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Environmental Aspects of Stormpav Green Pavement Using SWMM at Padungan Commercial Center

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Abstract: This study aims to investigate the effect of permeable pavements' water quality, comprising StormPav, the new innovated permeable pavement by UNIMAS researchers, and Porous Concrete (PC) at Padungan Commercial Centre using the Stormwater Management Model (SWMM). Urban stormwater runoff is extremely polluted with various pollutants such as total suspended solids (TSS) and Total Phosphorus (TP). Therefore, permeable pavements (PP) are proposed to be implemented in the study area. The performance of the PP system of StormPav and PC was investigated using Low Impact Development (LID) control in SWMM. The exponential functions and parameters of TSS and TP loads generated from the commercial centre were obtained from past studies. The results found that the StormPav shows significant results in reducing runoff during high storm events about 25% to 37% compared to PC about 20% to 29% respectively. PC shows better performance at removing runoff for small storm events with runoff reduction of about 56% to 59% compared to StormPav at about 44% to 49%. The stormwater quality entering groundwater is improved using the PP system. From the simulation, PC performed better than StormPav at reducing both pollutants for high and low rainfall intensity with TSS and TP removal of about 99% and 98% respectively. Besides, StormPav removed 99% of TSS and 87% of TP during low rainfall intensity, but about 63% and 45% respectively of TSS and TP during high rainfall intensity. The finding indicates that StormPav can be used for stormwater management to reduce groundwater pollution.

Keywords: Stormpav Green Pavement Using SWMM

1. Introduction

Here The volume and quality of runoff water entering lakes and streams are significantly reduced as a result of urbanisation, changing the landscapes from natural grassland and forest to a hardscape environment. Urban stormwater is one type of 'non-point source contamination that comes from several different sources. The "polluted runoff" is often referred to as various contaminants such as suspended solids, arsenic, nitrogen, oils, heavy metals, and diseases that can be carried away by stormwater runoff. The impermeable surfaces transport a variety of contaminants into urban areas, including nutrients, silt, bacteria, pesticides, and chloride. It is expected that these pollutants would cause water quality deterioration in local rivers and streams, thereby impairing the quality of marine life and polluting supplies of drinking water. Increased runoff from impermeable surfaces results in dangerous flooding, significant erosion damage to stream channels, decreased groundwater recharge, and habitat destruction for fisheries.

Numerous studies have demonstrated that stormwater runoff contains common pollutants such as total suspended solids (TSS), chemical or biochemical oxygen demand (COD/BOD), trace metals (usually Cd, Cr, Cu, Ni, Pb, and Zn), and various species of Nitrogen (N) and Phosphorus (P) (Müller et al., 2020). From the list, the Total Suspended Solids (TSS) and Total Phosphorus (TP) are among the major pollutants in stormwater runoff and TSS is the most found pollutant during stormwater monitoring (Song et al., 2019; Masoud Saatsaz et al., 2011; Aryal et al., 2010; Yang & Toor, 2018; Rădulescu et al., 2019; Robertson et al., 2019; Wakida et al., 2014). Permeable pavement has been widely recognised as one of several eco-technologies for LID that improves stormwater quality. Porous concrete (PC), porous asphalt (PA), permeable interlocking concrete paver (PICP), concrete grid paver (CGP), and plastic reinforcing grid paver (PGP) are the most widely used paving materials of permeable pavements (Alam et al., 2019).

A permeable pavement is made out of either open pavers, concrete, or asphalt, all of which are connected by an underlying stone reservoir. Permeable pavement collects precipitation and surface runoff and stores it in a reservoir, gently enabling water to infiltrate into the soil below or drain through a drain tile. Permeable pavements are frequently utilised in low-traffic areas such as low- volume roads, parking lots, sidewalks, and driveways. Past studies have demonstrated that permeable pavements can effectively reduce the concentration of some pollutants either by

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Corresponding author: roslankhairisya@gmail.com.my physically trapping them in the pavement or soil, chemically through bacteria and other microbes that can degrade and consume those pollutants, or biologically by trapping them in the pavement (Yu et al., 2015; Parthasarathy & Narayanan, 2014; Li et al., 2017; Selbig & Buer, 2018; Turco et al., 2020).

An innovative Permeable Pavement with Precast Micro-Detention storage (StormPav) system is proposed, and its environmental aspects were investigated Figure 1. StormPav Green Pavement is a new invention that offers various structural, environmental, and economic advantages over conventional impervious asphalt and concrete pavements, which have several environmental and economic disadvantages (Bateni et al., 2019).

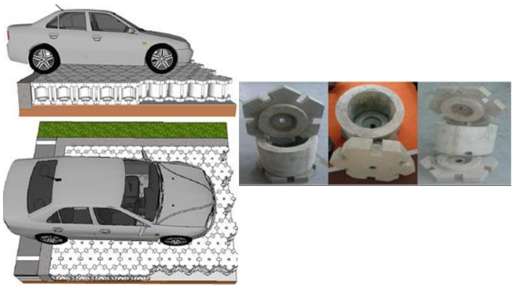


Figure 1. StormPav, a green pavement with micro detention storage (Bateni et al., 2019; Bateni et al., 2021).

The water quality parameters were determined to assess the environmental benefit, which is one of the components of sustainable development. The system has an empty hollow character, which can reduce the clogging effect, prevent system disconnection, and thereby enhances its efficiency while managing the stormwater runoff (Bateni, N. 2020). StormPav products were initiated in 2013 and fabricated in 2015, then experimentally tested and investigated in laboratory and field studies for various structural, roadworks, hydraulics, and hydrological application and simulated in various scenarios with an application of modelling such as Stormwater Management Model (SWMM) and Flow 3D. Past studies were compiled in a review paper of StormPav green pavement in Bateni, N. (2021).

This paper aims to identify the effect of the implementation of StormPav, a new green infrastructure innovation on stormwater runoff quality in urban areas and its efficiency in reducing pollutants in stormwater runoff using the SWMM. The study focuses on Total Suspended Solids (TSS) and Total Phosphorus (TP).

2. Methodology

All figures should be possible, as close as possible to the first reference to them in the paper. Please ensure that all the figures are of 300 DPI resolutions as this will facilitate good output.

3. Equations

In this study, the SWMM was used to simulate three scenarios comprises of the existing condition of asphalt road pavement and permeable pavements using PC and StormPav. Low Impact Development (LID) control, integrated with the water quality model to study the water quality performance of the PPs system has been used by previous researchers (Gülbaz, 2019; Chow et al., 2012; Rezaei et al., 2019). In this study, the TSS and TP were used as the pollutants for the water quality aspect in SWMM where the pollutants loads were compared between PC and StormPav to evaluate their environmental performance.

The study area is Padungan, a popular commercial centre in Kuching, Sarawak (Figure 2). The area is lined with Chinese shophouses, built mostly circa 1920 and 1930 during the rubber boom. Some buildings are decorated with elegance and interesting architectural details can be found at the back of the buildings. Coffee shops, pubs and restaurants, handicraft shops and unusual retailers including an entire block of fruit and flower sellers can be seen in the area. It plays an important part in connecting many roads in Kuching. Due to the importance of the Padungan area, constant commercial development is necessary to keep its functionality as a business centre. The continuous development of the area may cause stormwater runoff pollution in the area to worsen as the business centre is known to generate large volumes of rainwater runoff which can carry considerable quantities of pollution. The Padungan area is considered to be quite large and hence, the study site is kept within two rows of shophouses (Mah et al.,2018). Most permeable pavements have no sufficient strength to sustain heavy loads so, they are not meant to be constructed on heavy-traffic roads (Admute et al., 2017). Thus, in this case study, only the backstreet behind the shophouses will be utilised because of the low traffic activities.

Figure 2. Padungan Commercial Center

The next procedure was the selection of rainfall intensity, where four sets of rainfall scenarios were chosen to test the final model with different rainfall conditions. The intensity–duration–frequency (IDF) curves for the area in the Malaysian Urban Stormwater Management Manual were obtained through Hydrological Procedure (HP) 26. These curves were created using 100-year hydrological data for 2, 5, 10, 20, 50, and 100-year return periods. They were created to be used by researchers working in various topic areas. The rainfall durations are shown on the "X" axis, while the intensities are shown on the "Y" axis in IDF curves. In the shape of diagonal curves, the rainfall frequencies are depicted. For the two selected durations, namely 0.25 hr/15mins and 1 hr, return periods of 2 years and 10 years were chosen. For example, to get the first rainfall intensity, find the 1-hour length on the "X" axis and the intersection of the vertical line with the 5-minute return time.

The rainfall intensity of that return period and duration will be determined by the intersection of the horizontal line with this point's "Y" axis. Similarly, the process was performed for different lengths of time and with different return periods. As a result, three durations were applied to each return period in order to discover the matching rainfalls.

As a result, a total of four distinct rainfalls were recorded. Figure 3 and Table 1 show the rainfall totals that were achieved. The rainfall intensities were then used to simulate water quality modelling using SWMM.

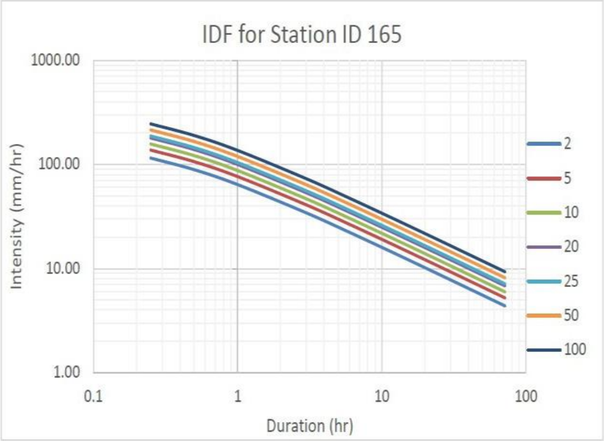
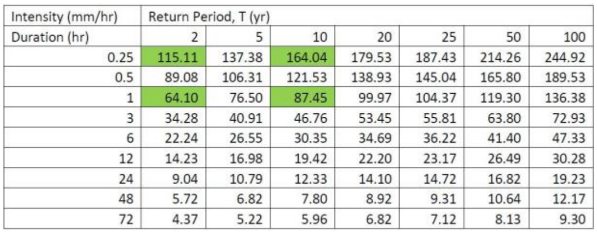


Figure 3. Kampung Tambey's IDF Curve

Table 1. Kampung Tambey's Rainfall Intensity with Different Return Periods and Durations



Intensity (mm/hr)	Return Period, T (yr)						
Duration (hr)	2	5	10	20	25	50	100
0.25	115.11	137.38	164.04	179.53	187.43	214.26	244.92
0.5	89.08	106.31	121.53	138.93	145.04	165.80	189.53
1	64.10	76.50	87.45	99.97	104.37	119.30	136.38
3	34.28	40.91	46.76	53.45	55.81	63.80	72.93
6	22.24	26.55	30.35	34.69	36.22	41.40	47.33
12	14.23	16.98	19.42	22.20	23.17	26.49	30.28
24	9.04	10.79	12.33	14.10	14.72	16.82	19.23
48	5.72	6.82	7.80	8.92	9.31	10.64	12.17
72	4.37	5.22	5.96	6.82	7.12	8.13	9.30

After obtaining all the information on the study area, the procedure continued with the development of the SWMM model, where the process starts with setting the properties and parameters of water quality data, hydraulic data, and hydrological data. Then, the model was calibrated and validated before specifying the properties of LID practices. In this case study, there are three scenarios to be presented which are the implementation of StormPav Green Pavement and Porous Concrete (PC). Figure 4 illustrates the flowchart of SWMM water quality modelling. The process starts with setting the properties and parameters of water quality data, hydraulic data, and hydrological data. Then, the model was calibrated and validated before specifying the properties of LID practices. In this case study, there are three scenarios to be presented, which are the implementation of StormPav Green Pavement and Porous Concrete (PC). Then, the simulation results were analysed and evaluated.

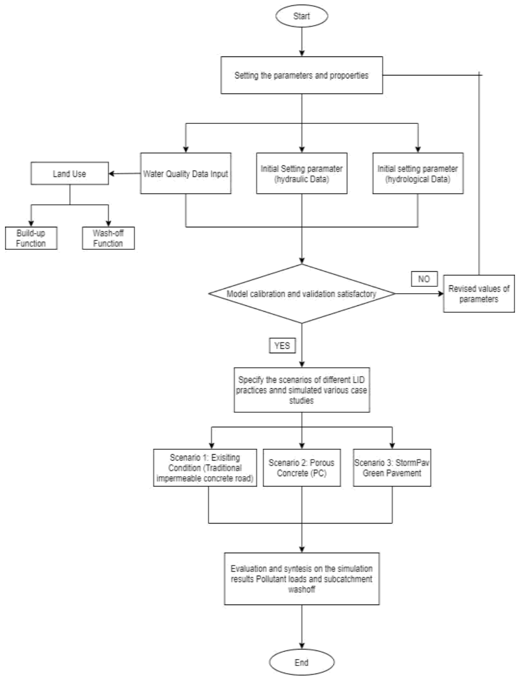
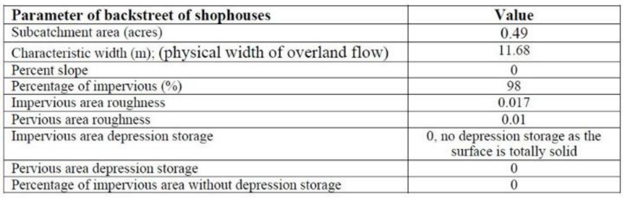


Figure 4. Flowchart of SWMM Water Quality Modelling for the PPs system in Padungan

The SWMM model requires numerous data layers and parameters in order to simulate runoff and pollutant loads in the watershed. This section describes the parameters used for the water quality and water quantity module.

3.1. Sub-catchment Parameters

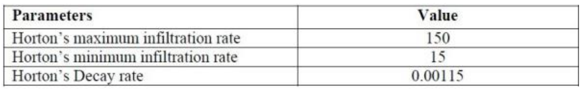


Parameter of backstreet of shophouses	Value
Subcatchment area (acres)	0.49
Characteristic width (m): (physical width of overland flow)	11.68
Percent slope	0
Percentage of impervious (%)	98
Impervious area roughness	0.017
Pervious area roughness	0.01
Impervious area depression storage	0, no depression storage as the surface is totally solid
Pervious area depression storage	0
Percentage of impervious area without depression storage	0

3.2. Infiltration Rate

The values were chosen due to the similar land use between the study sites in existing literature and in this case study, which was commercial.

Table 2. Infiltration Rate Used for This Case Study



Parameters	Value
Horton's maximum infiltration rate	150
Horton's minimum infiltration rate	15
Horton's Decay rate	0.00115

By using build-up and wash-off equations, SWMM is capable of simulating pollutant distribution. It is necessary to correctly parameterise the equation for various land uses to use the full potential of SWMMM.

$$Buildup = C_1 \cdot (1 - \exp(-C_2 \cdot t))$$

$$Washoff = C_3 \cdot Runoff^{C_4} \cdot Buildup'$$

Three equations of build-up (power, exponential, and saturation) and three equations of wash-off (exponential, rating curve, and event mean concentration. Exponential build-up and exponential wash-off equation parameters are frequently mentioned in the literature. Therefore, this project only considered parameters of the exponential build-up and wash-off equations, so the results are comparable. The equations are as follows:

In Eq. 1, on the left-hand side, the buildup term is the pollutant buildup in mass per unit area or unit curb length, and the number of previous dry weather days is on the right-hand side. In Eq. 2, the left-hand washoff term is the washoff load in the mass unit per hour, the right-hand runoff term is the runoff rate per unit area (inches/h or mm/h), and Buildup 'is the accumulation of contaminants in total mass units. C1 is the maximum potential buildup (mass per unit area or unit curb length), and C2 is the constant buildup rate regulating pollutant speed of pollutant build-up (1/days), C3 is the wash-off coefficient, and C4 is the wash-off exponent. Table 3 shows the exponential functions of this case study. The values were obtained from existing literature.

Table 3. Build-Up and Wash-Off Function used in this Case Study

Parameter	B_{min}	B_{exp}	W_c	W_{exp}
TSS	15	0.8	1.4	0.9
TP	0.5	0.1	0.4	1

Two LID elements StormPav and Porous Concrete (PC) were used in this model. Since this was just a hypothetical scenario, parameterisation of LID structures was mostly done by assuming the values and making an educated guess using the help of existing literature. Table 4 shows the LID control parameters such as the surface layer, storage layer and pavement layer for both PC and StormPav.

Table 4. PC and StormPav Parameters

Parameters	PC	StormPav
Surface Layer		
• Surface (m^2)	933	1.6/unit
• Vegetation volume fraction	0	0
• Surface roughness	0.017	0.017
• Surface slope (%)	1	0
Pavement Layer		
• Thickness (mm)	80	75
• Void ratio (voids/solids)	0.15	0.11
• Impervious surface fraction	0.85	0.88
• Permeability (mm/hr)	200	220
• Clogging factor	0	0
Storage Layer		
• Thickness (mm)	300	300
• Void ratio	0.4	0.7
• Seepage rate (mm/hr)	20	20

The pollutant removal efficiency of each permeable pavement can be determined by comparing pollutant load with and without implementation of LID Practice. The equation is shown below:

$$Pollutant\ Removal\ Efficiency = \frac{P_1 - P_2}{P_1} \times 100\%$$

Where;

P_1 = Pollutant Load without LID Control

P_2 = Pollutant Load with LID Control

4. Result

The data and analysis from the SWMM model simulation are presented to evaluate the performance of the StormPav pollutant runoff reduction and removal efficiency. The case studies presented three scenarios, Scenario 1: Existing condition with asphalt road pavement, Scenario 2: Permeable pavement with porous concrete (PC) and Scenario 3: StormPav permeable pavement of UNIMAS innovation.

Figure 5 illustrates the runoff responses of porous concrete (PC) and StormPav for four different rainfall events. Both StormPav and PC managed to reduce the peak flow rate of the runoff in the simulation. Figure 5 (a) and (c) illustrates that stormwater passing through PC and StormPav only shows sign of runoff at approximately 4 minutes after the rainfall compared to the existing condition in which runoff appears at minute three after the rainfall. For Figures 5 (b) and (d), the runoff only appears approximately 12 minutes after the rainfall, while the runoff appears one minute early for the existing condition. This shows that Stormpav and PC could delay runoff by approximately 1 minute by continuously absorbing the stormwater through the void particles between the pavement layers before the stormwater seeps into the storage underneath. The runoff only appears after all the voids have been completely occupied by stormwater.

Table 5. Summary of Runoff Removal Efficiency

Intensity (mm/hr)	Depth (mm)	Return Period (yr)	Duration (hr)	PC (%)	StormPav (%)
155.11	38.78	2	0.25	56.58	49.98
64.1	64.1	2	1	29.65	37.23
164.04	41.01	10	0.25	49.96	44.78
87.45	87.45	10	1	20.09	25.10

Table 5 shows that porous concrete (PC) and StormPav reduced up to 40% of runoff for rainfall depths of 64.1 mm and 41.01 mm. Meanwhile, the runoff reduction efficiency for both LID controls was reduced by less than 40% for volume or depth more than 50mm. This also shows that the higher the duration and the return period, the lower the efficiency of reduction. PC and StormPav, which experienced a 15-minute rainfall duration of a 2-year return period, could reduce more runoff compared to when they experienced a 1-hour rainfall duration for the same return period. To put this perspective into values, PC and StormPav, which experienced a 15-minute rainfall of a 2-year return period, could reduce runoff by 56% and 49% respectively. However, the efficiency of the permeable pavements decreased to 29% and 37% respectively when the rainfall duration increased from 15 minutes to 1 hour. The 10-year return period shows a similar pattern. To compare the return periods, the LID controls reduced more runoff for a 2-year return period of 15-min duration compared to a 10-year return period of the exact rainfall duration. For example, PC and StormPav showed a runoff reduction efficiency of 56% and 49% respectively for a 2-yr return period and 15-minute rainfall. The efficiency reduced to 49% and 44% for PC and StormPav respectively for a 10-year return period rainfall. The trend is similar for a 1-hour duration.

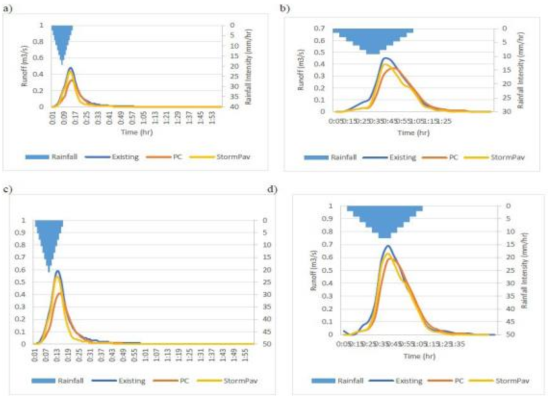


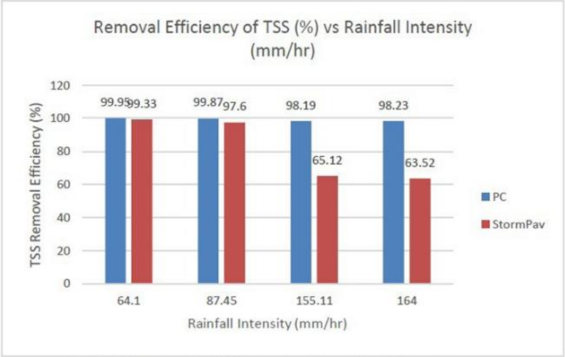
Figure 5. Runoff Hydrograph for Pavements Based on 2 and 10 yrs ARI (a) 15 min 2 yrs Storm Event, (b) 1 hr 2 yrs Storm Event, (c) 15 min 10 yrs Storm Event and (d) 1 hr 10 yrs Storm Event.

Table 6 shows the pollutants removal efficiency for PC and StormPav. It can be observed that as rainfall intensity increased, the pollutant removal efficiency decreased. For Porous concrete (PC), the TSS removal efficiency decreased from 99% to 98% as the intensity increased from 64.1 mm/ hr to 164.04 mm/hr while the TP removal efficiency decreased from 98% to 91%. StormPav showed the same trend that as the rainfall intensities increased, the TSS and TP removal efficiency reduced from 99% to 63% and 87% to 45% respectively. The change in pollutant removal effectiveness over time is primarily influenced by the intensity of rainfall and the nature of the rainwater pollutants. The permeable pavement relies mostly on pollution removal and adsorption and has little biological effects in a short time. Permeable pavement will continue to capture pollutants in internal water as rainfall intensity rises. Pollutants will accumulate on the permeable pavement; as rainfall intensity increases, some pollutants will be washed away; as the concentration of pollutants in the water permeable pavement increases, the removal rate decreases (Zheng, C., 2018). The permeable pavement will continually intercept pollutants as rainfall intensity increases. Some pollutants will be washed out as a result of the constant rainfall, and the rate of pollution removal will decrease. This is in accordance with (Liu, C. Y., et al., 2017), where for low and high rainfall intensities, the pollutant load removal performances of permeable pavements for TSS and TP all dropped as the intensity of the rainfall rose. The other reason could be that as the intensity of the rainfall increased, the permeable pavements became quickly saturated, giving pollutants less time to enter, adsorb, and retain, resulting in insufficiency of the pollutant removing process in the permeable pavements. Meanwhile, more particles were trapped on the surface of the permeable pavements during lower-intensity rainfalls, resulting in high removal efficiencies for TSS and sediment-associated components.

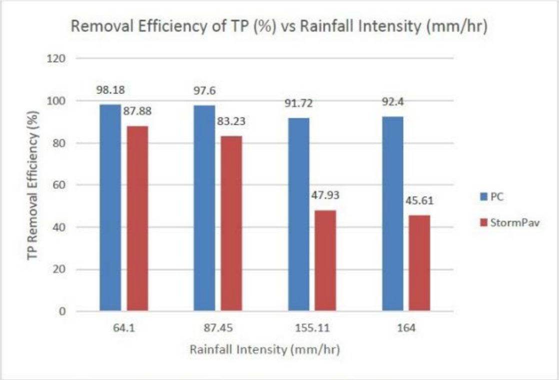
Table 6. TSS and TP Removal efficiency for PC and StormPav

Intensity (mm/hr)	Depth (mm)	Porous Concrete		StormPav	
		TSS (%)	TP (%)	TSS (%)	TP (%)
155.11	38.78	98.18	91.72	65.12	47.93
64.1	64.1	99.95	98.18	99.33	87.88
164.04	41.01	98.23	92.40	63.52	45.61
87.45	87.45	99.87	97.60	97.60	83.23

Figure 6 shows the comparison of pollutant removal efficiency between StormPav and PC. At low rainfall intensity, both PC and StormPav had a high TSS removal efficiency of 99% each while 98% and 87% respectively for TP removal efficiency. However, as the rainfall intensity increased, StormPav saw a huge decline in efficiency, reducing as low as 63% for TSS and 45% for TP, while the PC remained consistent, with only a slight drop in efficiency despite the increase in rainfall intensity. PC performed better at reducing pollutants compared to StormPav. This is because the porous concrete has a thicker pavement compared to StormPav. Table 4 shows that PC has a pavement thickness of 80mm while StormPav has a thickness of 75 mm. In the current investigation, raising the thickness of the gravel layer from 75 mm to 80 mm could considerably improve pollutant removal efficiency; hence, great TSS and TP load reductions were demonstrated from permeable pavements with thicker gravel layers. Stormwater runoff will go over a longer course as the thickness of the gravel layer grows, resulting in more absorption and removal of runoff contaminants. As a result, permeable pavements with thicker gravel layers have more capacity for adsorption, interception, filtration, and ion exchange for runoff pollutants (Liu, W., et al., 2020). In practice, however, a thicker gravel layer necessitates a larger building expense. As a result, increasing the thickness of the gravel layer is not always cost-effective. Ideally, the ideal thickness of the gravel layer should be chosen by taking into account its overall performance in terms of runoff retention, pollution removal, and other aspects such as traffic load and economics.



a) TSS removal efficiency (%) for all storm events



b) TP removal efficiency (%) for all storm events

Figure 6. Relationship between Removal Efficiency of TSS and TP for PC and StormPav with Rainfall Intensity

5. Conclusions

It is found that the PC can remove up to 99% of TSS and 98% of TP in low rainfall intensity, whereas the efficiency only decreased as low as 98% for TSS and 91% of TP at high rainfall intensity. Meanwhile, StormPav performed extremely well at reducing TSS and TP at low rainfall intensity with a removal efficiency of 99% and 87% respectively. At a high rainfall intensity of more than 100mm/hr, the StormPav shows a reduction of less than 65% of TSS and 45% of TP.

In conclusion, porous concrete (PC) performed better at removing TSS and TP compared to StormPav due to the layered design characteristics that can be clogged, compared to StormPav with its hollow cylindrical rain barrel. This is because the StomPav is designed as a submerged micro-detention pond storage with the purpose to store water at micro-scale to attenuate runoff and mitigate flash floods as well as reduce clogging effects. Hence, it can be deduced that StormPav can be promoted as a permeable pavement system for stormwater runoff reduction as well as water quality improvement.

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