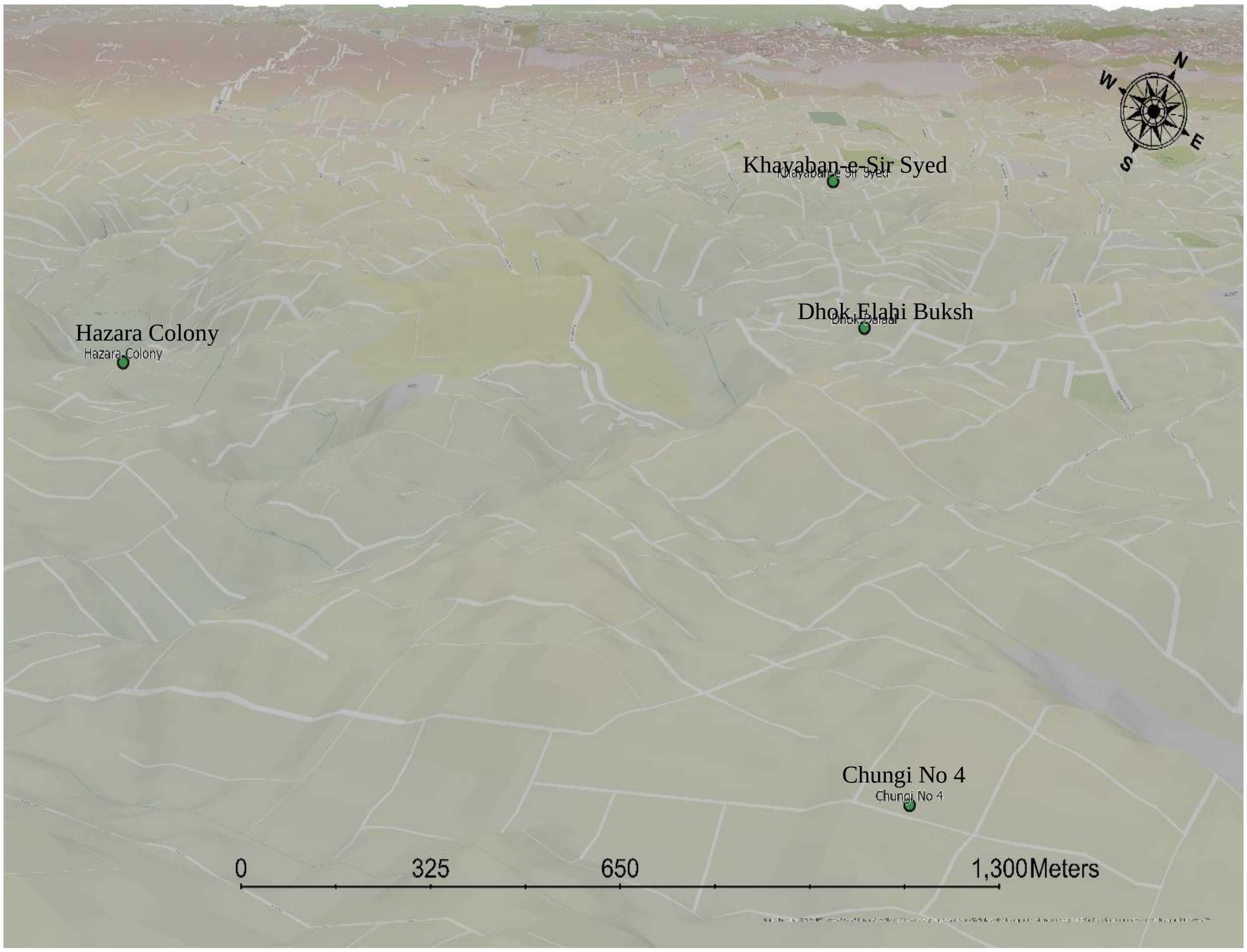

Figure 7: Closer view of areas identified as low-lying zones

Figure-7 shows low lying areas with a zoomed in view. Although, there are no such undulations on ground, but 'vertical exaggeration factor' of '5' was applied to amplify the undulations to clearly show the low-lying regions. It is now evident from the above analysis that the construction of permeable pavements in such areas of lower elevation will have significant reduction in surface runoff from rainfall, ultimately leading to reduced risk of urban flooding.

3.1.3 Analysis from Elevation Profiles

Elevation profiles of Chungi No 4, Dhok Elahi Bukhsh, Gawal Mandi and Hazara Colony represented below have been obtained from 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%
Gawalmandi	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%

From analysis of low-lying regions of Rawalpindi undertaken through ARC GIS vis-à-vis the elevation profiles obtained, it can be concluded that if permeable pavements are constructed in this region, the risk of urban flooding can be reduced as well as load on the drainage infrastructure can be significantly decreased as the pavement will allow water to infiltrate and recharge the ground water.

3.2 Maximum Rainfalls in Major Urban Cities of Pakistan

Data below in Table 2 has been obtained from Pakistan Meteorological Department website. From the province of Punjab, Rawalpindi records the highest rainfall in 24 hours as 78.3 in. This rainfall will be used for this research as an important parameter while utilizing Pervious Pave software to determine the thickness of reservoir layer.

Table 2: Historical maximum rainfalls of major cities recorded in 24 hours *(Pakistan Metereological 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

3.3 Application of 'Pervious Pave' Software

3.3.1 Purpose

Pervious Pave is a software developed by American Concrete Pavement Association (ACPA) which provides results for structural and hydrological requirements for pervious concrete pavements. Purpose of utilizing this software was to determine thickness of pervious concrete and reservoir layer which will then be tested in laboratory for infiltration capacity. Comparing this capacity with design storm precipitation of Rawalpindi is going to provide results useful for analyzing the effectiveness of these pavements. Since there is no proper method available for determining thickness of permeable pavements, therefore, using this software was need of the research.

3.3.2 Project Tab

For this research, a design period of 20 years. For collectors or arterial streets, the range given is 75%-95% is given. Therefore, 95% reliability has been selected.

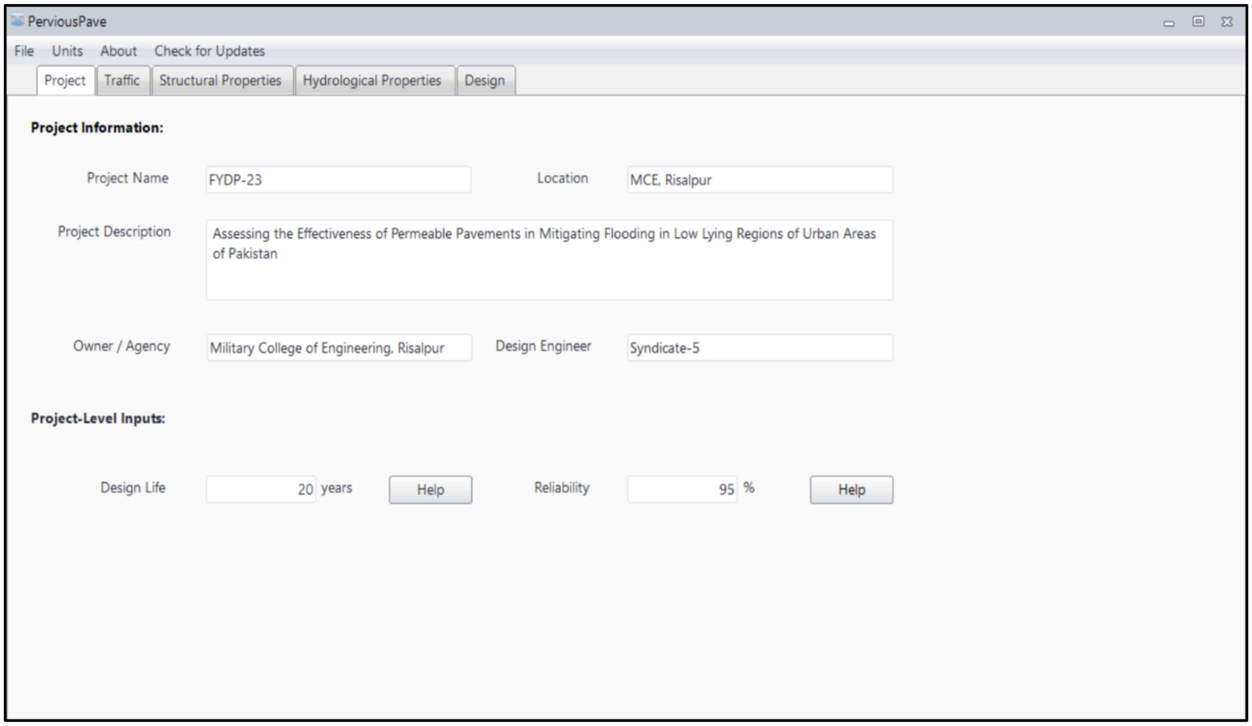

Figure 12 Project Tab of Pervious Pave Software

3.3.3 Traffic Tab

For load spectra, 'Collector' has been selected as the reliability of 95% is also against collector roads. Moreover, ADTT of 50 has been set as default for collector roads. Therefore, same has been selected with a growth percentage of 4%. Percentage of traffic on design lane has been set at 100%.

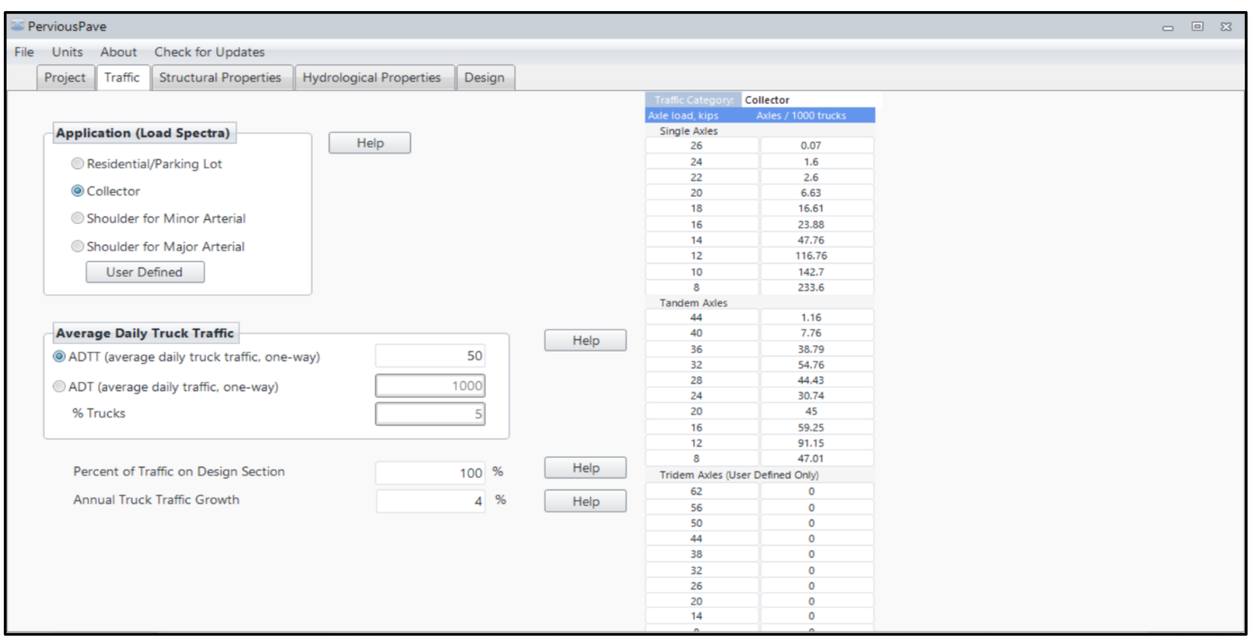

Figure 13: Traffic Tab of Pervious Pave Software

3.3.4 Structural Properties Tab

Resilient modulus of subgrade (MRSG) of 3500 psi has been taken which is the lower limit given for the range of Class ‘C’ soil type. The range of MRSG for this class is 3500-4275 psi.

Composite Modulus of subgrade has been calculated with the help of software by selecting 1 reservoir layer. The anticipated thickness has been set as 8 inch and resilient modulus of subgrade has been set as 25000 psi which is the default average value.

For compressive strength (fc’) of 3000 psi, range for 28-day flexural strength of concrete given is 400-550 psi. Therefore, MR selected is 550 psi for average fc’ of 3000 psi. The modulus of elasticity (E) is then automatically calculated by software.

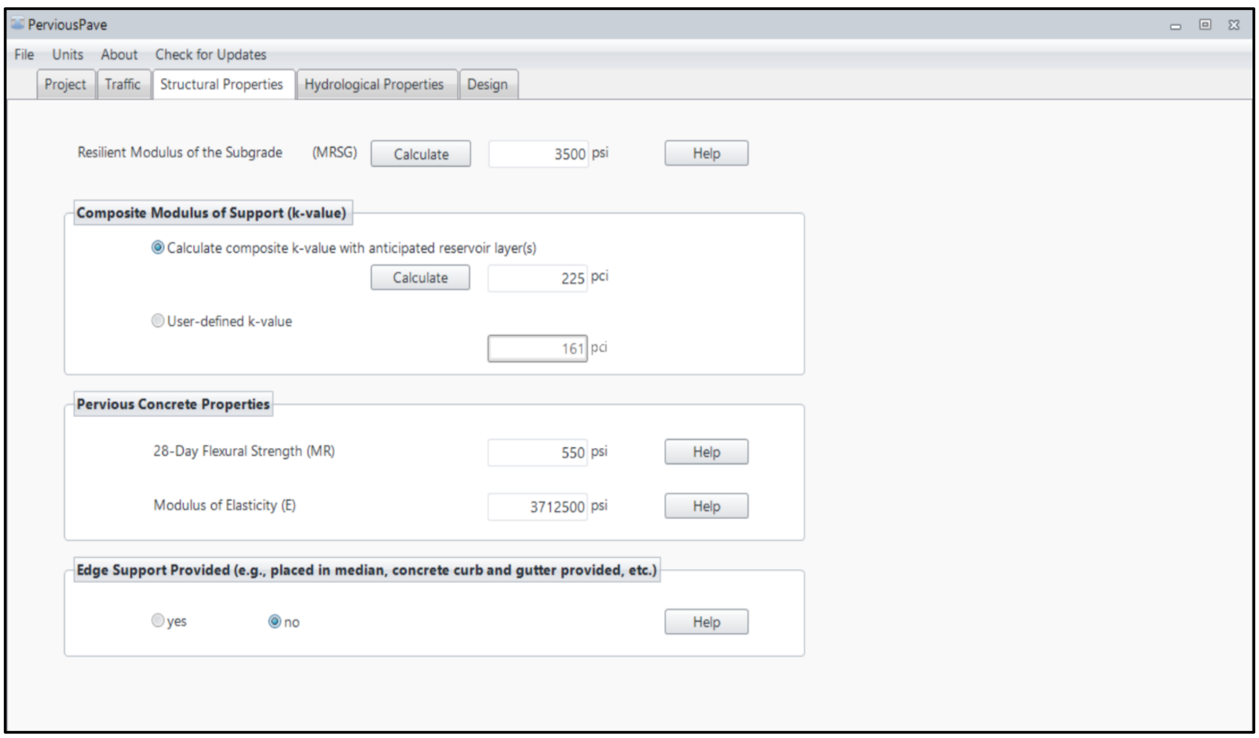

Figure 14: Structural Properties Tab of Pervious Pave Software

3.3.5 Hydrological Properties Tab

If it is assumed that a 5 km long strip of road shall be constructed as pervious concrete pavement with a width of 3.5 m, therefore, the area of pervious concrete in ft^2 becomes $5x1000x3.5x3.281^2$=188,386 ft^2. Non-pervious area to be drained is unknown so can be taken as 1.5 times the pervious concrete area i.e. 1.5x188,386=282,580 ft^2.

Infiltration rate of soil for Potohar Plateau region which includes Rawalpindi is roughly 0.5-1 inch/hr. (Malik, Ashraf, Bahzad, & Aslam, 2019). Therefore, the lower value i.e. 0.5 inch/hr has been selected.

The percentage of voids of pervious concrete and reservoir layer material are 15% and 40% respectively. These values are assumed since they have been calculated through tests to be optimum values for effective drainage of surface runoff.

Design storm precipitation is 78.03 inches which is the maximum rainfall Rawalpindi has received historically so far, as indicated in table 2. The maximum detention time of water in pervious section is set at 24 hours.

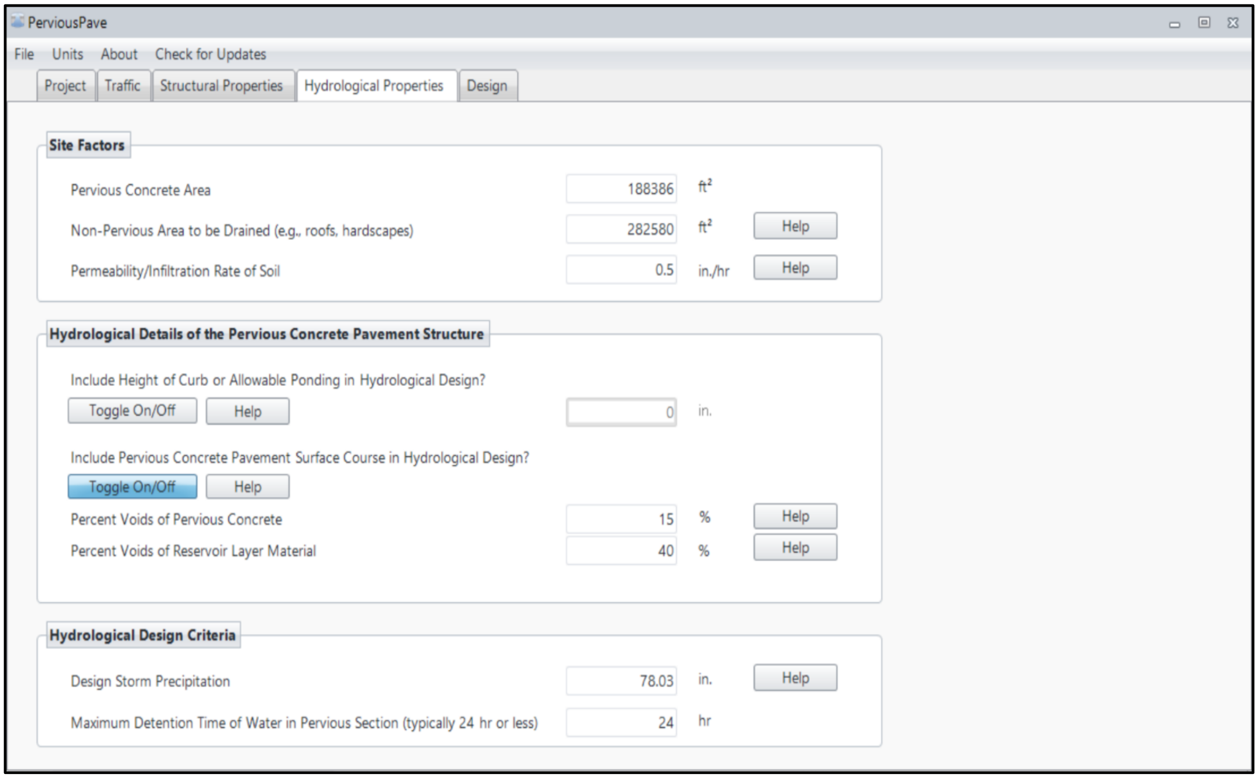

Figure 15: Hydrological Properties Tab of Pervious Pave Software

3.3.6 Design Tab

When structural analysis is run on the software, the required pervious concrete thickness is found to be 6.5 inches.

When hydrological analysis is run, the volume of water processed is found to be 78494.3 ft^3. The thickness of reservoir layer required to process this water effectively within the specified detention time is found to be 10.06 or 11 inches.

Normally, the thickness of reservoir layer varies from 6-12 inches depending on various factors discussed above. 11 inches lies within this range, therefore, there is no need to increase the area of pervious concrete or percentage voids in the reservoir layer.

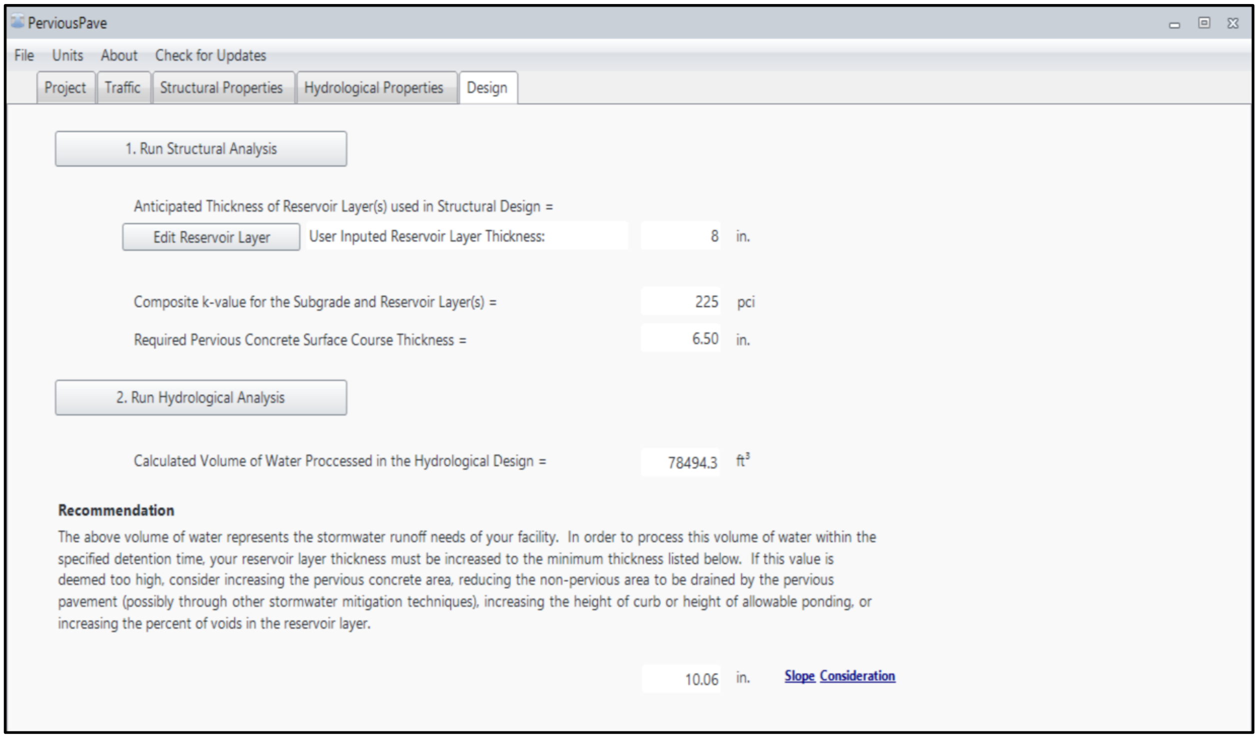

Figure 16: Design Tab of Pervious Pave Software

3.4 Methodology for Structural Design

The AASHTO road test performed in late 1950’s in Ottawa, Illinois only incorporated conventional concrete and asphalt. No permeable pavements were constructed. Therefore, using this method to design pervious concrete may produce results which are not precise. In order to properly use this method and configure its inputs in such a way that it can be used for design of pervious concrete, thorough testing of flexural strength, compressive strength, elastic modulus and Poisson’s ratio is required. This research does not include testing of such parameters. Rather, the test values already obtained from ASTM standards testing performed at University of Arkansas, Fayetteville shall be used. 28-days compressive strength of a coarse-graded pervious mix was found to be about 1400 psi (Smith, 2019). Flexural strength varied from 150 psi to 550 psi (Pervious Concrete Pavement, 2011).

3.4.1 Selection of Gradation

National Ready Mixed Concrete Association’s Guideline to Proportioning Pervious Concrete Mixtures (NRMCA) suggests using AASHTO No 67 for pervious concrete mix (NRMCA, 2020). But the gradation was adjusted so that the mix only includes the aggregate sizes from the gradation that would be retained on No. 4 sieve and above. These sizes included aggregates retained on 1/2”, 3/8” and No 4 sieve. Percentage passing for each of these sizes were 67%,33% and 0% (Smith, 2019).

3.4.2 Water/Cement (W/C) Ratio Against Percentages of Fly Ash

ASTM C305-14 and ASTM C1437-15 tests were performed at University of Arkansas. ASTM C305-14 was used to prepare various paste batches with varying W/C ratio. ASTM C1437-15 was then followed to check their consistencies. W/C ratio for 0%, 15% and 30% fly ash were found to be 0.41, 0.38, 0.375.

3.4.3 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

3.4.4 Flexural Strength

$$R = \frac{PL}{bd^2} \quad (4)$$

where,

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

3.4.5 Determination of Slab Thickness

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

$$log_{10}(W_{18}) = Z_R S_O + 7.35 log_{10}(D+1) - 0.06 + \frac{log_{10}\left(\frac{\Delta PSI}{3}\right)}{1 + \frac{1.624 \times 10^7}{(D+1)^{8.46}}} + (4.22 - 0.32\text{p}_t) log_{10}\left(\frac{S'_c C_d (D^{0.75} - 1.132)}{215.63J\left(D^{0.75} - \frac{18.42}{\left(\frac{E_c}{k}\right)^{0.25}}\right)}\right) \quad 5$$

Where,

W_{18} = estimated amount of 18,000 lb. equivalent single-axle loads (ESAL's)

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

S_O = combined standard error of traffic & performance prediction; design's reliability

ΔPSI = 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 transf

E_c = elastic modulus of concrete (psi)

k = modulus of subgrade reaction (pci)

3.4.6 Design Traffic Loads (W_{18})

As permeable pavements are not usually applicable for highways, therefore, traffic loads for urban streets will be used.

Table 4: Traffic Loads for Design

Minimum ESALs	Average ESALs	Maximum ESALs
$5x10^5$	$1x10^6$	$1.5x10^6$

3.4.7 Reliability (Z_r, S_o)

Value of standard normal deviate i.e -0.674 against reliability of 75% is taken based on average of values from AASHTO 93 guide (Christopher, Schwartz, & Boudreau, 2010).
Standard deviation of 0.35 is taken from Arkansas Department of Transportation roadway design guide (Arkansas, 2020).

3.4.8 Design Change in Pavement Serviceability Index (ΔPSI)

Taking p_t = 4.5 and p_o = 2.5 (Arkansas, 2020) ΔPSI=4.5-2.5=2

3.4.9 Concrete Modulus of Rupture (S'_c)

For concrete flexural strength, value of 230 psi has been selected since all the tests had almost similar results. Below is the most used relation to find the concrete flexural strength.

$$S'_c = \alpha(f'_c)^\beta \quad \textbf{6}$$

Where, α and β are coefficients obtained from laboratory testing performed at 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)

Value taken is 1.0 in this case as all the water in case of permeable pavements will drain.

3.4.11 Load Transfer Coefficient (J)

In case of permeable pavements, there are no load transfer devices (dowel bars and tie bars). Value of 4.0 is taken which is 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).

3.4.12 Elastic Modulus of Concrete (Ec)

Tests performed at University of Arkansas were not able to provide reliable results therefore the commonly used empirical relation between E_c and f'_c given below will be used.

$$E_c = 57000(f'_c)^{0.5} \quad \textbf{7}$$

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

3.4.13 Modulus of Subgrade Reaction (k)

To determine 'k', AASHTO's 1993 guide has been used. Subbase (open graded stone reservoir layer) thickness of 18'' is taken so as to gradually drain water into the subgrade. Subbase elastic modulus of 15,000 psi is taken from the lower limit for the range of 'Unbound Granular Materials' i.e. 15000 psi to 45000 psi.; The median value available on the chart for the roadbed resilient modulus of 7000 psi is taken. Using above values, following chart wil l determine modulus of subgrade reaction ‘k’ as 490 pci, as indicated through red arrows.

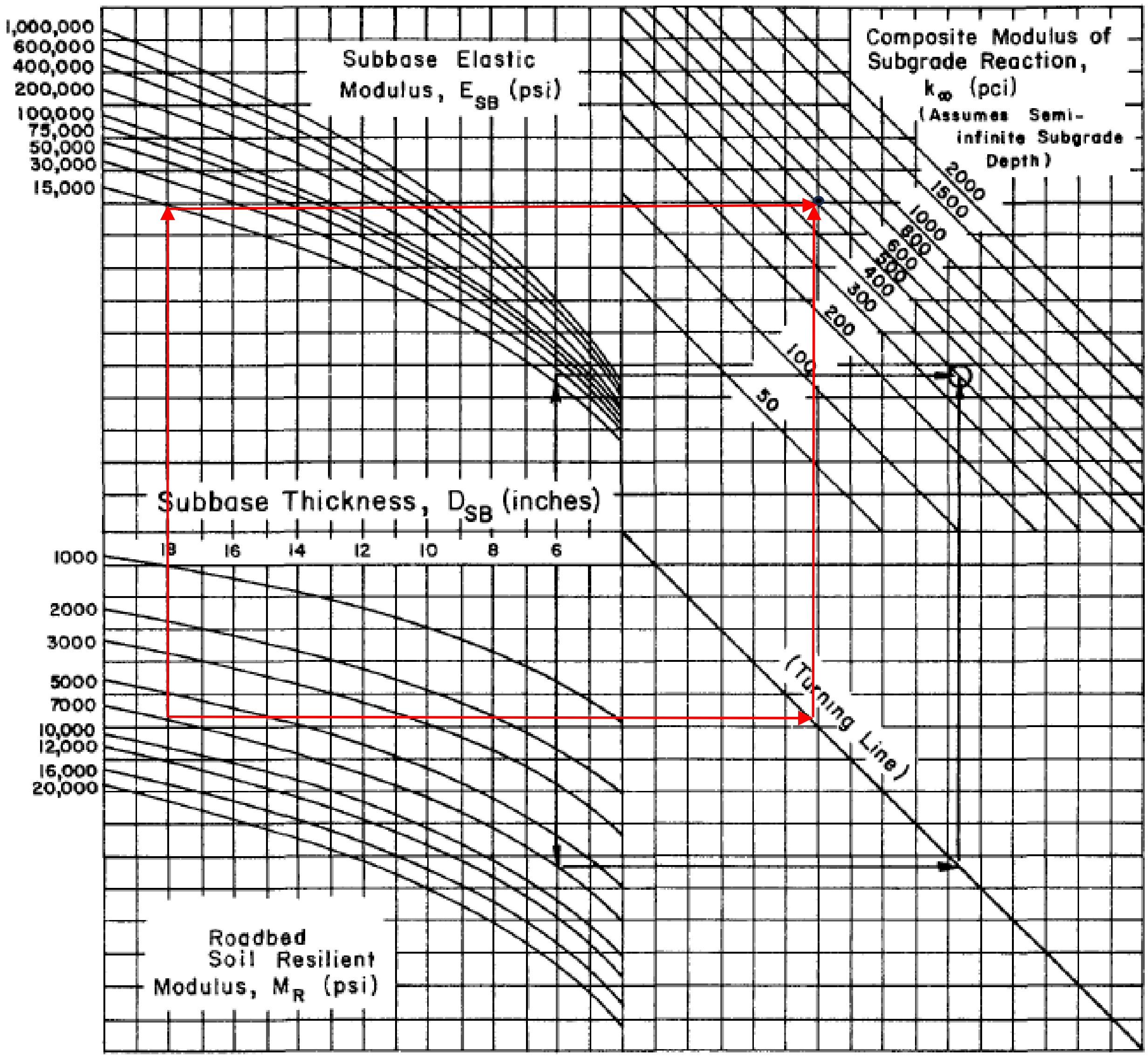

Figure 17: Chart for Determining Modulus of Subgrade Reaction '*k*'

3.4.14 Summary of Design Inputs

Design Input Parameter	Value	Source
W_{18}	$5x10^5$, $1x10^6$, $1.5x10^6$ ESALs	Assumed values for urban streets
R	75%	AASHTO 1993 Guide
S_O	0.35	ARDOT Guidelines
ΔPSI	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

3.4.15 Resulting Pervious Concrete Surface Thickness

Design ESALs	Pavement Thickness obtained from Equation 5	Design Pervious Concrete Thickness
$5x10^5$	10.24 in	10.5 in
$1x10^6$	11.53 in	12 in
$1.5x10^6$	12.33 in	12.5 in

Pavement thicknesses have been rounded off to nearest ½’’ as per recommendations of AASHTO (Bekele, 2011).

3.5 Summary

This chapter encompasses identification of low-lying areas and the maximum rainfall furthermore it deliberately describes the use and certain features of pervious pave software and closing the chapter covering different aspect of structural design including flexural strength, traffic load and reliability.

CHAPTER 4

EXPERIMENTATION

4.1 Experimental Setup

4.1.1 Sample preparation

To conduct permeability tests, a number of rectangular samples of pervious concrete were created, out of which three samples were selected with different gradations. These tests were conducted at the Geotech Laboratory situated in the Military College of Engineering, Risalpur Cantonment.

The mix design for this study was based on a review of existing literature, as there was no established mix design procedure for pervious concrete at the time. The study used previously researched mix proportions to explore the impact of coarse aggregate gradation on the hydraulic properties of the mixtures. Three different pervious concrete mixtures were produced, each with varying coarse aggregate gradations, as detailed in Table 4.

Based on the literature, the range of cement content for producing pervious concrete varies from 340 to 400 kg/m³. In this study, a cement content of 375 kg/m³ was used. The coarse aggregate content was 1,662 kg/m³, which corresponds to a cement-to-aggregate ratio of **1:4.4**, close to what was researched through literature. The water-to-cement ratio was set at 0.3, in line with other studies. Table 5 provides a summary of the material proportions used in this research.

The method used to compact and mold the rectangular samples, measuring 32 cm in length, 22.5 cm in width and 25.4 cm (10 inch) in thickness, involved rodding each sample 15 times over three layers. Unlike standard concrete, samples were demolded after a period of 7 days. This deviation from the typical 24-hour demolding period recommended by international standards was necessary because pervious concrete did not exhibit a sufficiently stable structure to allow for earlier demolding.

Figure 18: Pervious Concrete Sample (32 cm x 22.5 cm x 25.4 cm)

Table 4: Coarse Aggregate Proportions Used in Mixes

Samples	**% of retained material on sieve**		
	9.5 mm	**6.3 mm**	**4.75 mm**
1	0	100	0
2	0	50	50
3	30	40	30

Table 5: Coarse aggregate proportions used in Mixes

Material	**Proportion**
Cement (kg/m^3)	375
Course aggregate (kg/m^3)	1662
Water/cement ratio (by mass)	0.3
Cement/aggregate ration (by mass)	1:4.4

4.1.2 Falling Head Permeability Test

In the laboratory, a falling head apparatus was used to conduct the permeability tests. This device includes a valve and a measuring tube to monitor the height of the water column. For each type of pervious concrete mixture, experiment was performed five times to ensure an adequate sample size for the statistical analysis of the results.

Figure 19: Setting the Falling Head Permeability apparatus (left). Increasing water column height to 35 cm after closing the valve (right)

To prevent water from escaping through the sides during testing, the samples were wrapped in plastic film and again inserted into the mold to ensure no water leakage occurred during the tests. These tests were performed 28 days after the samples were molded.

The testing procedure began by introducing water into the apparatus. Once the sample was fully submerged, the valve at the bottom of the permeameter was shut, and the water column height upstream was raised to 30 cm. Upon opening the valve, the time taken for the water column height to drop from 30 cm to 5 cm was measured. This duration was then used in Equation (8) to calculate the hydraulic conductivity of the samples.

$$k = \frac{aL}{At}(\ln\frac{h_1}{h_2}) \quad (8)$$

In Equation (8), 'k' represents the hydraulic conductivity measured in centimeters per second (cm/s). The variable 'a' denotes the cross-sectional area of the standpipe i.e. $\boldsymbol{\pi(0.5)^2}$ **= 0.785 cm^2**, while **L=25.4 cm** is the thickness of the. '**A=32x22.5=720 cm^2** stands for the cross-sectional area of the specimen. The variable 't' is the time in seconds (s) it takes for the water level to drop from height 'h_1' to ' h_2', where ' **h_1=30 cm**' and ' **h_2 =5 cm**' are the initial and final water levels, respectively.

Figure 20: Setting up of apparatus (left). Pervious concrete sample over which apparatus has been placed (right).

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Falling Head Test

Following are the values of hydraulic conductivities which have been obtained from falling head test performed in the laboratory. It is pertinent to mention that the results obtained were in 'cm/sec' but for ease of comprehension of the reader, they have been converted to 'in/hour' in the same table so that they can be conveniently compared to the design storm precipitation i.e. 78.03 in.

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 depicted in red cells is the lowest hydraulic conductivity value, while 0.15 cm/s or 212.59 in/hr depicted in yellow cells is the lowest hydraulic conductivity value measured across all sample results. The hydraulic conductivity values obtained from the falling head tests were consistent across all three concrete mixes. This outcome suggests that the variations in coarse aggregate gradation employed in this study do not significantly influence the drainage properties of the pervious concrete. Moreover, the hydraulic conductivity values measured using this permeability test were found to range from 0.13 to 0.15 cm/s. These results fall within the spectrum commonly reported in the literature for pervious concrete mixes. Various authors who have studied this parameter in pervious concrete have published values ranging from 0.01 to 1.5 cm/s. (Schaefer, Wang, Suleiman, & Kevern, 2006). It was observed that the falling head test results differ significantly from constant head test results keeping in view the literature, with the falling head test yielding higher hydraulic conductivity values. This discrepancy could be attributed to the differences in equipment technology. In the falling head test, the samples were wrapped in plastic film to minimize or restrict lateral water flow. However, unlike the setup in the constant head permeameter, no external pressure was applied to the cores in the falling head test. This lack of external pressure might have led to a significant loss of water through the sides of the specimens, resulting in greater hydraulic conductivity values. (Montes & Haselbach, 2006).

5.2 Discussions

In Table 6, cells highlighted in red depict the lowest hydraulic conductivity value across all the sample results i.e. 0.11 cm/s or 158.4 in/hr. This value which is lowest across complete experiment is still much greater than the design storm precipitation (approximately two times) i.e. 78.03 inches recorded for 24-hour rainfall. Lowest value has been selected so to compare the safest possible result.

Although the design storm precipitation i.e. 78.03 inches has actually fallen for some specific time, maybe few hours but the rainfall gauge set for recording the rainfall was measured at the end of 24-hour period. As no data was available regarding the exact time for which the design storm precipitation took place, it was assumed for research purposes that the rainfall took place for 1 hour i.e. 78.03 in/hr and weather remained clear for next 23 hours. This assumption was important for two reasons. One, it keeps us on the safer side as assuming the rainfall for 1-hour actually means extremely high intensity rainfall. Pavements designed against this rainfall intensity will be safe for any intensity of precipitation. Second, it is easier to compare the hydraulic conductivity values with the design precipitation as the experimental values are also in 'inches/hour'.

Keeping above in view, since 155.90 in/hr (lowest measured hydraulic conductivity value) is much greater than 78.03 in/hr (design storm precipitation), it can be safely concluded that the pervious concrete pavement with gradation and specifications as mentioned in Table 4 and Table 5 with thicknesses as calculated in Section 3.4.15 can be employed in any area of Rawalpindi as per the predicted traffic ESALs mentioned against the ESALs.

CHAPTER 6

CONCLUSIONS

Based on the comprehensive research and analysis performed during our project on the effectiveness of permeable pavements in mitigating flooding in low-lying urban zones of Pakistan, few conclusions drawn have been given below:

1. The use of flow direction and localized depression tool of Geographic Information System (GIS) software and elevation profiles from Google Earth were instrumental in accurately identifying low-lying flood-prone areas in urban settings. Such areas matched the ones already identified by District Administration (Islamabad), hence, validating the analysis.
2. The application of both the Pervious Pave software and the AASHTO method for determining the thickness of pervious concrete pavements provided consistent results, validating the robustness of these design approaches in practical scenarios.
3. While calculating pavement thickness using the AASHTO's equation for rigid pavements, certain parameters were assumed or were taken from various guidelines. Since the lab results exhibited the effectiveness of these pavements, it showed that AASHTO method could also be used for pervious concrete pavements with certain assumptions.
4. Though gradation do not significantly influence the drainage properties, however, proper water/cement ratio and aggregate cement ratio are critical to achieve desired permeability and structural integrity, emphasizing the need for stringent quality control in material selection and pavement construction.
5. Permeable pavements are highly effective in managing extreme rainfall events in urban areas, as evidenced by the experimental data showing that a 10-inch thick pervious concrete pavement can sustain up to 158.4 inches of rainfall, far exceeding the highest recorded 24-hour rainfall in the region (78.3 inches).

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TABLE OF CONTENTS

ABSTRACT 4
CHAPTER 1 5
INTRODUCTION 5
1.1 Background Study 5
1.2 Problem Statement 5
1.3 Objectives 6
1.4 Organization of the Report 6
1.5 Significance 7
1.6 Summary 7
CHAPTER 2 8
LITERATURE REVIEW 8
2.1 Overview 8
2.2 Case Study of Portland 8
2.3 Cross-Sectional Details of Porous Asphalt 9
2.4 Cross-Sectional Details of Pervious Concrete 11
2.5 Hydrological Factors Involved in Design of Permeable Pavements 12
2.5.1 Infiltration Considerations 12
2.5.2 Intensity of Rainfall 12
2.5.3 Runoff Calculations 12
2.5.4 Storage Depth 13
2.6 Summary 13
CHAPTER 3 15
MATERIALS AND METHODOLOGY 15
3.1 Identification of Low-Lying Zones of Rawalpindi vis-à-vis Significance of Permeable Pavements 15
3.1.1 Background 15
3.1.1 Localized Depression Analysis 15
3.1.3 Analysis from Elevation Profiles 18
3.2 Maximum Rainfalls in Major Urban Cities of Pakistan 19
3.3 Application of 'Pervious Pave' Software 20
3.3.1 Purpose 20
3.3.2 Project Tab 20
1