ENHANCING STORMWATER DRAINAGE SYSTEM WITH PERMEABLE PAVEMENT: A SUSTAINABLE SOLUTION FOR KHULNA CITY

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ABSTRACT

In Bangladesh, cities are confronting a variety of environmental issues as the population is increasing. Because of population growth and rapid urbanization, land uses have switched from aquatic bodies and barren fields to impervious land and pavement. The problem with impermeable surfaces is that they prevent precipitation from naturally soaking into the ground, resulting in poor stormwater management occurs water logging in urban areas. In recent times, Khulna City has been experiencing water logging issues severely. As a result of an inadequate drainage system, poor management of stormwater, lack of permeable pavement, and water retention areas, Khulna City's residents frequently experience waterlogging during the rainy season. In addition to drainage issues, uncontrolled stormwater runoff poses serious threats to the environment and water quality. It also disrupts traffic and daily life, damages infrastructure, and interferes with other human activities. Permeable pavement system (PPS) is a sort of stormwater drainage strategy that allows rainfall to penetrate the groundwater and may significantly lessen water logging issues in urban, industrial, and commercial areas while also enhancing water quality. The research focuses on sustainable drainage systems with PPS, which reduce water logging and enhance groundwater levels and water quality. A theoretical hydraulic design of a PPS with an underdrain has been completed in this work to reduce surface runoff. This research has demonstrated that a 14-inch-deep permeable pavement may effectively capture 209.04 cubic feet of surface runoff which is produced by rigid pavement. In addition, the effective implementation of permeable pavement will contribute to the development of liveable and healthy communities and will advance urban areas toward sustainability by attaining SDG goal 11.

Keywords: *Sustainable Drainage System, Strom Water Management, Permeable Pavement, Water Logging, Khulna*

1. INTRODUCTION

Rapid urbanization and the requirement to handle ever-intense traffic have led to the development of an impermeable surface-based urbanization model (Pistocchi et al., 2015). Up to 70% of urban impermeable land is made up of driveways, parking lots, road pavement, and other impermeable surfaces related to vehicle traffic. The natural hydrological cycle in urban centers has been drastically altered by the recent increases in impervious surfaces. The runoff response time, peak, and volume of the runoff hydrograph are all enhanced, while the infiltration rate is considerably decreased as a result of the increased imperviousness (Konrad & Booth, 2005; Pagotto et al., 2000; White & Greer, 2006; G. Yang et al., 2011). Conventional drainage systems enhance the volume of runoff, peak flow, and pollutants carried to rivers by instantly transporting stormwater runoff to a stream via piped systems. Additionally, in cities with combined sewage systems, wastewater treatment facilities receive a mixture of black and grey water (from washing machines, toilets, and other sources) and impermeable surface water. Thus, combined sewage networks may overflow and flood during periods of high flow, discharging dangerous contaminants into the surrounding environment. On the other hand, enhanced imperviousness substantially hinders precipitation from penetrating the soil, thereby affecting groundwater restoration (Mullaney & Lucke, 2014; Stiefel et al., 2009). Therefore, implementing sustainable urban water management requires addressing all associated issues in an integrated manner, including improving the provision of urban drainage systems (Chandwadkar et al., 2022).

Bangladesh is experiencing environmental degradation due to rapid urbanization, an increase in population, and industrialization. With the population growth, cities of Bangladesh are facing various environmental problems like water logging, solid waste disposal, black smoke from vehicular and industrial emissions, air and noise pollution, pollution of water bodies by industrial discharge, etc. Out of these, water logging has become a very common problem in recent years. The water logging problem is particularly serious in Bangladesh's southwest. On July 16, 2017, The Daily Stars (The-Daily-Star, 2017) aired an article titled "Waterlogging: A Never-ending Crisis in Khulna City."

After Dhaka and Chittagong, Khulna is the third-largest city in Bangladesh. Khulna District is 4,394.46 square kilometers (1,696.71 square miles) in size, whereas the city is 59.57 square kilometers (23.00 square miles). When compared between1998 to 2018, the overall area of the built-up area was changed from 20.214 to 25.6815 square kilometers, a considerable reduction in the quantity of the surface water body, which was 5.9598 square kilometers, from 7.4502 square kilometers in 1998 (Marufuzzaman, 2019). Impermeable urban areas had an increase in surface runoff of 5.44% (17.00 mm in average runoff) between 2005 and 2020, whereas the vegetative land cover experienced a 13.34% decrease in area (Das & Esraz-Ul-Zannat, 2022). A notable cause of water logging in Khulna is the disappearance of the natural drainage system, an unplanned or inadequate drainage system, poor operational efficiency, and poor drainage system maintenance. Currently, the intensity and frequency of past exceptional heavy rainfall—which are often described as intensity-duration-frequency (IDF) curves or further generalized into the form of rainstorm intensity formula—determine the design of drainage systems in towns and cities. Urban drainage system capacity increases won't work since they won't deal with the root of the issue. As long as urbanization persists, there will be an increase in the drainage burden. Therefore, it is necessary to manage city runoff sustainably to preserve city hydrology, restore the land's natural ability to distribute precipitation, particularly to penetrate and replenish stormwater, improve water quality, and preserve the environmental benefits of city ecosystems. The widespread application of sustainable drainage systems (SuDS) is a practical way to increase drainage efficiency in city areas. Through the facilitation of storage, infiltration, and evapotranspiration processes (Ahiablame et al., 2012; Bressy et al., 2014), SuDS is an effective strategy for reducing the negative effects of imperviousness on stormwater runoff in city areas (Ballard et al., 2015; Palla & Gnecco, 2015). The use of sustainable drainage systems is replacing conventional drainage systems in stormwater management systems, which are an essential component of civil infrastructure (Saurí & Palau-Rof, 2017). One of the most well-known types of SuDS is permeable pavement systems or PPS. PPS is made expressly to encourage rainwater to seep into the pavement and structure, where it is filtered by the different layers of pavement. PPS reduces the need for additional areas for detention facilities by combining a hard surface with infiltration and detention technology. Because they make efficient use of available space, let water percolate through the paving surface and into the soil layers below, and offer a sturdy surface for walkers or light vehicle usage, permeable pavements are an obvious choice for managing stormwater in the cities (Sansalone et al., 2008; Shackel et al., 2008). In low-traffic roads with speed limits of 55 kph (35 mph) or less, driveways, pathways, patios, sidewalks, courtyards, lanes, and parking lots are common places for the usage of permeable pavements.

In this study, a small portion of road no-16 in the Mujgunni residential area, Khulna has been selected to evaluate the amount of surface runoff because of rainfall and a theoretical design section of PPS has been provided to penetrate this runoff into soil. So, the objectives of this research are-

1) To examine the current drainage situation in the selected study area.
2) To explain the characteristics of permeable pavement and its drainage capabilities concerning urban stormwater management.
3) To provide an environmental solution for ensuring a sustainable drainage system through permeable pavement

2. METHODOLOGY

This research is a mixed-method inquiry. Most of the information required for this research will be a mixture of both quantitative and qualitative. In the qualitative approach, data from existing stakeholders, key informant opinions has been collected. Different tools such as photography, semi-structured questionnaire surveys, key informant interviews and recordings, and personal observation have been used for primary data collection. In the qualitative approach, data from different statistical sources and literature have been analyzed for secondary data collection. The literature has been reviewed to find out the research gap, existing solution, and further scope of the research. This research consisted of five phases which describe the whole procedure and activities from the start of the research until the end.

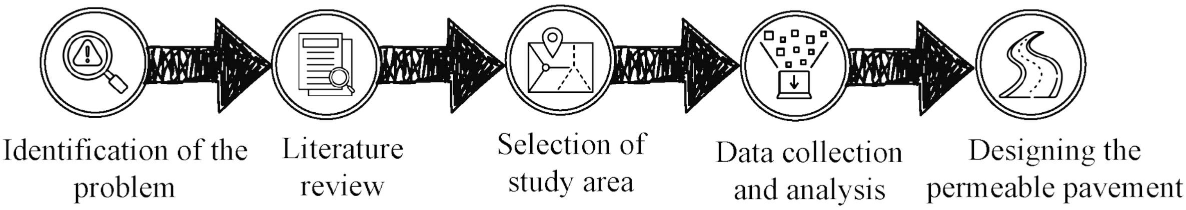

Figure 1: Flow chart of methodology

3. Literature Review

The Google Scholar database was utilized to identify works on permeable pavements. A green system for managing runoff for drainage that includes collecting, conserving, treating, and reusing stormwater runoff is called a sustainable drainage system. Though the systems do allow for a wider range of applications, permeable pavement is an excellent stormwater management option for a wide variety of cities, commercial, and industrial sectors (Grabowiecki & Scholz, 2006). Permeable pavement is designed for light-duty and frequent usage. PPS has emerged as a crucial component of SuDS, despite an absence of high-caliber research in this specific field relative to other fields of study. PPS are excellent in managing runoff and reusing water (Imran et al., 2013). When in good condition, permeable pavements can handle the runoff of rainfall events greater than a storm event that occurs once every 100 years (Shaffer, 2009), with infiltration rates ranging from 130 mm/h to several thousand mm/h (Volder et al., 2009). According to earlier research, depending on the designed system, permeable pavements can lower peak flow by 7–43% and total surface runoff by 1–40% (Hu et al., 2018). It was discovered that flooding durations and amounts are reduced by around 71% and 18.29%, respectively, when a reservoir depth of 240 mm. Reductions in flooding volumes and intervals were found to be around 98.5% and 81%, respectively, at a reservoir depth of 328 mm beneath the porous asphalt. Changing the reservoir depth to 400 mm resulted in no surface flooding being seen (Al-Busaltan et al., 2021). Permeable pavements might offer a first degree of water quality treatment in a stormwater harvesting system if they are correctly constructed and maintained. (Selbig et al., 2019) assessed how well permeable pavements may enhance stormwater runoff quality and came to the following conclusions: metals were eliminated by up to 49%, total phosphorus load was decreased by up to 43%, and suspended particles were reduced by about 60%. In Nantes, France, (Pagotto et al., 2000) compared the effectiveness of permeable pavement with conventional pavement and found that there was a 74% decrease in heavy metals, 87% retention of solids, and 90% interception of hydrocarbons. In low-traffic roads with speed limits of 55 kph (35 mph) or less, driveways, pathways, patios, sidewalks, courtyards, lanes, and parking lots are common places for the usage of permeable pavements.

A permeable pavement system's required design thickness for allowing water to percolate into its base course depends on several factors, including the pavement's contributing area, the rate at which subgrade infiltration occurs, the type of base course material used, the volume of runoff generated by the chosen design rainfall intensity, and the system's need for stormwater management (Kamali et al., 2017; Q. Yang et al., 2019). However, as of yet, no standardized structural design process has been implemented for any kind of permeable pavement (Kuruppu et al., 2019). Optimizing runoff reduction and nutrient removal is the main design objective of permeable pavement. To achieve this, designers have the option of using either an improved (Level 2) or baseline (Level 1) permeable pavement design, which maximizes runoff and nutrient reduction (Table 1).

Table 1: Guidelines for Permeable Pavement Design (VA-DEQ-STORMWATER-DESIGN-SPECIFICATION-NO-7, 2022)

Level 1 Design	**Level 2 Design**
Infiltration of soil is less than 0.5 in/hr.	The rate of soil infiltration is more than 0.5 in/hr.
Need for an underdrain	Underdrain is not necessary
CDA = The permeable pavement area plus upgradient parking, as long as the ratio of external contributing area to permeable pavement does not exceed 2:1.	CDA = The permeable pavement area

Three distinct sizes of permeable pavement may be installed: micro-scale pavement (total area of between 250 and 1000 square feet), small-scale pavement (total area between 1000 and 10,000 square feet), and large-scale pavement (total area greater than 10,000 square feet) (VA-DEQ-STORMWATER-DESIGN-SPECIFICATION-NO-7, 2022). A permeable surface serves as the top layer of a PPS, with many sub-base layers consisting of different materials with varying thicknesses and compositions based on the intended use (Figure 2).

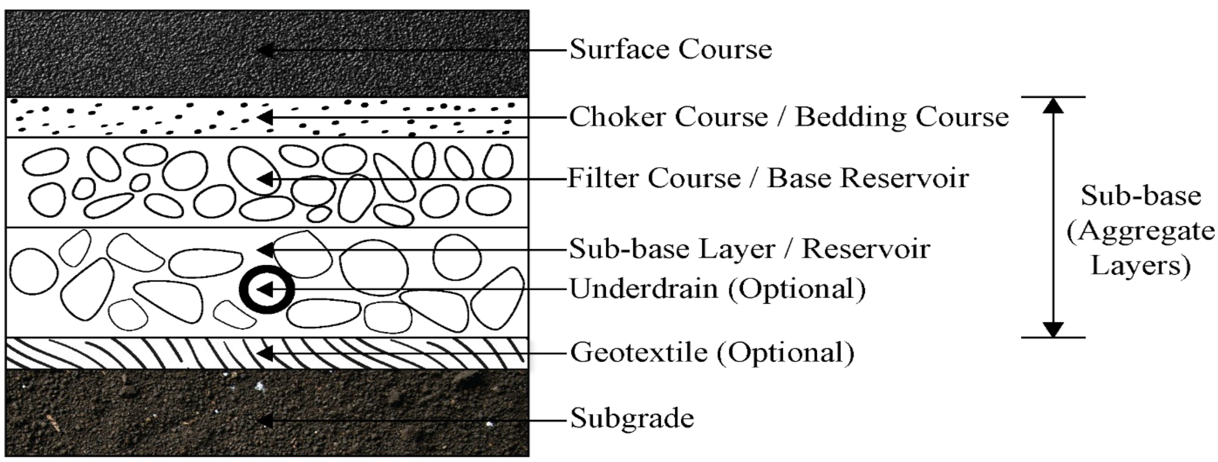

Figure 2: General cross-section of permeable pavement

4. Selection of Study Area

Every road in Khulna that has lanes and is used by light-duty vehicles can be chosen to have permeable pavement as a replacement for traditional pavement. In this study, Mujgunni Residential Area road no.16, Khulna has been used as an example which is located in ward no- 14. This study area is closely adjacent to ward no-09 which is extremely waterlogged in the rainy season. Though the selected study site is not an urban flood-prone area, no. 16 road can not be used during the rainy season. After surveying the study area, it has been determined that the insufficient storm drainage network is the cause of the stormwater not being removed. Besides, there aren't enough natural surfaces to store water. In addition, the road's nonporous paving materials prevent water from soaking up and seeping into the earth. Thus, during the rainy season, a situation of waterlogging arises.

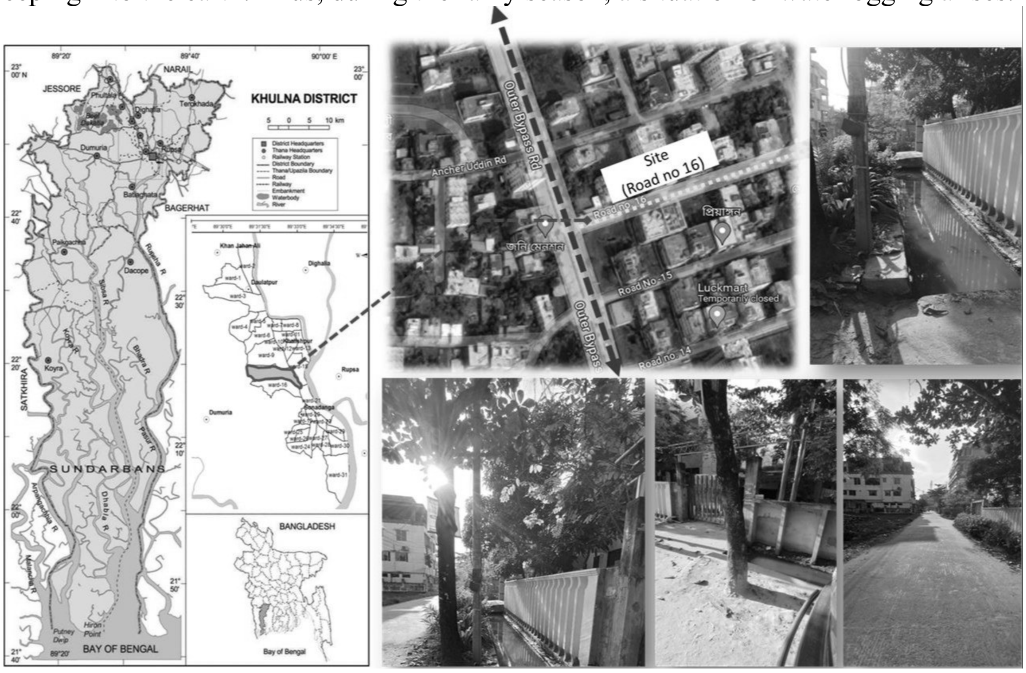

Figure 3: Observation of selected study area

5. Collection of Data and Analysis

5.1.1.1 Soil condition of the study area

Soil type: Clay soil (Roy et al., 2005) - Hydrologic Soil Group D
Runoff coefficient of Clay soil: 0.42-0.51 (Khadka, 2019)
Infiltration rate of Clay soil: 1-5 mm/hr

5.1.1.2 Precipitation data of study area

In all measured months, the depth of precipitation was less than 2 cm.

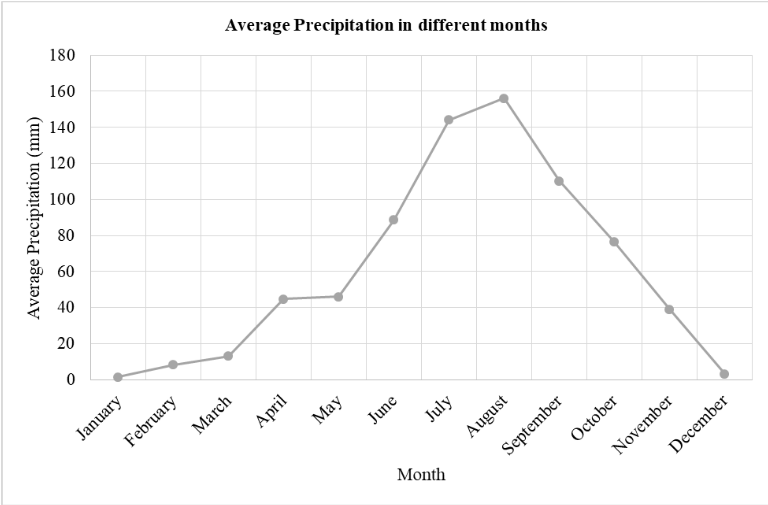

Figure 4: Precipitation data of khulna (Weather-and-Climate, n.d.)

6. Designing the Permeable Pavement

This research has been conducted using a theoretical design. Since the chosen research area's soil infiltration rate is less than 0.5 inches per hour, Level 1 permeable pavement design has been completed on a micro-scale. An underdrain is necessary because clay soil has relatively little infiltration, so a permeable pavement system with underdrain has been designed.

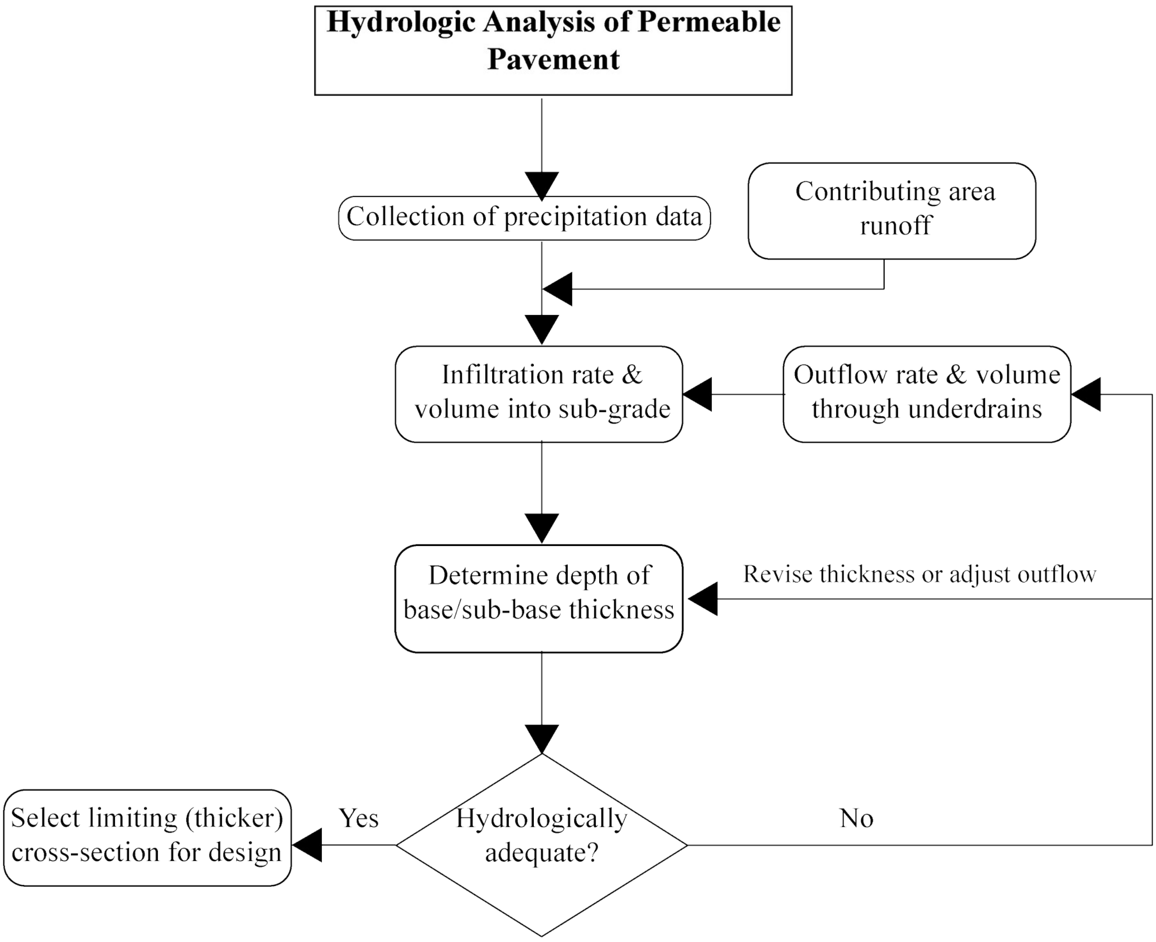

Figure 5: Flow chart of hydrologic analysis of permeable pavement (author)

7. Strom water Runoff Calculation

It was assumed that width of the road = 3.8m (12.47ft) and length of the road = 10m (32.81ft)

Area of the road = (12.47×32.81) sft =409.14 sft < 1000 sft

A one-inch rainstorm yields 62 gallons of water for every 100 square feet of surface.

So, the volume of runoff water = 409.14×0.62×6.15 (calculated for maximum value of precipitation from figure) = 1560.051 gallon = 209.04 ft^3

8. Rainfall Intensity Calculation

$$i_{d,T} = \frac{69.536 - 23.457\ ln(-ln(1-\frac{1}{T}))}{d^{0.686}}$$ (Afrin et al., 2015) (1)

It is assumed that storm event, d=15mins=0.25 hour and design period, T=1.5 years (Wahab et al., 2016)

So, accrding to equation 1 rainfall intensity, $i_{d,T}$ = 174.27 mm/hr = 6.797 in/hr

9. Depth of Runoff Calculation

Peak runoff flow rate, $Q = CiA$ (2)

Runoff coefficient, C = 0.95 (the runoff coefficient for impermeable surfaces) (Minnesota-Stormwater-Manual, 2021)
Rainfall intensity, i = 6.797 in/hr
Drainage area, A = 409.14 sft = 0.0094 acre (as the assumed surface area will be permeable)

According to equation 2, peak runoff flow rate, Q = 0.06 cfs

Depth of runoff, $d_c = \frac{Q}{3600} \times t$ (3)

Duration of the storm, t= 15 mins = 900 s

So, considering equation 3 the depth of runoff, d_c = 0.015 ft

10. Underdrain Outflow Rate Calculation

$q_u = k \times m$ (4)

Hydraulic conductivity for the reservoir layer, k= assume 100 ft/day
Underdrain pipe slope, m = assumed 1%

Underdrain outflow rate, $q_u = 100 \times 0.01$=1 ft/day

11. Depth of Base/Sub-base Reservoir Layer Calculation

$$d_p = \frac{\{(d_c \times R) + P - (\frac{1}{2} \times t_f) - (q_u \times t_f)\}}{V_r} \quad (5)$$

(VA-DEQ-STORMWATER-DESIGN-SPECIFICATION-NO-7, 2022)

Depth of runoff from the contributing drainage area (not including the permeable pavement surface) for the Treatment Volume (T_v/A_c), or other design storm, d_c = 0.015 ft

The ratio of the contributing drainage area (A_c) (not including the permeable pavement surface) to the permeable pavement surface area (A_p), R =2 (VA-DEQ-STORMWATER-DESIGN-SPECIFICATION-NO-7, 2022)

The rainfall depth for the Treatment Volume, P = 6.15 inch = 0.51 ft

The infiltration rate for the clay soils, i = 3 mm/hr (Taking the average value of infiltration rate of clay soil) = 0.24ft/day

The time to fill the reservoir layer, t_f = assumed 2 hours or 0.083 day

The void ratio for the reservoir layer, V_r= 0.4 (according to ASTMC29)

Outflow through Underdrain, q_u= 1ft/day

Considering equation 5, the required depth of the reservoir, d_p =1.18ft

12. Storage Volume Calculation

$$V_s = A_p(d_p n + 0.5 i t_f)$$ (Minnesota-Stormwater-Manual, 2021)

(6)

The surface area of the permeable pavement, A_p = 409.14 ft^2

Porosity, n = $\frac{0.4}{1+0.4}$ = 0.29

So, the storage volume, $V_s = 409.14(1.18 \times 0.29 + 0.4 \times 0.24 \times 0.083)$ = 143.27 ft^3

13. Specification of the Material for Designed PPS

The surface of pavement: Permeable Asphalt (PA) was chosen as the design, build, and maintenance guide for porous asphalt called Porous Asphalt Pavement for Stormwater Management is available from the National Asphalt Pavement Association (NAPA).

Choker course/ Bedding course: 2 in-depth of ASTM D448 size No. 8 stone was recommended (VA-DEQ-STORMWATER-DESIGN-SPECIFICATION-NO-7, 2022)

Reservoir Layer: 14 in (as per calculation) depth of ASTM D448 size No. 57 stone (e.g. 1 1/2 to ½ inch in size) or No. 2 Stone (e.g. 3 inch to 3/4 inch in size) was recommended

Underdrain: 4 to 6-inch diameter perforated PVC (AASHTO M 252) pipe was recommended to be installed at a minimum 1% slope

Geotextile Layer: A needled, non-woven, polypropylene geotextile with Grab Tensile Strength equal to or greater than 120 lbs (ASTM D4632), with a Mullen Burst Strength equal to or greater than 225 lbs./sq. in was recommended (VA-DEQ-STORMWATER-DESIGN-SPECIFICATION-NO-7, 2022) .

14.DISCUSSION

Quantitative and qualitative analyses for permeable pavement systems were carried out in this work. Despite being installed on clay-rich soils, a theoretical PPS design demonstrated that the permeable pavement significantly decreased the quantity of stormwater runoff by utilizing the appropriate underdrains. 409.14 sft rigid surface can produce approximately 209.04 ft^3 surface runoff. If the same surface is replaced by permeable pavement, it will be able to permeate 209.04 ft^3 surface runoff by 14 in (1.18ft) depth of reservoir by maintaining the maximum void ratio of 0.4 for the suggested ASTM D448 size No. 57 or No.2 stone aggregates.

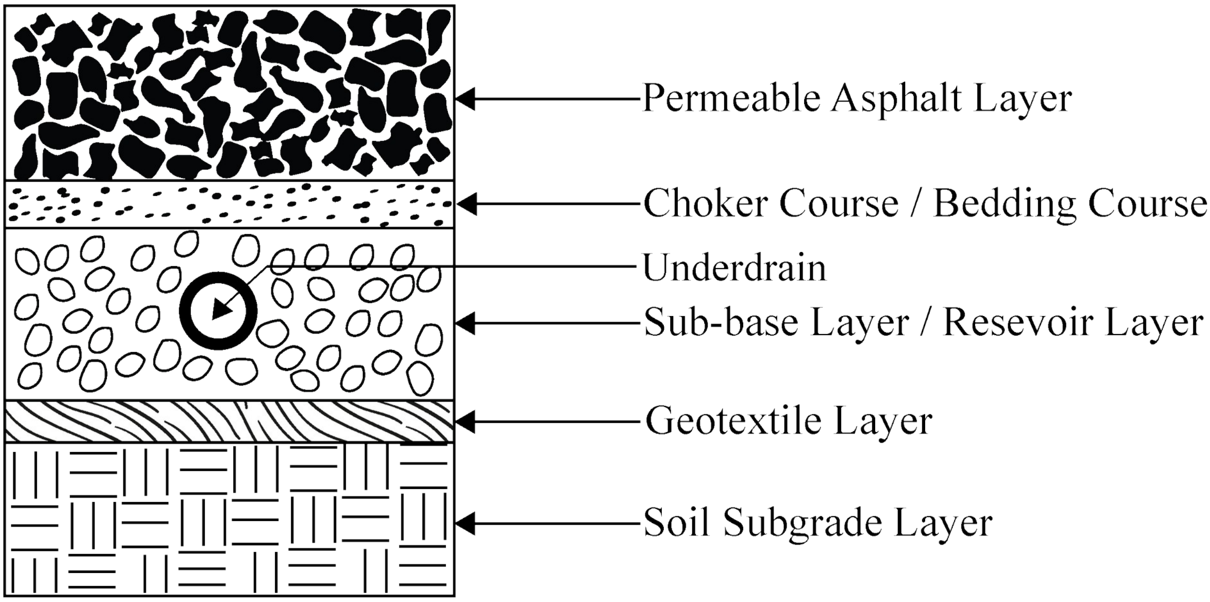

Figure 6: Proposed design cross-section for permeable pavement

15.CONCLUSION

There is no substitute for a quick and effective road network when it comes to a city's growth and prosperity. As road development has an impact on the dispersion of stormwater, there is a decrease in groundwater recharge and an increase in stormwater discharge. Disasters caused by urban flooding might occur if this is not addressed appropriately. This study showed that a permeable pavement system with asphalt surface can be a sustainable solution for surface runoff management and groundwater recharge. Despite being clay soil, permeable pavement with a drainage system can penetrate the surface runoff which is produced by rigid surfaces. When the rainwater penetrates the soil, different layers of permeable pavement will help to filtrate the water which ultimately improves the groundwater level and it will also help in achieving SDG goal 11 for Khulna, Bangladesh.

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