EFFECTIVE MANAGEMENT OF STORMWATER INCORPORATING PERMEABLE PAVEMENTS: A WAY TOWARDS SUSTAINABILITY

FINAL YEAR PROJECT UG

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CERTIFICATION

This is to certify that the

Final Year Project Titled

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has been accepted towards the requirements.

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TABLE OF CONTENTS

LIST OF ABBREVIATIONS

PP	Permeable Pavements
PC	Permeable Concrete
PCP	Permeable Concrete Pavements
WASH	Water, Sanitation, and Hygiene
SCMs	Supplementary Cementitious Materials
ESALs	Equivalent Single Axle Loads
OPC	Ordinary Portland Cement
w/c Ratio	Water Cement Ratio
c/a Ratio	Cement Aggregate Ratio

TABLE OF FIGURES

ABSTRACT

Climate change has intensified rainfall in Pakistan, necessitating innovative stormwater management strategies. This thesis explores the potential of PCPs. They can sustainably reduce surface runoff and boost groundwater recharge in urban areas. The study uses a mixed-method approach. It integrates field experiments and computer simulations. They assess various factors that affect PCP performance. We evaluate the effectiveness of PCPs in reducing runoff volume and peak flow rates.

Findings reveal that PCPs significantly reduce surface runoff and delay peak discharge. It thereby mitigates flood risks. Also, PCPs help recharge groundwater. They add to environmental sustainability and urban resilience against stormwater challenges. PCPs emerge as a viable and eco-friendly alternative for stormwater management. They offer benefits such as runoff reduction and groundwater recharge. This addresses the dual challenges of urbanization and climate change. Future research should focus on long-term performance and evaluation of PCPs. It should establish broad guidelines for wider use.

CHAPTER 1

INTRODUCTION

1.1 Brief description

Permeable pavements allow rainwater to infiltrate through their structure, unlike the conventional pavements. They incorporate pores in their structure that are responsible for the permeability of Permeable Concrete Pavement (PCP). PCPs provide a practical solution to urban stormwater management. It allows rainwater to infiltrate through their structure and significantly reduces surface runoff.

This study aims to formulate the mix design of PCP in Pakistan and provide a practical pavement design for practical use. It also provides an insight into the potential of PCP to enhance stormwater management and how it's a step toward sustainability. The research explores how permeability is achieved in PCPs and studies the relations between different mix design parameters. It also provides a drainage design for the PCPs in Pakistan. Furthermore, it explores the application of PCP in Pakistan.

1.2 Existing research

The PPs have been widely studied. They offer substantial environmental benefits, including runoff reduction, groundwater recharge, and pollution mitigation.

(Madrazo-Uribeetxebarria et al. 2023) found that the aggregate size in PCP significantly influences horizontal hydraulic conductivity. Additionally, studies by (Alsubih et al., 2017) and (Liu and Chui, 2017) highlighted that rainfall duration and initial wetting conditions critically impact the outflow duration of PPs. This emphasizes the importance of these factors in stormwater management.

Structural integrity is also an important aspect of PPs. Research has identified that the pore structure within the PC plays a dominant role in determining its hydraulic performance. This affects properties such as water permeability, mechanical strength, and durability.

(Weiss et al., 2019) and (Kuruppu et al., 2019) both highlight the need for further research on PPs, particularly in the areas of structural and materials properties, hydrologic performance, water quality, and maintenance. Weiss emphasizes the importance of addressing these research needs to fully integrate PPs in urban roads.

Kuruppu underscored the need for practical solutions and new knowledge to overcome the limitations of PCP. Sanicola et al. (2018) further supports the potential of PPs in reducing the environmental impacts of urbanization but also calls for more targeted research to address misconceptions and barriers to their widespread implementation. These studies collectively underscore the need for continued research to enhance the performance and applicability of PPs in urban environments.

1.3 Research Objectives

The objectives set forth hence are:

- Mix Design Formulation for Permeable Pavements in Pakistan
- Drainage Design for PPs in Pakistan.
- Establishing Guidelines for the effective use of PPs
- Recommend minimum layer thickness based on ESALs for use of PPs in roadways.

1.4 Relevance To National Need

Pakistan has faced the challenges of climate change and rapid urbanization. In the last decade, the intensity of rainfall events across the country has significantly increased. This has led to abnormal rainfall trends. Therefore, there is a concern about effective stormwater management in cities like Lahore, Islamabad, and Karachi.

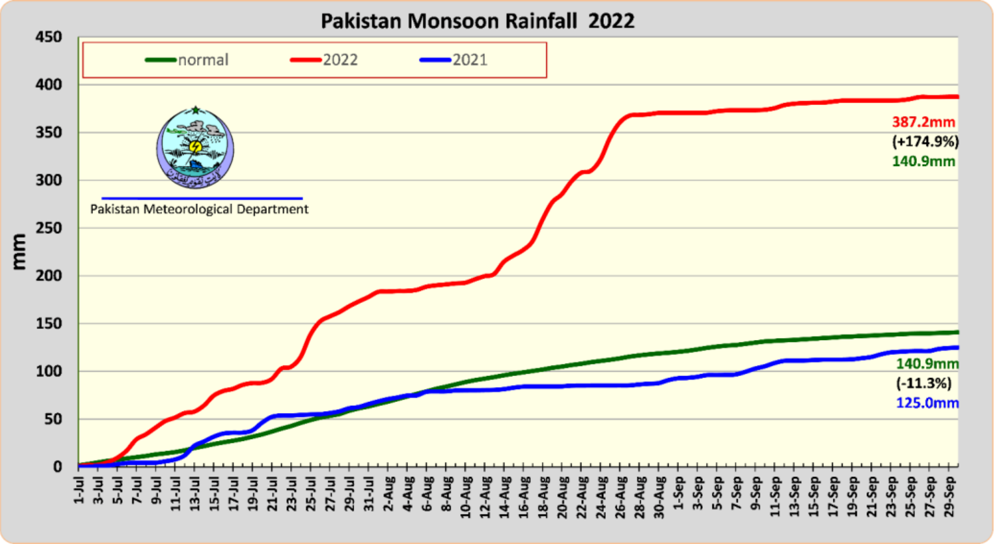
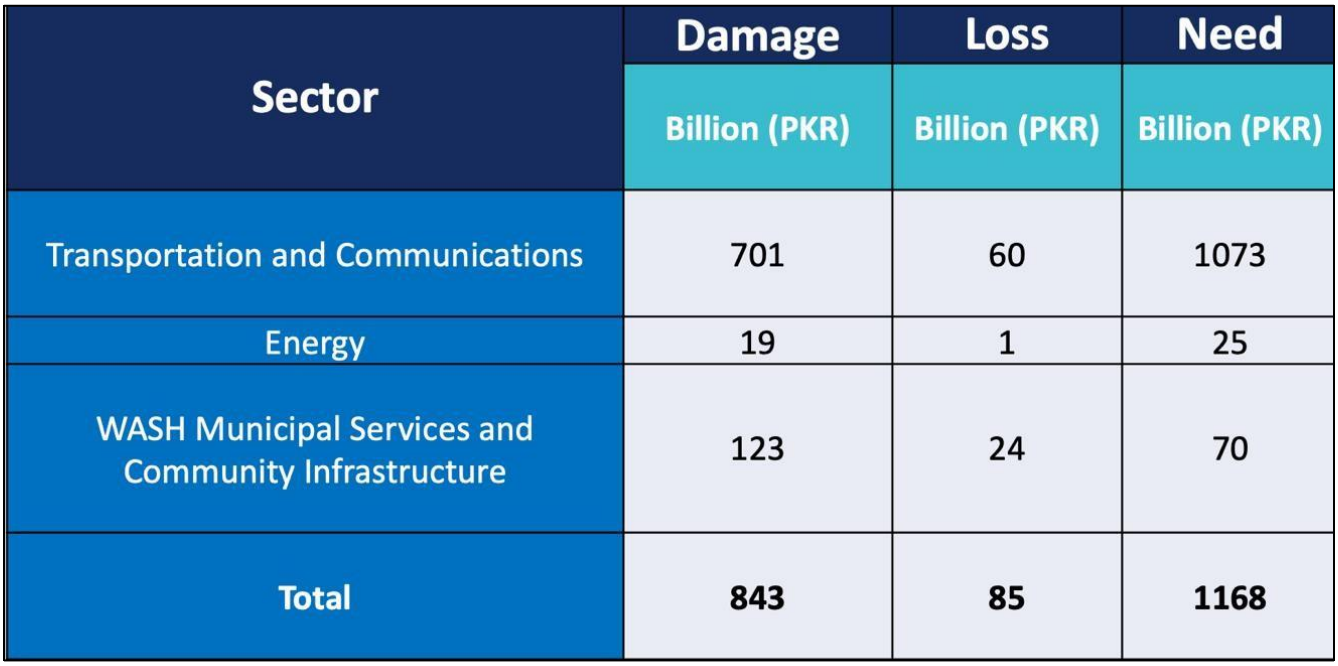


Figure 1: Monsoon rainfall patterns in Pakistan, 2022 (Pakistan Meteorological Department-CDPC, 2022).

In 2022, Pakistan faced a severe flood crisis affecting Sindh and Balochistan, resulting in substantial human and financial losses. During July and August of that year, Pakistan experienced an abnormal 211% surge in rainfall compared to past averages.

Pakistan has a road density of approximately 0.567 kilometers per square kilometer. Given these conditions, innovative stormwater strategies incorporating PPs emerged as a promising approach to address the pressing issue.

The impact of these climatic anomalies affects sectors such as transportation, municipal services, and energy. This financial burden placed a significant strain on national resources, underscoring the urgent need for resilient infrastructure and adaptive strategies.



Sector	Damage	Loss	Need
	Billion (PKR)	Billion (PKR)	Billion (PKR)
Transportation and Communications	701	60	1073
Energy	19	1	25
WASH Municipal Services and Community Infrastructure	123	24	70
Total	**843**	**85**	**1168**

***Figure 2**: Flood damage assessment in Pakistan, 2022 (NDMA, 2022).*

The transportation and communication sector lost $281 million, while the WASH (Water, Sanitation, and Hygiene) Municipal Services and Community Infrastructure suffered losses of $112 million. Additionally, the energy sector had a loss of $3 million. The cumulative damage across all sectors totaled approximately $3,927 million.

1.5 Area of Application

PPs can be used in various sectors, each one having unique advantages and implementation challenges. The key areas of application include the following:

1. **Urban Street and Roads:**

   Permeable pavements are useful in urban areas where impervious surfaces dominate. By allowing water to infiltrate through the pavement, PPs help manage stormwater at the source. It can reduce the burden on municipal drainage systems. This application is crucial in cities like Karachi, Lahore, and Islamabad, where rapid urbanization has led to increased flooding risks.

2. **Parking Lots:**

   PPs are useful in Parking lots. PPs in parking lots can enhance groundwater recharge and reduce the heat island effect. They also play their part in reducing stormwater runoff.

3. **Pedestrian Walkways and Bike Lanes:**

   PPs also provide functional benefits in walkways and bike lanes. PPs also improve the aesthetic appeal and environmental quality of pedestrian and cyclist pathways. These surfaces provide a safer, non-slip alternative in wet conditions, promoting sustainable transportation options.

4. **Public Parks and Recreational Areas:**

   PPs can be used in public parks and recreational facilities. They can blend seamlessly with green spaces. This application supports eco-friendly urban design by improving water management and reducing surface erosion.

5. **Highways and Major Roads:**

   While its challenging due to higher traffic loads, PPs can be designed for use on highways and major roads. This will require proper maintenance practices to make sure that the PCP shows durability and performance.

1.6 Organization Report

This thesis is organized into five main chapters, each focusing on a distinct aspect of the study on effective stormwater management using permeable pavements (PPs).

Chapter 1: Introduction

This chapter introduces the study. It begins with a brief description of permeable pavements and highlights their significance in stormwater management. Existing research on permeable pavements is discussed. The research objectives are outlined, and the relevance of this study to

Pakistan is explained.

Chapter 2: Literature Review

The literature review explores various aspects of permeable pavements. This includes materials used, void ratio, density, compressive strength, and infiltration rate. It examines previous studies on the environmental and structural benefits of permeable pavements. Challenges associated with their implementation are also discussed. This chapter provides a solid theoretical foundation. It helps in understanding the performance and benefits of permeable pavements in urban stormwater management.

Chapter 3: Methodology

This chapter details the methodology adopted for the study. It describes the material selection process, including the types of cement, aggregates, and admixtures used. The chapter outlines the mix design formulation for permeable concrete. It explains the testing and experimental evaluation methods employed. It also discusses the drainage design of permeable concrete pavement. This covers full infiltration, partial infiltration, and no infiltration scenarios.

Chapter 4: Results and Analysis

In this chapter, the findings of the study are presented and analyzed. It includes an analysis of the mix design parameters, such as aggregate size, water-cement ratio, porosity, and cement-aggregate ratio. The chapter also examines the relationship between these parameters and the strength and infiltration rate of the permeable concrete. Additionally, it presents a recommended mix design and drainage design for permeable concrete in Pakistan.

Chapter 5: Conclusion

The final chapter summarizes the key findings of the study and their implications for urban stormwater management. It discusses the potential of PPs to reduce surface runoff, recharge groundwater, and enhance urban resilience against flooding. The chapter also provides future recommendations for research and practical applications of PPs in urban areas.

CHAPTER 2

LITERATURE REVIEW

2.1 Permeable Pavement

Permeable concrete (PC) is a type of permeable pavement with a high interconnected pore structure that allows efficient drainage of water through its matrix (Yahia et al., 2014). PC is a sustainable solution for managing stormwater and reducing urban heat island effects. PC is more permeable and clog-resistant than PC. This is especially true at porosity levels above 20% (Fwa et al., 2015).

It allows for water infiltration, decreases urban heating, replenishes groundwater, and reduces flash flooding. Recent research has focused on enhancing the physical and mechanical properties of permeable concrete, with promising results in terms of increased compressive strength and permeability flow rate (Aravind & Abdulrehman, 2021).

PPs are effective, sustainable urban drainage solutions for managing stormwater quantity and quality. They can reduce runoff volume and peak flow rates a lot. Studies show they cut runoff by 30-65% in storms (Shafique et al., 2018). PPs can handle all runoff for rain up to 15-25 mm. This is the 81-91% percentile in some areas (Castillo-Rodríguez et al., 2021).

They also improve water quality. They filter out pollutants as water soaks through the pavement (Singer et al., 2022). Despite their proven benefits, misconceptions and barriers to widespread implementation persist (Sanicola**,** 2018). Recent research has developed maintenance procedures to reduce clogging. Clogging mainly happens in the top 1.5-2.5 cm of the PPS (Singer et al., 2022).

2.2 Material Used in Permeable Pavement

In PCPs, the materials used enhance the permeability of the PC. These materials allow for interconnected voids in the PC so that water can infiltrate through its surface. PCPs are designed to manage stormwater and reduce carbon emissions in urban areas.

These pavements have coarse aggregates, cement, and little to no fine aggregates. This mix creates a porous structure (Aravind & Abdulrehman, 2021). We can add materials to boost performance. These include recycled concrete, glass, rubber, and grit (Tota-Maharaj et al., 2021).

Some designs use organic matter, like compost, to improve pollutant retention and treatment (Bentarzi et al., 2013). Additives like fly ash and aluminum powder can increase strength and cut permeability (Aravind & Abdulrehman, 2021).

Pavement design needs balance. The right materials and mix affect strength, water flow, and longevity. This balance is key for managing stormwater and ensuring durability in cities. The following materials are used in permeable concrete.

1. **Cement:**

   Cement acts as the binding agent in PC. It provides the strength to the PC. Therefore, a specific grade of cement is required to ensure the durability and permeability of the PCP.

2. **Aggregate:**

   Aggregate choice plays a critical role in permeable pavement mix design. The size, shape, and gradation of aggregates influence the porosity and permeability of the concrete. Single-sized aggregates are used in PC to create an open matrix that allows water to pass through (Madrazo-Uribeetxebarria et al., 2023).

3. **Water:**

   Water is used to hydrate the cement and aid in the chemical reactions necessary for concrete curing. The water-cement ratio is controlled to achieve the desired balance between workability and strength.

4. **Admixtures:**

   Chemical admixtures are added to the PC to enhance its properties. These include plasticizers, superplasticizers, and viscosity-modifying agents to improve workability, strength, and durability

5. **SCMs:**

   SCMs such as fly ash, slag, and silica fume are incorporated to improve the performance of PCs. These materials enhance durability but reduce permeability. However, they have environmental benefits by recycling industrial by-products

Since the goal is to achieve permeability in the pavement, the fine aggregates (sand) are not used in the PC. It leaves open voids that allow water to pass through and increase the infiltration rate of the pavement.

2.3 Void Ratio

PCPs has an open-void structure. It helps urban water management but struggles to balance porosity, strength, and durability. Research shows that porosity is the main factor in permeable concrete properties.

The void ratio in the PC matrix plays the most important part in the ability of PCP to let water pass through its surface. In order to have a working PCP, the voids should be sufficient to have the necessary strength to withstand traffic load and also allow water to infiltrate.

More pores improve flow but reduce strength and durability against freezing (Liu et al., 2018). The best mix designs balance porosity, aggregate size, and water-binder ratio. They are crucial for achieving the desired performance in PC (Liu et al., 2018; De Souza Risson et al., 2023). There should be voids of around 15-30% for a fully functional PCP (AlShareedah, O., & Nassiri, S. 2022).

2.4 Density of Permeable Concrete

Since the PC has a high void content, it has a low density. The PC concrete has a lower density compared to that of a conventional one. The density of permeable concrete should be in the range of 600 to 2000 kg/m³ (Lian and Zhuge 2010). This lower density results in interconnected voids that are necessary for water infiltration.

However, it also impacts the compressive strength of the concrete. Therefore, a balance between density and structural performance is required (Kevern, Schaefer, & Wang 2009).

Density control and aggregate size greatly impact performance. Non-pavement applications need a density of at least 1740 kg/m³. This is to meet minimum strength requirements. For pavement applications, the necessary density is 1960 kg/m³ (Sičáková & Kováč, 2020).

2.5 Compressive Strength Permeable Concrete

The compressive strength determines the ability of the PC to withstand loads. So, it is an important factor to consider. Since the PC has voids in it, its strength is decreased. This is the reason why PCP has lower compressive strength compared to conventional concrete. PCP has a range of 2.8 to 28 MPa compressive strength. This strength can be increased with the use of SCMs (AlShareedah, O., & Nassiri, S. 2022).

High-volume roads need even higher strength (Ab Latif et al., 2023). Compressive strength is inversely related to porosity and permeability. Strength drops as porosity rises (Tan et al., 2020). Water-cement ratio, curing time, and aggregate type shape concrete's strength (Naderi et al., 2018). The best strength depends on the use. However, a balance of strength and permeability is key. For example, (Tan et al., 2020) found an equilibrium point at 16% effective porosity, yielding a compressive strength of 21.5 MPa. It had a permeability coefficient of 3.2 mm/s, which may serve as a reference for optimal performance.

2.6 Infiltration Rate of Permeable Concrete

The infiltration rate of PC is another important factor to consider. Simply put, it is the measure of how quickly water can pass through its structure. This plays a crucial part in effective stormwater management. For a functional PCP, the infiltration rate of the PC should be greater than 1 mm/sec (Elango, K. S., et al., 2020).

Permeable concrete infiltration rates vary widely depending on mix design and testing methods. Studies have reported rates from 0.36 to 1.87 cm/s using surface infiltration tests (Poornachandra Vaddy et al., 2020). Rates can be up to 20,000 cm/h (55.6 cm/s) for mixes with only coarse aggregate (Malaiškienė et al., 2020).

The infiltration rate is influenced by factors such as aggregate content, compaction method, and ring size used in testing. Larger rings have lower rates. An optimal size of 270 mm is best for field measurements (Poornachandra Vaddy et al., 2020).

Additionally, various testing methods, including constant head, falling head, and modified ASTM C1701, can produce varying results. This is due to non-linear flow behavior (Lederle et al., 2020). Overall, permeable concrete can achieve infiltration rates that are suitable for various stormwater management applications.

CHAPTER 3

METHODOLOGY

3.1 Overview

This section outlines the methodology used to achieve the research objectives. It ensures a systematic approach to developing and evaluating PCPs.

Firstly, a thorough literature review was conducted. It was done to understand the existing knowledge and practices about PPs. It provided insights into the potential benefits of PCPs for stormwater management. This also highlighted the key factors influencing the performance of PCP. In short, this study helped us to decide the subsequent phases of the research.

The second phase involved the study and formulation of a mix design for PCP. The mix design used locally available materials in Pakistan. It was based on the guidelines and findings from the literature review. This process had two steps. First, we selected and tested materials. This was to ensure they met the needed criteria for permeability and strength.

Material testing was a critical step in this research. We evaluated various materials for PCP. These include cement, aggregates, and admixtures. The properties of these materials were tested. It was done to see how they impact the permeability and durability of the final concrete mix.

In the next step, experimental evaluation was conducted to determine the performance of the mix design. This involved creating sample batches and testing them for various parameters. These parameters included void ratio, density, compressive strength, permeability, and infiltration rate. We analyzed the relationships between different mix design parameters to optimize the formulation.

The last phase of the study was to make guidelines and recommendations for the practical use of PCP in Pakistan. This included establishing minimum layer thickness based on ESALs. Additionally, we considered the drainage design and factors for effective stormwater management.

The next sections describe detailed processes and experiments. They show the rigorous approach taken to meet the research goals.

3.2 Material Selection

All the materials selected for this study were locally available in Pakistan. ASTM standards and cost were the guides. They ensured that the mix design would be effective and cheap.

3.2.1 Portland Cement

In this research, OPC was used as the cementitious binding material. It was sourced from a local cement factory near Islamabad. The cement was grade 43. It was made to ASTM C150 standards. This ensured it met the needed criteria for strength and durability. The selection was based on a literature review. It stressed the importance of using high-quality, local materials. These are needed to get the needed permeability and strength in PCP.

3.2.2 Aggregate

The aggregate used in the mix design was obtained from the Margalla crush, a well-known source of quality aggregate in Pakistan. We used and tested various aggregate sizes to determine their suitability for PCP. These included 3/4 inch, 1/2 inch, and 3/8 inch aggregate. Additionally, more coarser aggregates were initially considered. However, it was found that the more coarse aggregates produced lower strength in the final concrete mix. So, the study proceeded with 3/4 inch, 1/2 inch, and 3/8 inch aggregates. These sizes provided the best balance of strength and permeability.

3.2.3 Super Plasticizer

We used Sikament 518, a superplasticizer. It improves the workability and performance of the permeable concrete mix. This superplasticizer was procured from the SIKA head office in Rawalpindi. Sikament 518 is known for its excellent properties, including:

- It provides up to 25% water reduction. This reduction helps achieve higher strength and durability.

- It greatly improves the workability of the concrete mix. This makes it easier to handle and place.
- By reducing the w/c ratio, Sikament 518 contributes to higher compressive strength in the final product.

3.3 Mix Design Formulation for Permeable Concrete

We considered many parameters for the mix design and tested various mix samples to find the optimal mix design. The parameters included aggregate size, void ratio, water-cement ratio, and cement-aggregate ratio. Each factor was crucial as it determined the permeability, strength, and performance of the PCP.

3.3.1 Mix Desing Parameters

The part of the research aims to develop an optimal mix design for permeable concrete pavements in Pakistan. The optimized mix design ensures effective stormwater management, structural performance, and economic feasibility. The following sections detail the mix design parameters considered in this study:

Aggregate Size

Aggregate size determines the permeability and strength. Therefore, we evaluated various sizes. These sizes were chosen for their ability to form an open matrix. Aggregate size should allow water to flow well while keeping enough strength.

Void Ratio

The void ratio represents the proportion of void spaces in the concrete. It directly impacts the permeability. The right void ratio lets the pavement handle stormwater well. It does this without losing strength. The required void ratio was between 15% to 30%. This range provides a balance between the permeability and load-bearing capacity of PCP.

Water Cement Ratio

The w/c ratio is a key parameter influencing both the workability and strength of the concrete mix. A lower w/c ratio enhances strength but reduces workability. A higher w/c ratio improves workability but reduces strength. We tested various w/c ratios to identify the optimal ratio that supports both permeability and durability.

Cement Aggregate Ratio

The mix design for PC does not include fines. It only has cement and aggregate. This adjustment helps achieve the open-graded structure required for permeability. So, the c/a ratio is valid. It replaces the conventional cement-sand-aggregate ratio. We experimented with different cement-aggregate ratios. It was done to determine the most effective combination for achieving the desired mechanical properties and permeability.

3.4 Testing and Experimental Evaluation

We conducted all tests in this study following ASTM standards. This was to ensure accuracy and reliability. Additionally, three samples of each mix design were tested. This gave the most consistent and representative results.

3.4.1 Aggregate Test

Aggregates are vital to the performance of PCPs and control their durability. We performed many aggregate tests to check their properties and see if they were suitable for the research. All aggregate tests were as per ASTM standards. These tests ensure that the aggregates for PCPs meet the criteria for strength, durability, and permeability.

Shape Test

The shape of the aggregate affects the permeability and strength of the PC. The shape test helps determine the angles, roundness, and texture of aggregates. The angular aggregates provide higher strength and better interlocking. However, the rounded aggregates improve permeability but have less interlocking.

The shape test of aggregate is a visual inspection and geometric measurement of aggregates. It categorized aggregates based on their shapes. This test was performed as per ASTM D4791.

Specific Gravity Test

Specific gravity is the density of the aggregates relative to that of water. It influences the weight, stability, and strength of the concrete mix. The specific gravity test on aggregate was performed according to ASTM C127.

The procedure begins with preparing a sample of coarse aggregate. The sample is washed to remove dust and coatings. The sample is then submerged in water for 24 ± 4 hours to ensure full saturation. After soaking, the aggregate is removed. Its surface is towel-dried to reach a saturated surface dry (SSD) condition.

This means the surfaces are damp but not dripping, and no free water is present. The SSD sample is weighed. Immediately after this, the aggregate is put in water and weighed. This measures the submerged weight, ensuring no air bubbles are on the surface.

The next step involves drying the aggregate in an oven at 110°C ± 5°C to a constant weight. After drying, the sample is allowed to cool to room temperature. Then, it is weighed again. These weights are used to find the specific gravity and absorption of the aggregate. The formulas used include the apparent specific gravity.

They also include bulk-specific gravity (both SSD and dry) and absorption percentage. The calculations help find the density of the aggregate particles. They find it relative to the density of water and the amount of water the aggregate can absorb. The apparent specific gravity is calculated using the formula:

$$\textbf{Apparent Specific Gravity} = \frac{\mathrm{Wdry}}{Wdry-Wsub}\,\mathbf{x100} \tag{1}$$

The bulk specific gravity (SSD) is calculated as:

$$\textbf{Bulk Specific Gravity (SSD)} = \frac{\mathrm{Wssd}}{Wssd-Wsub}\,\mathbf{x100} \tag{2}$$

The bulk specific gravity (dry) is determined by:

$$\textbf{Bulk Specific Gravity (Dry)} = \frac{\mathrm{Wdry}}{Wssd-Wsub}\,\mathbf{x100} \tag{3}$$

The absorption percentage is calculated using:

$$\textbf{Absorption} = \frac{Wssd - Wdry}{Wdry} \textbf{x100} \qquad \textbf{(4)}$$

where,

- $\mathbf{W_{SSD}}$: Weight of the aggregate in the Saturated Surface Dry (SSD) condition.
- $\mathbf{W_{dry}}$: Oven-dry weight of the aggregate.
- $\mathbf{W_{sub}}$: Submerged weight of the aggregate.

Impact Test

The impact test measures the toughness of the aggregate. It tests its resistance to sudden impact or shock. This property is important. It ensures the pavement can handle traffic and other dynamic loads.

This test was performed following ASTM standard C131. In this test, we hit Aggregates in a standardized apparatus. Then, we measure the resulting pieces. The percentage of crushed material indicates the impact value.

Abrasion Resistance Test

Abrasion resistance measures how well the aggregate can withstand wear. This wear comes from friction or traffic. High abrasion resistance indicates a longer-lasting pavement surface. It basically measures the hardness of the aggregate. This test was performed using ASTM C 131 guidelines.

First, a representative sample of the aggregate is prepared. The sample is sieved to obtain specific size fractions and then dried to a constant weight. The weight varies based on the gradation of the aggregate. But it generally falls between 5,000 and 10,000 grams.

Next, the prepared aggregate sample is put in the LA abrasion machine. It is put in with a set number of steel spheres. The machine consists of a hollow, cylindrical drum that rotates horizontally. The number of steel spheres used depends on the gradation of the aggregate. It typically ranges from 6 to 12 spheres. The drum is rotated at a speed of 30 to 33 revolutions per minute (RPM) for a total of 500 revolutions. This rotation makes the sample hit by the steel spheres. It subjects it to abrasion and impact.

After completing the rotation, remove the aggregate from the drum and sieve it over a No. 12 (1.70 mm) sieve to separate the fine material generated by the abrasion process. We wash the material left on the sieve to remove fine particles. Then, we dry it until it reaches a constant weight.

The wear, or abrasion loss, percentage is found by comparing the weight of the material left on the No. 12 sieve to the original weight of the sample. The formula used is:

$$\textbf{Abrasion Loss (\%)} = \frac{\textbf{Origional weight}-\textbf{Ratained weight}}{\boldsymbol{Origional\,weight}}\,\textbf{x100} \qquad \textbf{(5)}$$

3.4.2 Fresh State Test

The fresh state of PC needs to be tested to verify that it has the properties required for the best performance. Fresh state of PC concrete needs to tested for it density and void ratio. The following tests were performed on the fresh state of PC.

Density Test

The ASTM C1688 density test is for fresh, permeable concrete. It finds the unit weight of freshly mixed Permeable concrete. This test is important to ensure the quality and consistency of PC.

The test starts with preparing the density test cone and tampers. You must make sure both are clean and dry. The mass of the empty density test cone is recorded. A sample of fresh PC is then obtained. It is from a representative mix. The sample is taken using standardized procedures.

Next, the density test cone is placed on a flat, non-absorptive surface. It is filled with PC in three equal layers. Each layer is compacted uniformly with 25 strokes of the tamper. After filling and compacting all three layers, the top surface of the concrete is struck off. It is made level with the top of the cone using a straightedge or trowel. The cone filled with compacted concrete is then weighed.

We calculate the density of the concrete and use the mass of the concrete and the known volume of the cone. This volume is derived from its dimensions. The density is calculated in mass per volume. It is reported in units like kilograms per cubic meter (kg/m³).

$$\textbf{Density} = \frac{\textbf{Volume of cone}\boldsymbol{snsity}}{\boldsymbol{Mass\ of\ cone}} \qquad \textbf{(6)}$$

Void Ratio Test

The ASTM C1688 test method determines the void content of a fresh PC. It involves several critical steps. First, you need to calculate the density of the fresh PC as mentioned. Once you have that, the next step is to calculate the theoretical density (T).

We calculate T from the mix design's component proportions and densities. The components are cement, aggregate, water, and any additives. The void content (V) is then determined using the formula:

$$\mathbf{V= (1 - \frac{\mathit{Desnsity}}{Theoretical\ Density}) \ x100} \tag{7}$$

This gives the void content as a percentage. It represents the volume of voids relative to the total volume of the fresh state of PC.

3.4.3 Hardened State Test

In order to verify that the PC maintained the required properties after setting we need to perform various test on the hardened state or the set state of concrete. These tests are required to check the properties of the concrete such as density, void ratio, compressive strength, and the infiltration rate. All these tests are performed as per ASTM standard.

Density Test

The ASTM C1754 test method determines the density and void content of the hardened PC. It has several detailed steps.

At first, we get a sample of a sample cylinder of PC. The sample is a cylinder must have a diameter of at least 100 mm (4 inches) and a height equal to the diameter. The sample is dried in an oven at 105°C ± 5°C (221°F ± 9°F) for a minimum of 24 hours or until it reaches a constant mass.

After drying, the sample cools to room temperature. This prevents moisture absorption. We weigh the dry sample. You will also need to calculate the volume of the sample. The volume is calculated using the formula:

$$\mathbf{V=\pi(\frac{d}{2})^2 \ x \ h} \tag{8}$$

where,

- d is the diameter of the sample.
- h is the height to the sample.

The sample is then submerged in water for at least 24 hours to achieve full saturation. After it is saturated, the sample is taken from the water. It is dried with a towel to remove excess water without drawing water out of the pores. Then, it is weighed.

The bulk density (ρb) is calculated using the formula:

$$\mathrm{Pb} = \frac{\boldsymbol{Wd}}{\mathbf{V}} \tag{9}$$

where,

- Wd is the dry weight of the sample.
- V is its volume.

Void Ratio Test

Void ratio in the hardened state of PC plays an important role in the permeability and infiltration rate. Therefore, it is important to evaluate the void ratio. The void ratio is also determined by ASTM C1745. The void content (V) is determined using the formula:

$$\mathbf{V= (1 - \frac{Pb}{Ps})\ x100} \tag{10}$$

where,

- ρb is the bulk density.
- ρs is the density of the solid materials in the concrete.

Compression Strength Test

The PC strength test shows if the concrete meets the required strength. It must also keep its permeability. PC is designed to let water pass through. So, it usually has less compressive strength than comventional concrete. Nonetheless, it must still be sufficient to support the intended loads. The ASTM C39 test measures compressive strength.

The method has several key steps. They make sure the results are accurate and reliable. The procedure starts with preparing the cylindrical test specimens. They are usually 150 mm (6 inches) in diameter and 300 mm (12 inches) in height. They may be other specified dimensions. We cast these specimens in molds. Then, we let them cure under controlled conditions until the test age, usually 28 days. We test the sample's strength after 7 days. We do this because the PCP is usually opened to traffic after 7 days. So, the strength at 7 days is crucial.

In order to test, remove the specimens from the curing tank and wipe off any surface moisture. The ends of the specimens are then checked for planeness. Flat, upright ends are essential for accurate testing. If needed, cap or grind the ends. This will make them flat and perpendicular.

The specimen is placed in a compression testing machine. It is aligned carefully to spread the load evenly during testing. The load is applied continuously and without shock. It is at a constant rate until the specimen fails. The maximum load carried by the specimen before failure is recorded. The compressive strength (fc) is then calculated using the formula:

$$fc=\frac{P}{A} \tag{11}$$

where,

- P is the maximum load applied to the specimen.
- A is the cross-sectional area of the specimen.

Infiltration Test

The infiltration rate of permeable concrete (PC) is crucial. It measures its ability to let water pass through. This ability helps it manage stormwater and recharge groundwater. The infiltration rate is key for cutting surface water accumulation. It reduces flooding risk and lessens the urban heat island effect. It does this by letting water go through the pavement and evaporate.

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The ASTM C1701 test method determines the infiltration rate of PC. The test starts by picking a representative area of the PCP. Then, it cleans the surface to remove any debris or loose material. An infiltration ring has a 12-inch diameter. It is placed on the cleaned surface. It is positioned to form a watertight seal with the concrete. If needed, seal the ring's edge with the plumber's putty or a similar material. This stops water from leaking.

The test area is pre-wetted by pouring a known volume of water, usually about 3.6 liters, into the ring. The water is allowed to soak in completely. After wetting, the ring is refilled with the same volume of water. Then, we measure how long it takes for the water to soak into the concrete.

This duration, along with the volume of water and the cross-sectional area of the ring, is used to calculate the infiltration rate using the formula:

$$\mathbf{I}=\frac{V}{A*T} \tag{12}$$

where,

- V is the volume of water used (in cubic inches or liters).
- A is the cross-sectional area of the infiltration ring (in square inches or square meters).
- T is the time taken for the water to infiltrate (in seconds)

This rate is usually in inches per hour or millimeters per hour. It measures the PC's permeability and its effectiveness in managing stormwater.

3.5 Drainage Design of Permeable Concrete Pavement

The drainage design of PCP plays an important role in the effective performance of PCPs. Even if the PC has all required properties to let water pass through, without a proper drainage system, the pavement will fail. Therefore, the drainage system needs to be considered.

The drainage design system needs to consider the existing soil conditions for the optimal performance. Economical considerations also play an important role in drainage design. In general there are three options when it comes to the drainage design.

- Full infiltration
- Partial infiltration

- No infiltration

3.5.1 Full infiltration

In full infiltration the PCP is permeable throughout starting from the permeable layer all the way down to the subbase layer. In this setup the water goes directly to the ground surface or to the ground water. Therefore, all the pavement layers are required to be permeable. It is because of this fact that this PCP has lower strength.

The full infiltration PCP is suitable for specific areas where the hydraulic conductivity of existing soil is less. This allows the water to go directly into the ground water rather than staying in the soil that can lead to expansion of contraction of the soil.

It also requires that your existing groundwater level should be lower from the subbase layer so that there is no risk of back flooding in the PCP.

3.5.2 Partial infiltration

The second option is the partial infiltration of the PCP. In this drainage design only the topmost layer that is the permeable layer allows water to pass through. In this design the permeable layer is followed by a filter layer that is also permeable.

The filter layer incorporates perforated pipes to drain the water out of the layer. The layers beneath that are the base and subbase layer are not permeable. In this drainage design you don’t need to worry about the hydraulic properties of the soil present beneath the PCP.

3.5.3 No Infiltration

The last option is the one where no infiltration occurs beneath the initial topmost permeable layer. This pavement design is applicable where the groundwater level is high or very close to the pavement. This pavement design exhibits better strength compared to the other two.

However, this design only reduces the surface runoff and requires a proper conventional drainage system to crater the stormwater. If the drainage system is not up to the mark to carter for the stormwater, back flooding will occur. Therefore, both the drainage system and proper PC is required for this drainage design to work.

CHAPTER 4

RESULTS AND ANALYSIS

4.1 Mix Design Parameters

This chapter presents the results of the tests conducted on the permeable concrete samples and discusses the findings. The test performed on the mix design parameters were to study the trends different parameters have on important properties such as the strength and infiltration rate of PCP.

4.1.1 Aggregate Size

The aggregate size of concrete plays in important role in the PCP. It controls the porosity and the strength of the PCP. Therefore we need to take an aggregate size that has reasonable infiltration rate while also having enough strength to take the traffic loading.

Relation between Aggregate Size and Infiltration Rate

In PC infiltration rate of the concrete is an important factor and its is controlled by the aggregate size. As we increase the aggregate size, the infiltration rate of the PCP increases. Experimental evaluation showed that the aggregate size and infiltration rate have a direct relation.

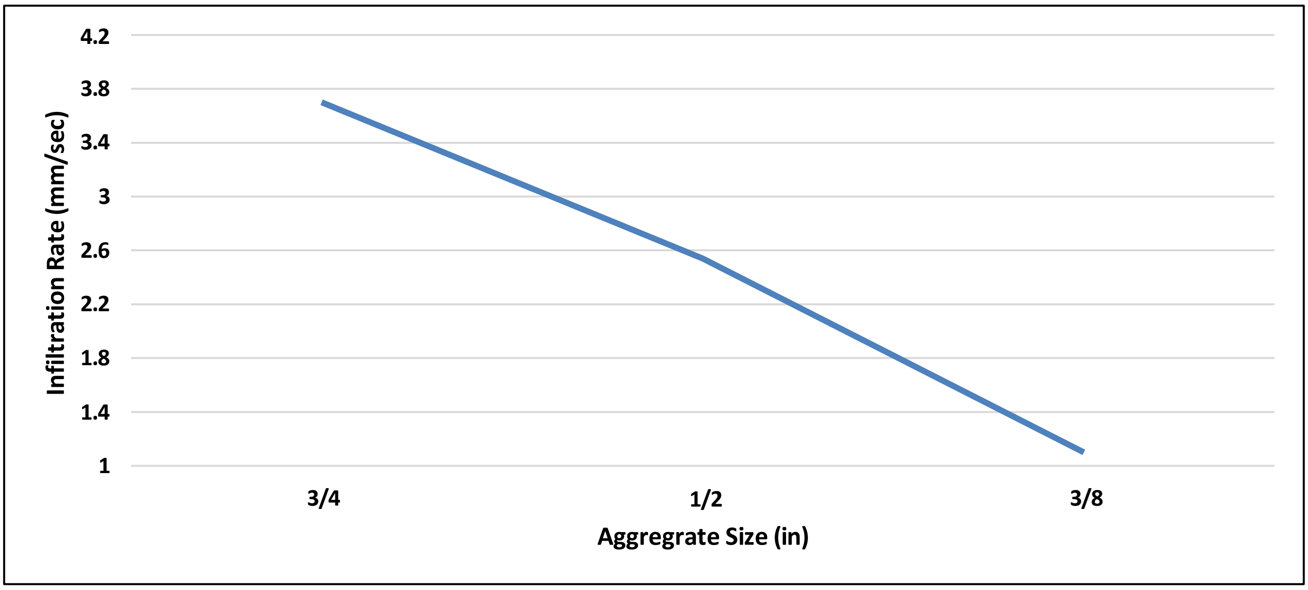

Figure 3: *Relation between Aggregate Size and Infiltration Rate*

Relation between Aggregate Size and Strength

The aggregate size is inversely proportional to the compressive strength of the PC. As we decreased the aggregate size, an increase in strength was observed. Therefore based on the results, the smaller size aggregate is better for achieving higher compressive strength in PC.

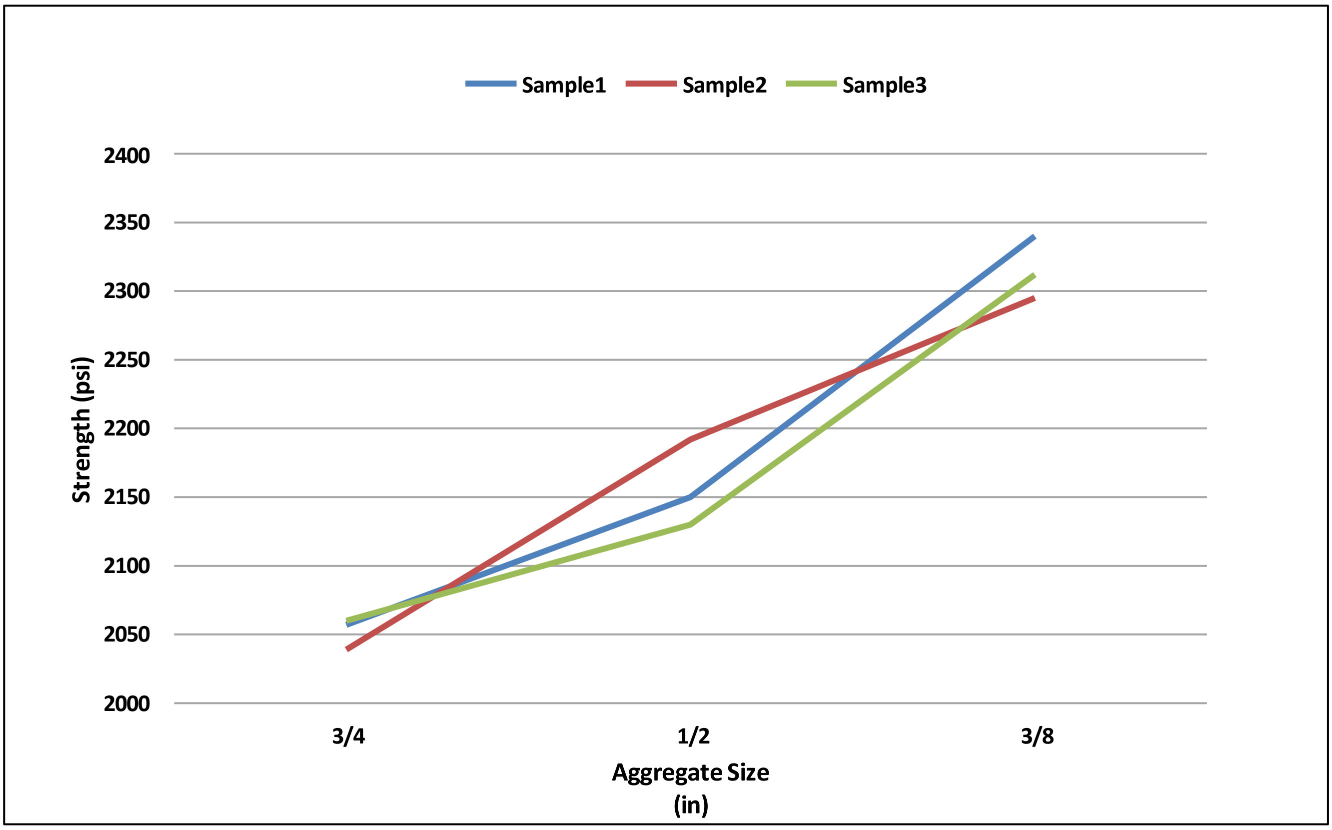

Figure 4: *Relation between Aggregate Size and Strength*

4.1.2 w/c Ratio

The w/c ratio also plays a critical role in the PCP. It plays a crucial role in the workability of the PC. Lower w/c ratios generally lead to higher permeability. It also improves mechanical properties. However, the optimal w/c ratio for balancing strength and permeability is around 0.32. Increasing the w/c ratio from 0.3 to 0.35 can enhance permeability and strength.

Relation between w/c ratio and Strength

The w/c ratio is directly proportional to the strength of the PC. The results show that as we increase the w/c ratio, there is an increase in the compressive strength of the PCP. Therefore, we need to aim for a bit higher w/c ratio compared to that of conventional concrete. This ensures that the concrete is workable and has acceptable strength.

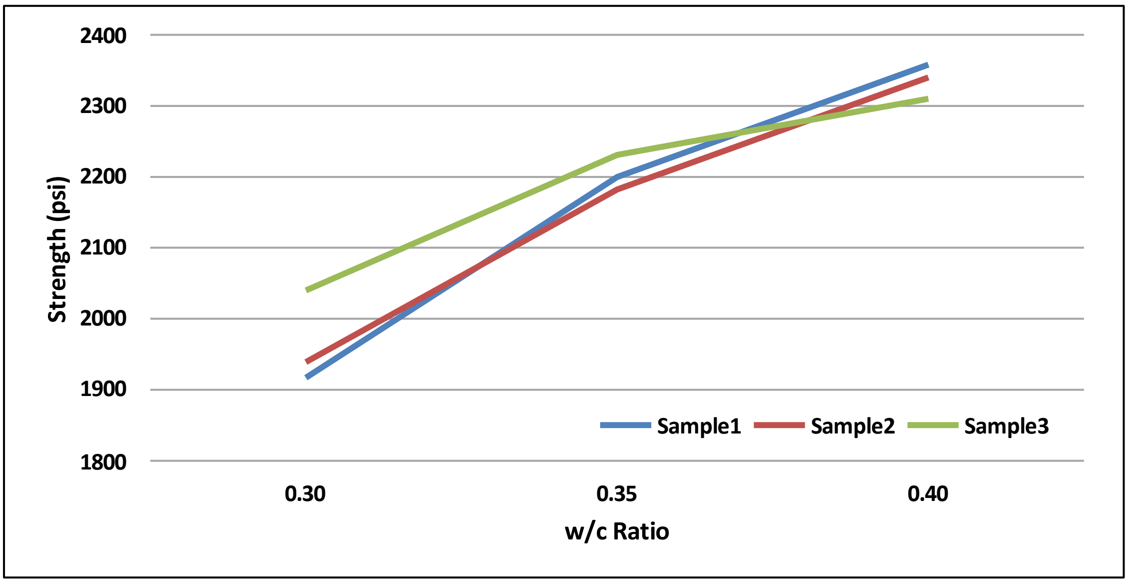

***Figure 5:** Relation between w/c Ratio and Strength*

Relation between w/c ratio and Infiltration Rate

The infiltration rate and w/c ratio are inversely proportional in the PC. The experimental evaluation showed that if we decrease the w/c ratio, we will have a better infiltration rate. However, it decreases strength, so generally, we have to choose a value that provides decent strength and infiltration rate.

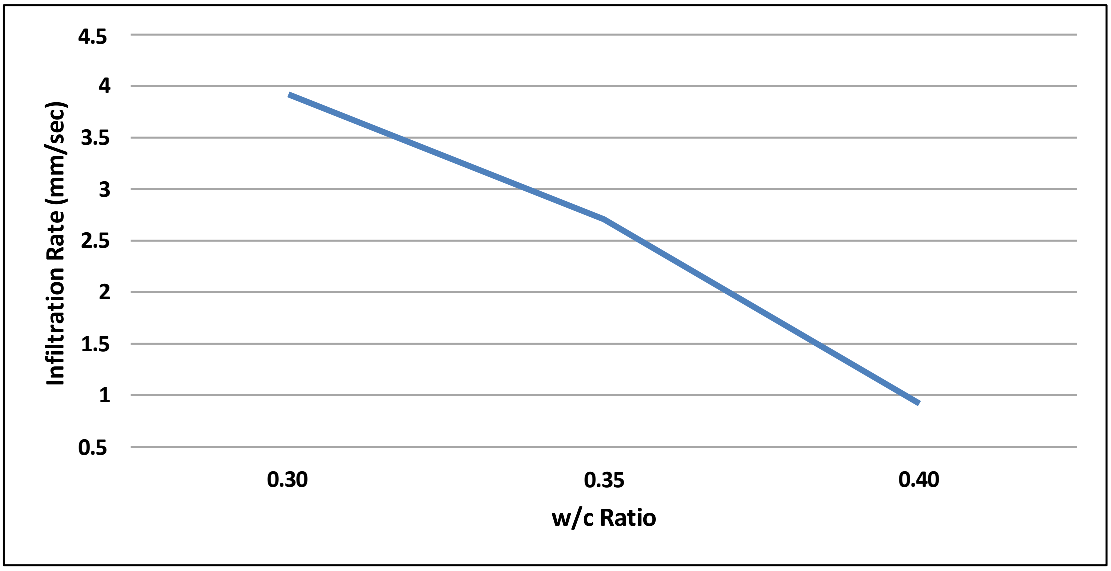

***Figure 6:** Relation between w/c Ratio and Infiltration Rate*

4.1.3 Porosity

PC has a vertical distribution of porosity, which affects strength and permeability. The porosity and pore structure of PC affects its clogging resistance and permeability. It showed the following relations with the strength and the infiltration rate.

Relation between Porosity and Strength

Porosity is an important factor in the PC. It greatly affects the strength of the PCP, as shown in the graph. The results showed that as we increase the porosity, the strength of the PCP decreases significantly. Therefore, for better strength, we need to keep porosity minimized to a certain point, as increasing it will cause the pavement to fail.

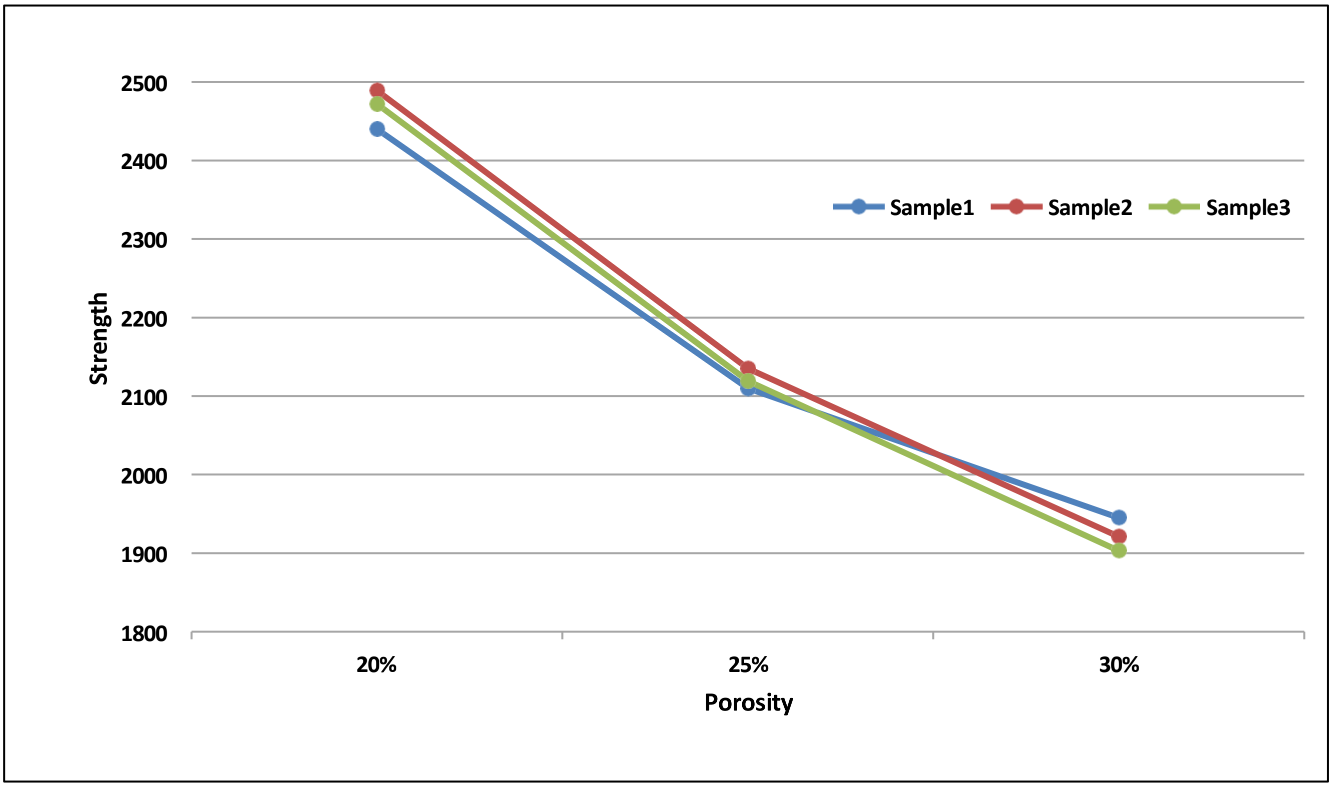

Figure 7: *Relation between Porosity and Strength*

Relation between Porosity and Infiltration Rate

Porosity played the opposite role when it comes to infiltration rate. Infiltration rate and porosity have a direct relation. So, as we increase the porosity, the infiltration rate increases, which is favorable for stormwater management.

However, when it comes to choosing a specific porosity for the PCP, we need to make careful decisions so that the pavement exhibits reasonable strength and enough infiltration rate to cater to the stormwater.

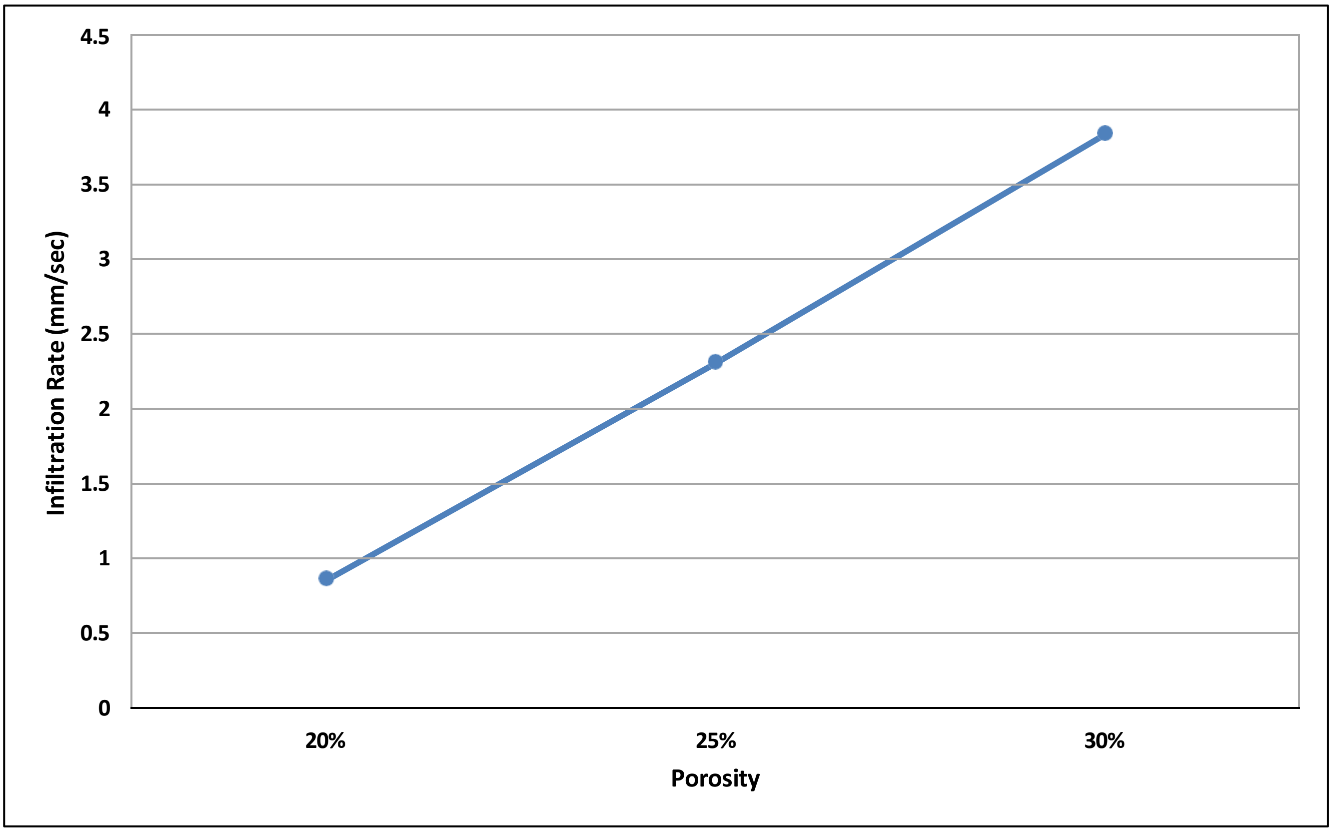

Figure 8: *Relation between Porosity and Infiltration Rate*

4.1.4 c/a Ratio

The c/a ratio is also a deciding factor in the effectiveness of CPC. The right c/a is necessary for a balance between the strength and the infiltration rate of PCP. The various tests conducted on the testing sample showed the following relations:

Relation between c/a ratio and Strength

The c/a ratio of PC shapes the strength of the pavement. Increasing the cement content in the mix greatly increases the strength of the PC while significantly reducing the permeability.

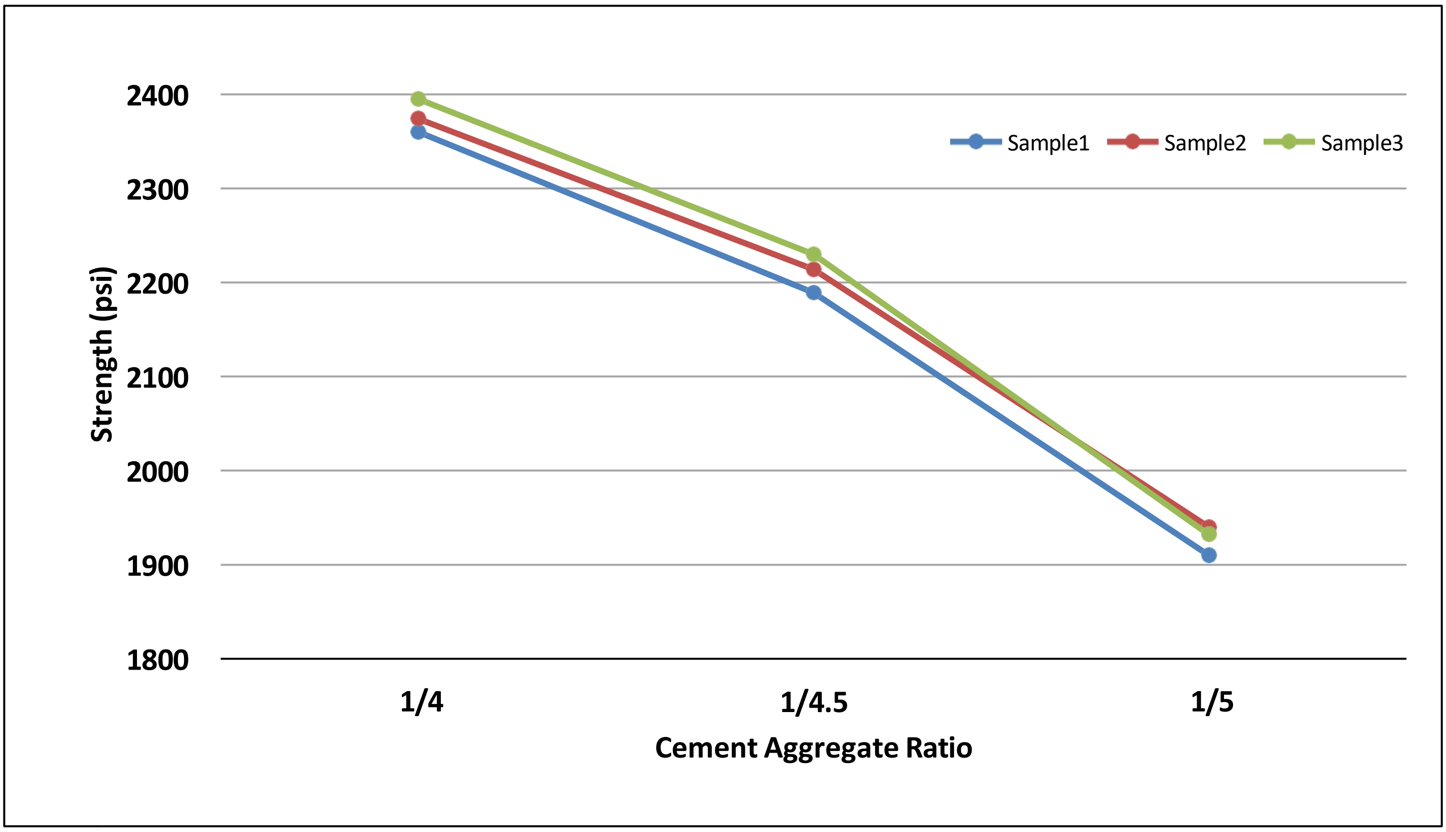

Figure 9: *Relation between Strength and c/a ratio.*

The trend shows that as we decrease the c/a ratio, the strength of the PCP increases. Therefore, for the best results, we need to take the c/a 1/4 so that our pavement has the required strength to take the traffic loads.

Relation between c/a ratio and Infiltration Rate

The c/a ratio showed an inverse relation with the infiltration rate of the PC. Therefore, as we increase the cement content in the PC while it increases the strength, it reduced the infiltration rate.

The trend obtained from the test results showed a decrease in the infiltration rate as we decrease the c/a ratio. However, this change was small. The resulting infiltration rate at the c/a ratio of 1/4 was within the acceptable range. The acceptable range is greater than 1mm/sec for a functional PCP.

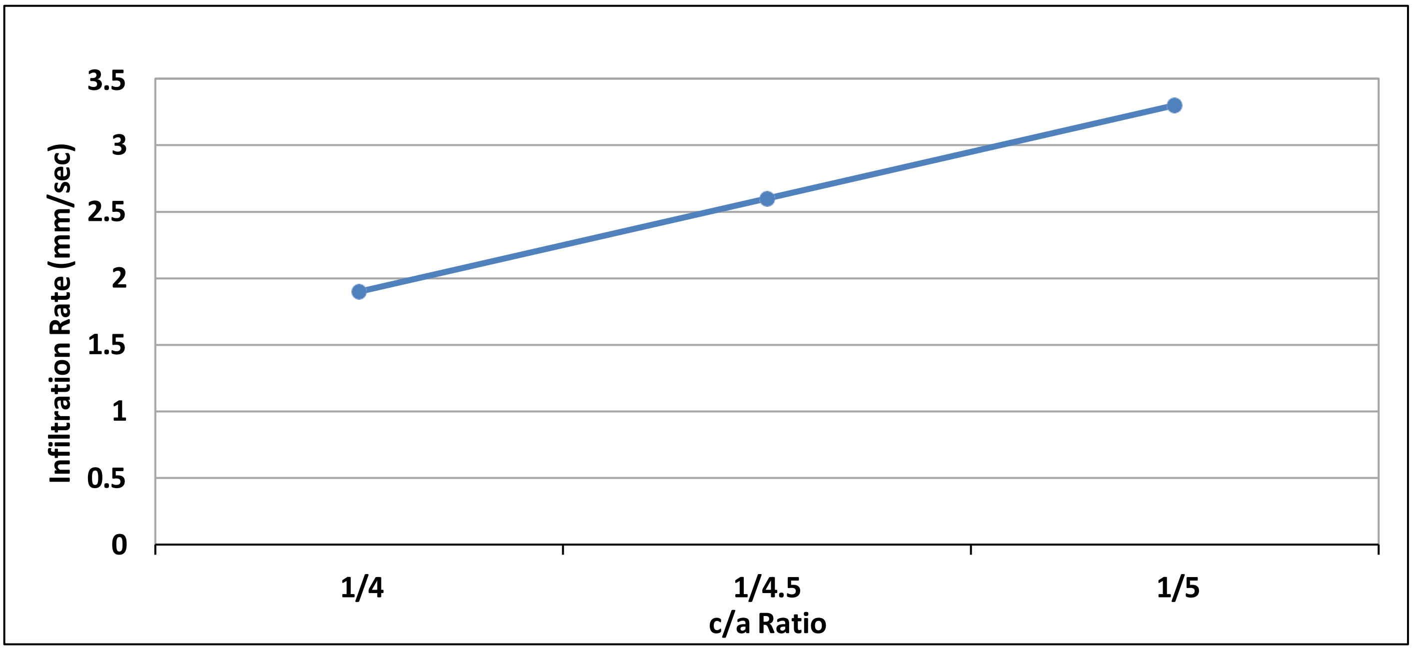

Figure 10: *Relation between Infiltration Rate and c/a ratio*

4.1.5 Relation between Strength and Infiltration Rate

The two of the most important parameters in the PCP are the compressive strength and the infiltration rate. All the other factors discussed earlier in the study directly or indirectly affect these two parameters. This fact is visible in the trends obtained by the different tests performed for the evaluation of the PCP.

However, the most important question is what's the relation between both of these factors. As shown by the trend from factors such as the w/c ratio, aggregate size, c/a ratio, and porosity, it seems that strength and infiltration rate are inversely related to each other.

Further experimental evaluation proved that both these parameters are inversely relational. As we increase the strength of the PCP, the infiltration rate decreases and vice versa. Here is the trend obtained between the infiltration and the strength.

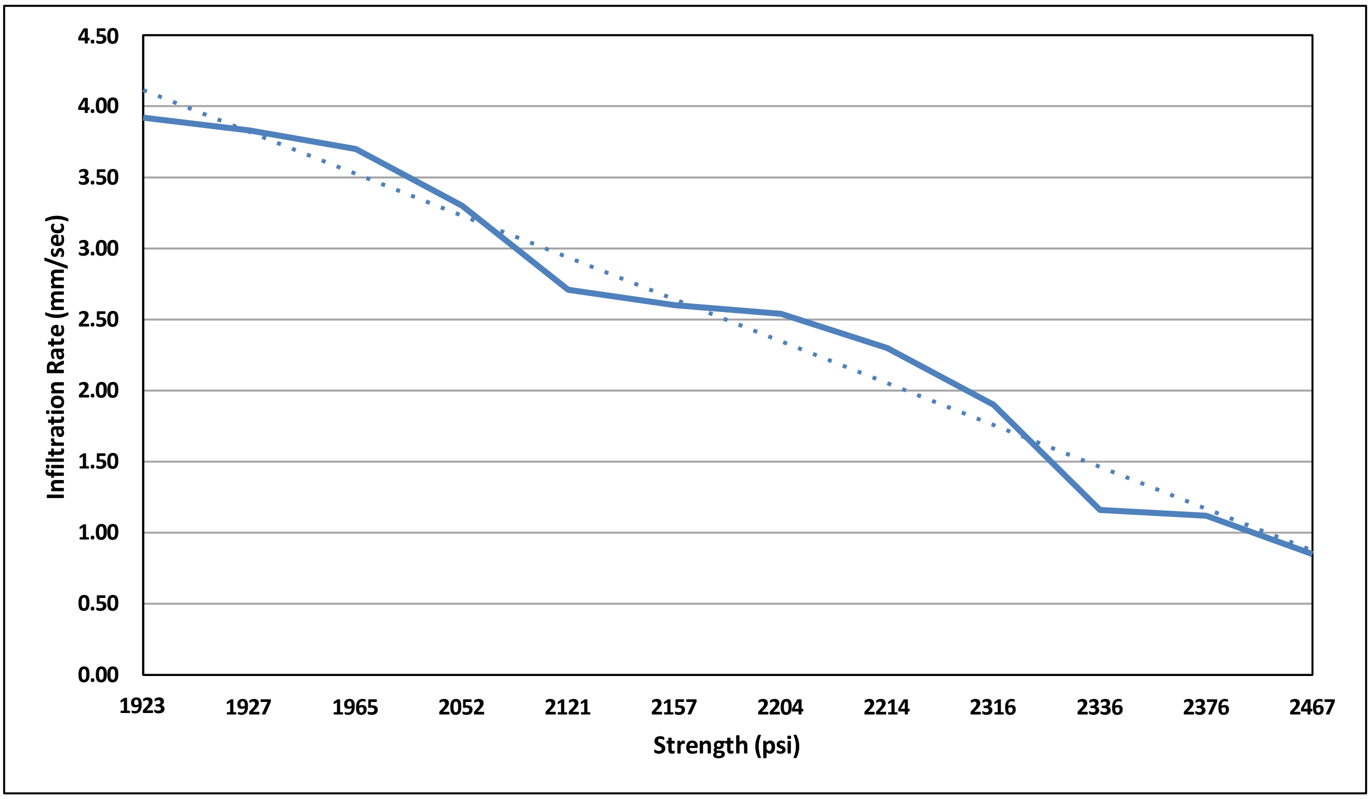

Figure 11: *Relation between Strength and Infiltration Rate*

4.2 Mix Design for Permeable Concrete in Pakistan

The experimental evaluation showed how different parameters are related to one another. So, it guided the way in choosing the right mix design for Pakistan. We tried out different mix designs to maintain reasonable strength when carrying traffic loads.

The second step was to check the infiltration rate and make sure it was in the acceptable range. We tested different mix designs in the acceptable ranges of both strength and infiltration rate. After testing and results, the final mix design obtained was:

Mix Design	
Aggregate Size	½ inches
w/c Ratio	0.35
Porosity	25%
c/a ratio	1/4

This mix resulted in the maximum compressive strength of ≈2400 psi. While the infiltration rate obtained was 1.15 mm/sec.

4.3 Drainage Design

When it comes to the drainage design, the best option in Pakistan is the partial infiltration of PCP. This option allows for stormwater management without having to worry about preparing all the pavement layers for drainage. The following pavement design is best suited for application in Pakistan.

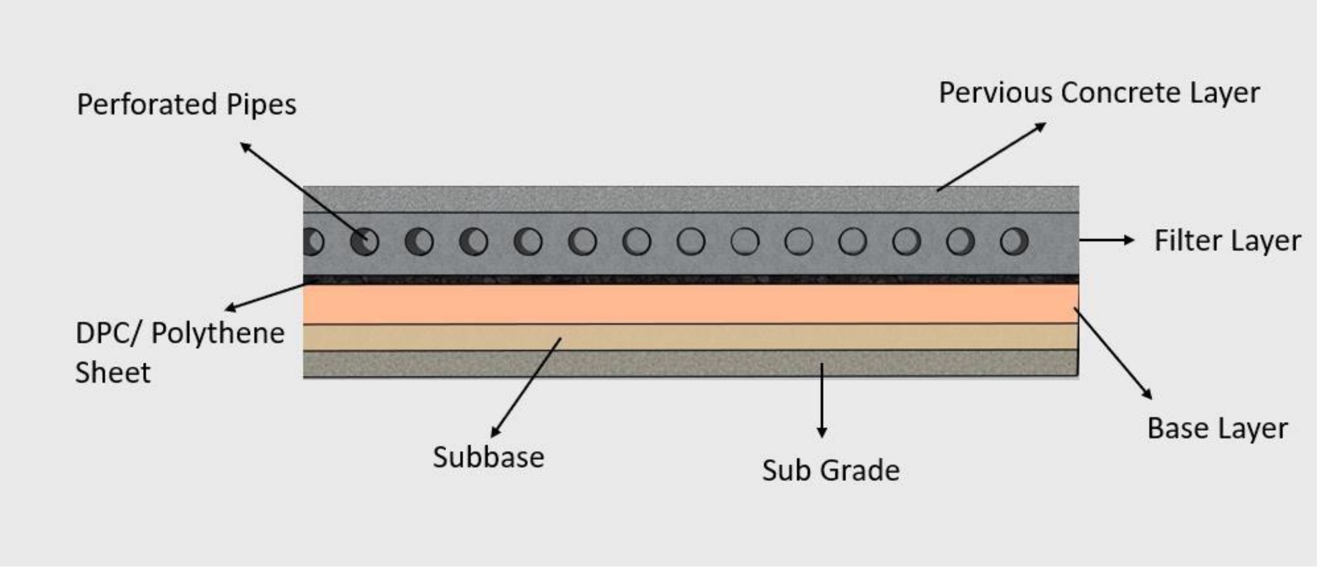

Figure 12: *Drainage Design of Permeable Concrete Pavement for Pakistan*

In this pavement, there is a permeable concrete layer at the top. This layer is followed by a filter layer that is made of coarse aggregates and incorporates perforated pipes for drainage. The stormwater from the PC layer will enter the filter layer, which will drain into the perforated pipes.

The excessive water that doesn't enter the drain pipes is drained by the natural slope of the pavement in the filter layer. The drainage pipes can be directed to groundwater recharge wells for sustainability. However, if not feasible, this paper can be stored or directed to the existing drainage system.

After the filter layer, there is a DPC of 3 inches to prevent water from entering the base and subbase layer. Depending on the budget constraints, a polythene sheet can also be used instead of the DPC; both play a similar role in preventing water from entering the layers beneath.

Since water doesn’t enter the base and subbase, the concrete material used in a concrete pavement will suffice. Lastly, there is the subgrade or existing natural ground. The subgrade needs to be provided based on the structural need of the pavement and the traffic load it will be subjected to.

4.1.1 Recommended Minimum Layer Thickness

The PCP need to have layers thicknesses sufficient enough in each layer to withstand the traffic loading. The experimental evaluation showed that the we need the filter layer to be thick enough to incorporate the drain pipes. Therefore, the PCP should has the filter layer at least 8 inches thick. This layer thickness provides enough strength and stormwater management capabilities.

Since water is not enter the base and subbase, their calculations are done as that of a conventional concrete pavement. Since the PCP act like a rigid pavement when subjected to loading so that pavement design against loading was done as that of a conventional rigid pavement.

The base layer in PCP needs to have a length of 10 inches. However, when it comes to the subbase that depends upon the structural needs. If the traffic loads are more there might be a need of subbase, but like most rigid pavements this layer can be skipped.

The most critical layer is the topmost permeable layer. Its thickness depends on the number of ESALs the pavement is subjected to. So depends upon the loads the pavement will be subjected to we calculated the layer thickness of the permeable layer.

We varied the number of EASAL to study the effect on the layer thickness. As we increase the W18 load the layer thickness also needs to be increased to have enough strength to withstand that load. We also varied the modulus of subgrade reaction to see its effect on the layer thickness.

As we increased the k value the trend showed that it required a smaller layer thickness. The following trend was obtained by the experimentation.

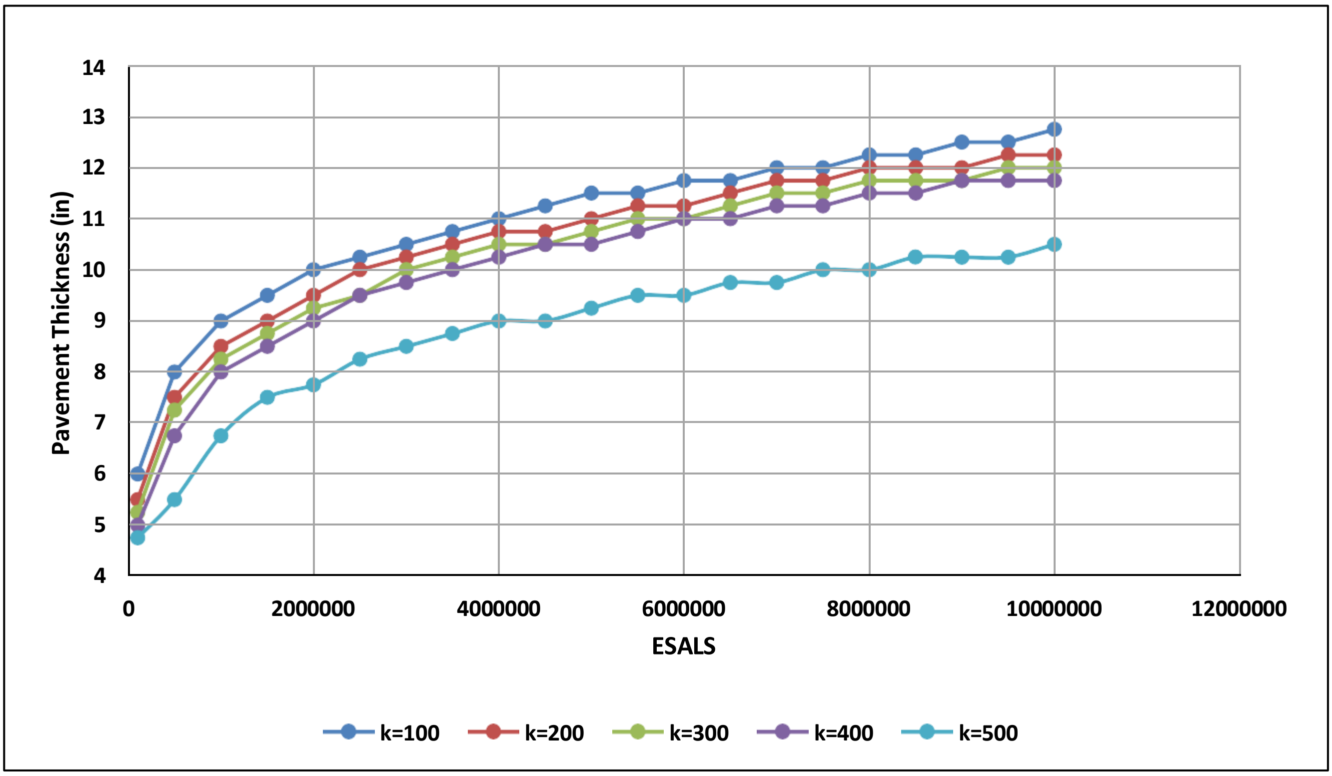

Figure 13: *Relation between ESALs Value of K and Pavement Thickness*

4.1.2 Curing Time

We performed the compressive strength test on test sample to obtain the trend of how the PC gains strength. These tests were performed on 1-d, 3-d, 7-d, and 14d. The trend obtained showed that the around 75% strength in 7d.

Therefore, based on that the following curing times are recommended for the pavement.

- 24 hours curing time for Pedestrian use.
- days curing time for normal vehicular traffic.
- 10 days curing time for heavy truck traffic.

Additionally, a sample of PCP was subjected to environmental conditions to see how it will affect the permeability of the pavement when exposed to the environment. The pavement was left in the open for around 50 days to observed the change in permeability.

Figure 14: *PCP exposed to dust and environment to check for clogging*

The results showed that the change was nearly negligible. The only thing the clogs the PCP permanently or significantly is the asphaltic particles. Therefore, proper separation needs to be provided where the PCP and asphaltic pavements are adjacent to one another.

CHAPTER 5

CONCLUSION

We investigated the use of PPs in stormwater management. They are a sustainable practice. We reviewed existing literature and case studies. They covered the performance of permeable pavements. We looked at their hydrology, environmental benefits, cost, and long-term sustainability.

5.1 Conclusion

The use of PCPs in stormwater management presents a sustainable solution for urban environments. This thesis demonstrates that PCPs offer significant hydrological, environmental, and economic benefits. PCPs address the challenges of stormwater runoff. They help urban infrastructure be resilient and sustainable. Future research and innovation in this field will further enhance the viability and effectiveness of PCPs. It will be a transition towards more sustainable urban landscapes.

The key findings of this study highlight the significant advantages of (PCPs) in various domains.

PCPs boost hydrological performance through enhanced stormwater infiltration rates. This leads to a reduction in surface runoff and peak flow rates. It thereby decreases urban flooding incidents and improves groundwater recharge.

PCPs also offer notable environmental benefits. They help reduce the urban heat island effect. They do this by letting water soak through the pavement and evaporate. This cools the surrounding area. Additionally, PCPs contribute to groundwater recharge, further enhancing their environmental impact.

Despite their higher initial installation costs compared to traditional pavements, PCPs prove economically feasible in the long run. The long-term benefits justify the upfront cost. These include lower stormwater costs and longer pavement life.

Moreover, PCPs promote sustainability in urban development by supporting green infrastructure. Their adaptability to various climates and urban settings makes them a versatile and effective solution for managing stormwater, aligning with sustainable urban development goals.

These findings have many practical implications, particularly for urban planners and civil engineers.

Adding PCPs to urban planning can greatly improve resilience. It protects against extreme weather from climate change. The strategic placement of PCPs in flood-prone areas should be a key consideration in mitigating flood risks effectively.

Civil engineers must adopt permeable pavement designs. These designs should maximize infiltration and durability. However, the selection of appropriate materials and the implementation of proper maintenance practices are crucial for the long-term performance of PCPs.

Furthermore, the promotion of PCPs through incentives and regulations is necessary. Setting rules and standards for the design, installation, and upkeep of permeable pavements can help their widespread use. It also ensures their effectiveness in managing stormwater.

5.2 Future Recommendation

While this study provides a comprehensive overview of the benefits of PCPs, there is still a need for further research. The following are several areas that require further research.

Long-Term Performance:

There is a need to study the long-term performance and durability of PCP. This study is required to be done in various climatic conditions. We also need to implement PCPs in road networks. This will help us understand how they react to real traffic.

Cost-Benefit Analysis:

Detailed cost-benefit analyses of PCP are also required. They consider different urban settings and scales of use. They can provide more insights into the economic feasibility of PPs in Pakistan.

Material Innovation:

Research on alternative materials can also be done to improve the strength of the PCPs. We need to try different sustainable options to cut the costs of PCPs while increasing their practicality and ease of use. Innovations in porous materials, additives, and construction techniques are promising areas for research.

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