SEMARAK ILMU
PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in Applied Sciences and Engineering Technology

Journal homepage:
https://semarakilmu.com.my/journals/index.php/applied_sciences_eng_tech/index
ISSN: 2462-1943

Performance of StormPav Green Pavement as Detention Pond Stormwater Management Infrastructure

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ARTICLE INFO

Article history:
Received 27 November 2026
Received in revised form 20 February 2026
Accepted 15 April 2026
Available online 4 May 2026

Keywords:
Detention pond; hydrology characteristics; permeable pavement; sustainable development; stormwater infrastructure

ABSTRACT

Implementation of green pavement practices can significantly improve the rainfall-runoff responses. StormPav, a system consisting of a micro-detention pond covered with precast honeycomb as surface and base structure layer is proposed to serve as an alternative green pavement application. The main focus of this study is to investigate the hydrological benefits of the proposed system. Detention storage capacity of the system was constructed under two different conditions, (i) various void capacities at road pavement thickness of 450 mm and (ii) 70% void capacity with different pavement thickness. The system can provide significant peak runoff reduction, resulting from the detention storage which is able to store the 10 to 100-year major storm events within duration of 20 to 30 minutes without overflow. In other words, such a condition allows the system to cope with the urban major storms which normally have a time of concentration of 10 to 15 minutes.

1. Introduction

Due to rapid development and urbanization, most of the city areas are paved with impervious surface. The traditional concrete pavement has a major drawback where it does not allow the infiltration of rainwater into the subsurface and hence settle down to the ground due to its impermeability [1,2]. Such a condition has disturbed the natural hydrologic cycle where infiltration rate to the ground is less, but runoff volume is higher [3]. The main focus of the conventional approaches for stormwater management is reducing the peak flows but not the runoff volumes, thereby it may lead to the occurrence of flood at downstream areas due to the excessive runoff. This is primarily a major issue in stormwater conveyance systems and it is normally addressed by enlarging the hydraulic capacity of the systems.

Porous pavement, consisting of porous paving materials, either porous concrete or asphalt [4], is used as one of the components in a stormwater management system. However, the porous surface of the pavement is prone to clogging due to the blocking of debris and fine particles in the pore spaces [5-7] This may induce a significant impact on the overall stormwater conveyance process. The only way to solve the issue is to remove the entire systems, however, a frequent replacement is impractical and expensive [8]. Therefore, permeable pavement becomes a preference while selecting the type of pavement. This is because it is effective in recharging groundwater, reducing runoff and reducing heat effect [9,10].

Permeable pavement which is made up of solid and stable characteristics modular interlocking blocks has the ability to sustain more traffic loading and provide an open joint structure for rainwater infiltration [11,12]. A traditional permeable pavement comprises of different layers which are surface pavers, bedding, subbase and base of aggregates materials with pores spaces of 0.5 to 50 mm and void volume of 15% to 40% [13]. The Interlocking Concrete Pavement Institute (ICPI) provided the guidelines for a list of block design [14].

A typical permeable pavement is normally designed with a maximum void content of 40%. Designing the void content with an appropriate value is essential because it may affect the selection the materials used for the layers, pavement thickness and etc. in order to meet the hydrological requirements and thereby provide a satisfactory performance [15].

Green pavement is a type of permeable pavement that has been widely used in stormwater management strategies since the 1990s [16] due to its environmental advantages such as reducing runoff, protecting the water supply and etc. It normally consists of a base and subbase to allow water to infiltrate during the occurrence of rainfall [17]. Its main idea is to absorb the rainwater rather than repel it. With the green pavement, the rainwater either infiltrates into the underlying soils or flows away through the subsurface drain [18]. The common applications of the green pavement are parking lots, pedestrian trails and low-speed roads such as residential and business access [19].

Nonetheless, the modular interlocking concrete blocks in the permeable pavement have shown the potential to be clogged by sediment at the bedding and base layer [20]. Hence, the current innovations of green pavement mainly emphasis on the uses of the different designed materials and their respective physical and hydrological benefits [12]. Pratt et al. [21] reported that about 55% of the simulated rainfall event was successfully retained by their designed green pavement. Meanwhile, the pavement designed by Alsubih et al. [22] showed an ability to retain a range of 40% to 92% rainwater within the structure.

This paper illustrates a modified permeable pavement system by Universiti Malaysia Sarawak researcher with discussion on the physical and hydrological benefits of the system. A precast honeycomb permeable pavement system namely StormPav was designed with a hollow cylinder which acts as micro-detention pond. A series of laboratory experiments were conducted to study the optimal hydrological performance of the system by mimicking the local rainfall intensity.

2. Materials and Methods

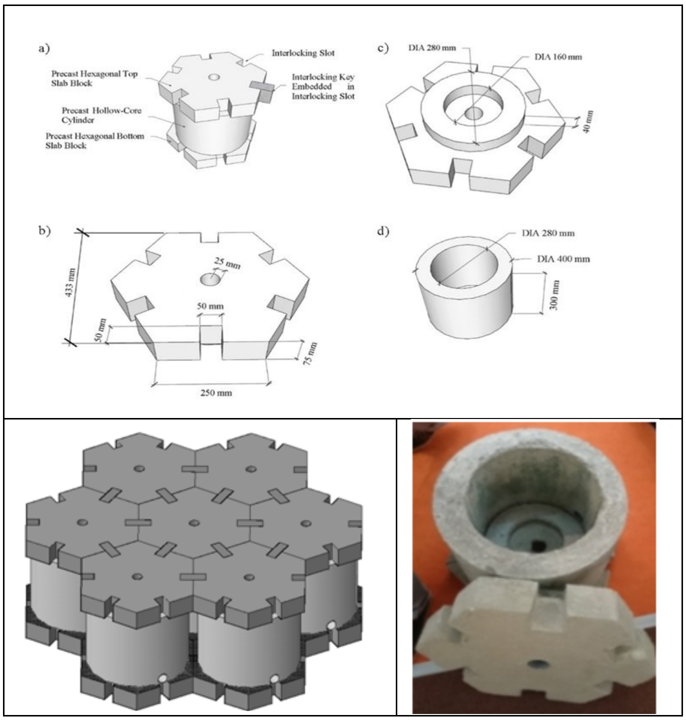
A.StormPav

Permeable pavement with micro-detention system, namely StormPav is basically a product of multipurpose road pavement for urban areas which is able to accommodate traffic loads and convey stormwater. The main idea is to utilise the spaces of the road subsurface layer for stormwater detention storage. A single unit of StormPav is basically a product of three pieces of precast concrete blocks. It consists of a top cover, a bottom plate and a hollow cylinder in between. The top cover acts as road pavement, the bottom plate serves as base plate and raft foundation and the hollow cylinder plays a role as micro-detention storage. As for the horizontal flow, the micro detention pond hollow cylinder tank has two openings of 0.04 m diameter hole opposite to each other, which are placed close to the bottom of the cylinder. The design of a single unit, arrangement and prototype set of the permeable pavement with micro-detention storage StormPav system were presented in Figure 1.

In this study, fibrous self-compacting concrete (SCC) of grade 50 concrete was the material used for the StormPav unit production. The micro-detention pond made up of the precast honeycomb lightweight-structure could percolate the rainwater, thereby allowing the groundwater recharge and runoff reduction. In addition, such a design could facilitate the surface pollutants removal and reduce the heat effect which in turn may help to mitigate the environmental issues.

The light colour of StormPav concrete pavement absorbed less heat from solar radiation. Moreover, due to its large open space (0.19 m^3/m^2 pavement area), the stored heat was minimised. These features may help to mitigate the heat island effects in urban areas.

Fig 1: StormPav structure: (a) measurements of a single unit, (b) arrangement of the system and (c) A single unit of the precast product



StormPav as green pavement key features is a product of precast honeycomb structure that enhance self-interlocking, rain water holding micro-detention pond and self-drying through side and bottom seepage of water. It have features of modularity, adaptability, portability and self-interlocking. It is actually a hollow cylinder covered with the top and bottom plates, reinforced with two layers of steel and optionally covered with a geotextile layer. The system is constructed on the flat subgrade soil and dry-stacked to form an interlocking paver that has the ability to provide structural support and durability which in turn yielding benefits in terms of permeability in stormwater management. The permeability of the system is accomplished through the under drainage system of the hollow cylinder/vessel residing beneath the subsurface of the pavement. The StormPav is designed to have a hexagonal shape in order to achieve better performance from the perspective of hydrological design and structural durability. Acting as the open passage for stormwater inflow and infiltration respectively, both the top and bottom layers comprises a central hole with 40mm diameter and six grooves as interlocking keys.

Series of research studies had been performed in StormPav since the development in 2013, which had been collected and reviewed in Bateni. et al., [23]. The actual products are fabricated in 2015, which are then tested and investigated for various structural, roadworks, hydraulics and hydrological assessments. With more manufactured and fabricated moulds to produce StormPav in 2016, the StormPav started it mass production to achieve more research accomplishment of the product. This comprises of small-scale field, modelling and laboratory studies on the hydrological performance, hydraulics and flow regime, and structural requirements to include determination on optimal structure materials and thickness, selection of parameters for model verification, stormwater quantity and quality, stormwater infiltration capacities and rate and pollutant removal efficiency.

The system was considered cost-effective as it used the precast honeycomb stricture to enhance self-interlocking and dry-stacked, to store rainwater through the micro-detention pond structure and to allow self-drying through the side and bottom seepage of water. In addition, the system reduced the installation time and saved the manpower due to its advantages in modularity, adaptability, portability and self-interlocking. In sum, StormPav is a user-and environmental-friendly product and seen its suitability to be applied at low-speed road especially parking lot, business centre and housing area. From the perspective of hydrological properties, the hollow cylindrical unreinforced concrete block in StormPav with service opening occupied an empty space of 0.19 m^3/m^2 and about 70% void of the pavement area. It drained the surface water at a rate of 84000 mm/hr. In sum, the water can be stored up to a depth of 0.213 m in the system.

B. Laboratory study

The rainfall intensities for this study were selected based on the recent 20-years statistical data from Department of Irrigation and Drainage Malaysia. Intensity Duration Frequency (IDF) curve for Kota Samarahan, Malaysia was used to extract the relevant weather conditions. The experiments were conducted with the aid of rainfall simulator [23]. The rainfall simulator was designed to mimic the hydrology cycle of the real-life water balance model. The flow pathways of the StormPav system was shown in Figure 2. In this case, the water balance model components were made up of the rainfall amount, surface runoff and drainage channel outflow. The total inflow and storage capacity represented the vertical components of the water balance model while the total outflow from the surface runoff, reservoir and drainage channel were the lateral components. To investigate the performance of micro-detention pond for runoff reduction and volume optimization, the water balance equation was used:

$$\mathrm{O(t) = I(t) + ds(t)} \qquad (1)$$

where I(t) is inflow, O(t) is outflow and ds(t) is the change of storage capacity.

The rainfall simulator was used to collect a series of data to determine the optimum height and volume of the hollow cylinder which acted as a micro-detention pond. Park et al. [24] reported that there are no any significant differences between the actual values and the experimental values obtained through rainfall simulator. In addition, rainfall simulator has shown a good performance while applying for generating artificial rain with controlled drop sizes, intensity and duration [25].

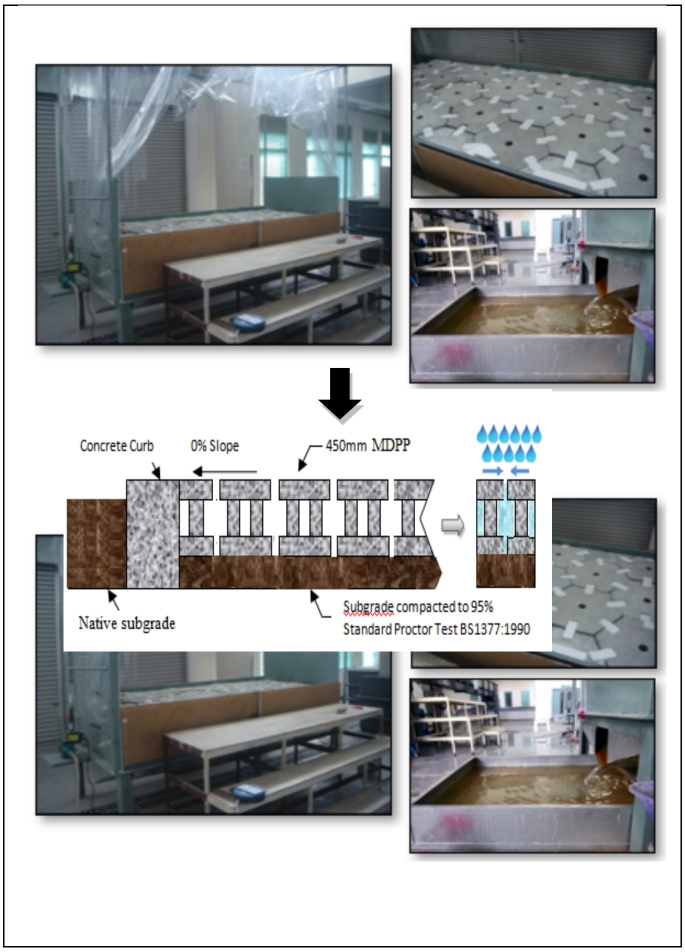


Fig 2: Experimentation with Rainfall Simulator, interlocking arrangement with white block key, stormwater discharge to the outflow tank and cross-section and flow path of the PPDS.

3. Results and Discussion

The laboratory results explain the relationships between the volume capacity design of StormPav with the hydrology benefits inset with the water balance model.

A. System design based on water balance model

The relationship between the inflow and outflow of the PPDS for the rainfall intensities range from 30 mm/hr to 220 mm/hr is shown in Figure 3. In this case, the StormPav void content is designed at 70% with a an underground detention drain with an empty space about 0.19 m^3/m^2. From the perspective of depth, volume and discharge, it shows a strong linear correlation between the input value and output value.

The plots as shown in Figure 3 can be explained in terms of the water balance model through the relationship between the inflow (I) and outflow (O) and thereby determine the changes in terms of the storage capacity. Through the mathematical calculation via the equations as, the change of the storage is considerably small, recorded at around 7%. On the other hand, the effectiveness of the systems can be significantly observed as the discharge rate and the infiltration rate is almost similar, showing an almost 100% drainage and conveyance effectiveness. The findings are in agreement with Alizadehtazi et al. [26] and Brown et al. [27]. A porous concrete structure in permeable pavement may help to minimise the excessive runoff. This is because the system has the ability to capture the rainfall and thereby allow it to flow into the ground. In this case, StormPav with similar structure has shown a similar property but better efficiency if compared to the previous studies [27,28].

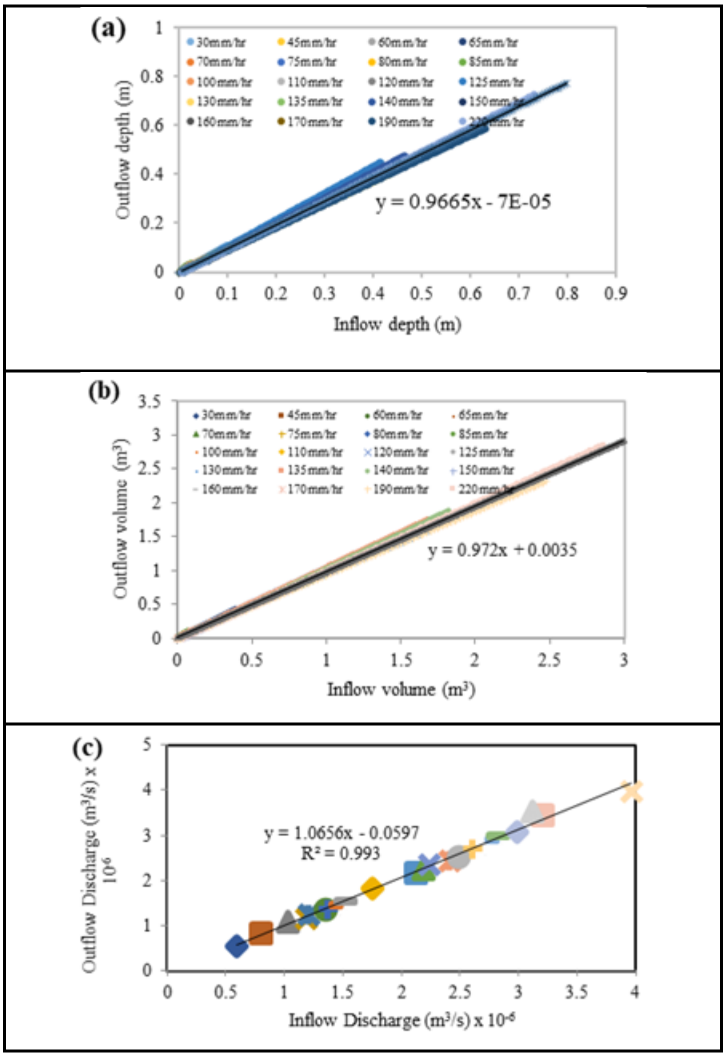


Fig 3: Relationship between Inflow and Outflow (a) water depth, (b) volume and (c) discharge

B. Storage capacity performance of Stormpav

Figure 4 illustrates the changes in storage capacity with respect to the depth of water and time in micro detention storage. A linear relationship is noticeable in water depth-storage plot as shown in Figure 4(a). The linear trend line graph can be applied to investigate the change of water depth in the StormPav corresponding to the changes in water volume. In addition, it has to highlight that the PPDS prototype was designed at a cylinder thickness of 300 mm with a void ratio of 70%. Based on the selected parameters, the allowable water depth of the system is 0.21 m (as shown in Table 2). Applying the designed water depth in the plot, depression storage of the system is determined, showing that the micro-detention storage has the ability to provide a maximum storage capacity of around 0.19 m^3/m^2 (equivalent to 190L/m^2). In previous studies, Park et al. [24] reported that a maximum water volume of 40L/m^2 could be retained in permeable pavement with void ratio of 30%; Boomsma and Huurman [28] found that water storage could reach as high as 140 L/m^2 for permeable pavement designed with porosity ratio of 35% and thickness of 400 mm; Zhang [29] showed that a block pavement structure with 30% of void capacity displayed an ability to create a maximum storage capacity of 48.2 L/m^2. In sum, a significant improvement is achieved by the StormPav system in this case as it can provide a higher depression storage capacity. This is because, although its thickness is similar to the typical permeable pavement, the system was designed with a higher void ratio.

Meanwhile, investigations from Figure 4(b) show that the designed StormPav system has great potential to provide benefits in terms of depression storage for a wide range of rainfall intensity. Since the time of concentration, t_c for most of the storm event is within 15 to 30 min, particularly observing such a value in the plot, the storage required is 0.15 m^3/m^2 which is less than the designed storage capacity (0.19 m^3/m^2). Based on the evaluations on storage capacity, the proposed StormPav system is clearly a better choice than the typical permeable pavement.

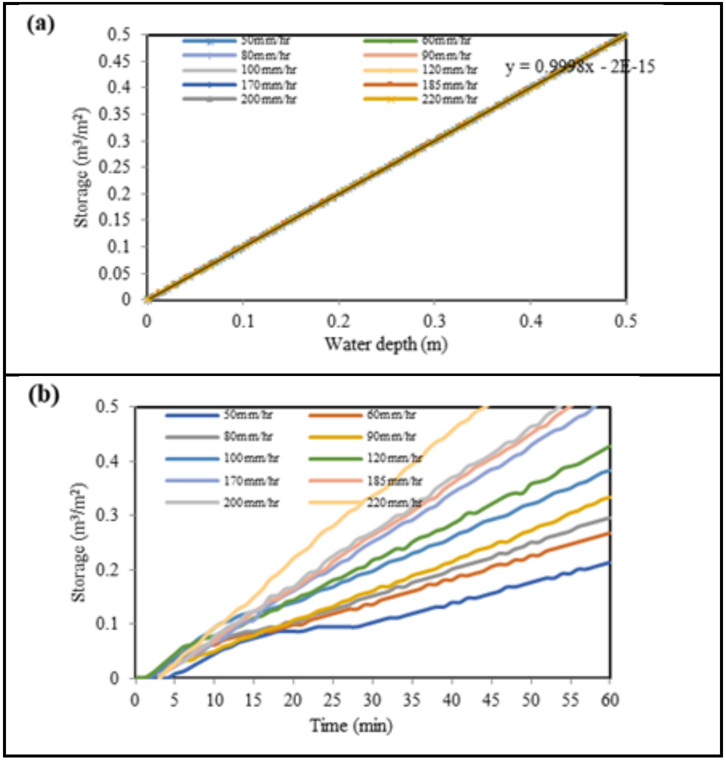


Fig 4: Detention Storage of StormPav over water depth and duration for various rainfall intensities, a. Water depth-Storage curve relationship for rainfall intensities from 50mm/hr to 215mm/hr and b. Time-Storage curve for various rainfall intensities

C. Relationship between depression storage capacity and area

Figure 5 exhibits the relationship between the water depth with the depression storage and time, respectively, for various areas at a storm event of 50-years 3-hours rainfall with an intensity of 100mm/hr. In this study, the thickness of StormPav is designed at 450 mm, containing a void ratio of 70% with an empty space of 0.19 m^3/m^2. The increasing of area results in the increasing of storage capacity but with a constant water depth of 0.21 m. For example, an area of 1 m^2 has the ability to provide a volume capacity of 0.19 m^3. Since the PPDS is principally designed for low-speed roads, such as car park and housing area, the provided storage capacity can reach a level higher than 1.9 m^3 because the total coverage of a car park as well as the residential area is always more than 10 m^2. Tennis et al. (2004) reported that, a parking lot which is constructed using pervious concrete, at a size of 9 acres (around 30000 m^2) in the urban area, can act hydrologically as a football grass field.

In addition, as depicted in Figure 5, under the investigated areas, the performance of StormPav system is considerably good, where in most of the cases, the recorded water depth is lower than the maximum value of 0.21 m, especially for the larger area condition. In other words, StormPav has seen its applicability in the area which is larger than 4 m^2.

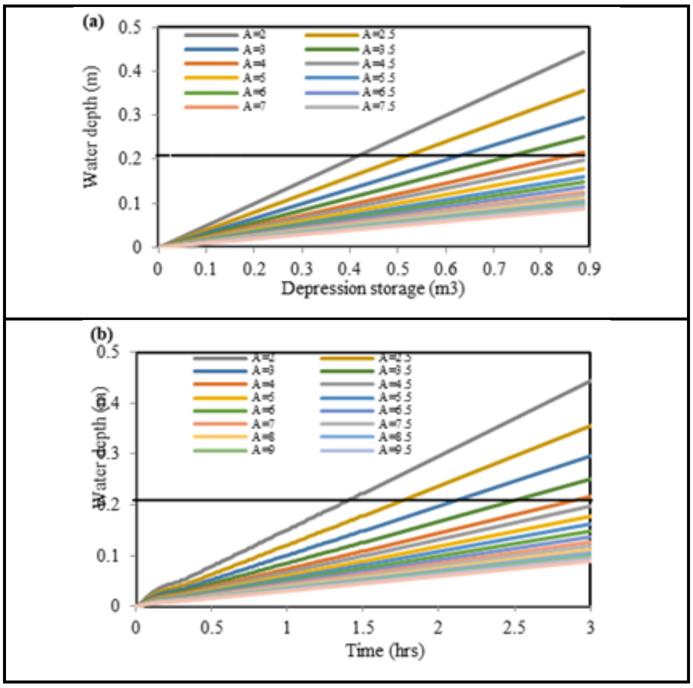


Fig 5: Relationship between depression storage and area, water depth with depression storage capacity and time for the various area at storm event of 50 years 3hrs rainfall duration of 100mm/hr

D. Design optimization of storage capacity

An ideal StormPav green pavement system should take all the hydrological perspectives into consideration during the design process. The storage capacity is one of the main aspects. Total storage capacity of a pervious concrete system consists not only the capacity of the pervious concrete pavement itself, but also the capacity of the subbase used. Theoretically, the storage capacity of the pervious concrete is effective due to its porous structure [30]. However, it is a challenging task to determine the design of the pervious concrete which can achieve an optimised performance. Therefore, a chart consisting of the relationship between depression storage, water depth, void capacity and structure thickness is proposed.

The optimised design of the StormPav system in terms of void capacity and structure thickness is contained in Figure 6. It can be used as a reference while designing the StormPav that serves for different purposes under different climate conditions to ensure the strength and durability of the designed system is well-suited for it to perform its role efficiently.

In Figure 6(a), the relationship between a wide range of the void capacity to their corresponding detention storage and water depth are presented. The three components are correlated where an increase in void capacity will result in the increase of depression storage and water depth of the system. In this study, the designed StormPav system has a thickness of 300 mm with a void ratio of 70%, and thereby it can achieve water storage of 0.19 m^3/m^2 (190 L/m^2). However, if the void ratio increase to 80%, the system will be able to detent about 220 L/m^2 of rainwater under the same structure thickness.

On the other hand, Figure 6 (b) presents the relationship among the StormPav structure thickness, detention storage and water depth. Fixing the designed void capacity at 70%, through altering the thickness of the cylindrical component in the StormPav, it is clearly observed that the changes of structure thickness may influence the depression storage. For example, with the thickness of 1000 mm, the system can provide a storing capacity of $0.65m^3/m^2$ with a water depth of about 0.7 m.

In sum, the relevant hydrology information, such as total rainfall events and total rainfall runoff that will be received from the impervious catchment, are essential to determine the inflow amount of stormwater while designing a StormPav so that it can function in an optimised manner.

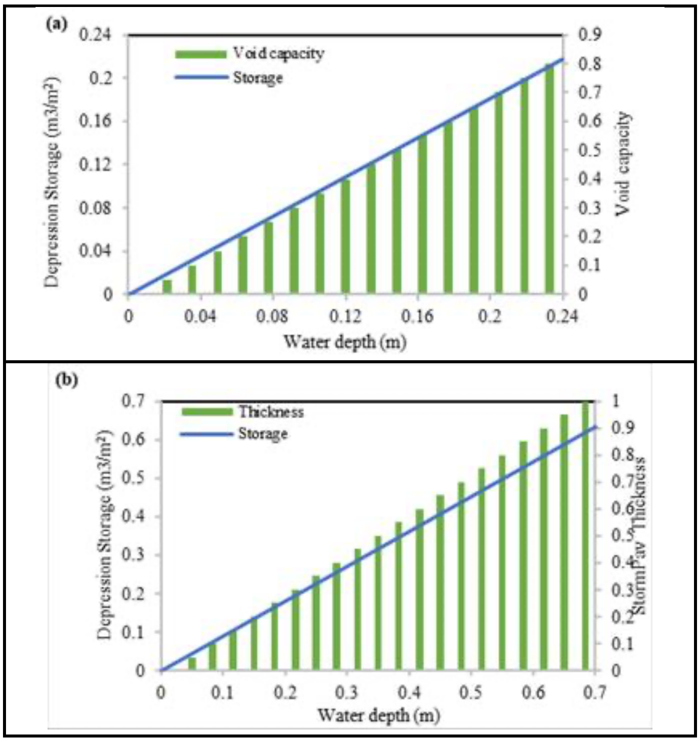


Fig 6: Size and Volume optimization with (a) various void capacities with existing design thickness, 450mm and (b) differences in PPDS structure thickness at 70% void capacity.

4. Conclusions

Green pavement practices become the main intention in urban areas as it plays a significant role in stormwater management to mitigate or prevent flooding issue caused by the rainwater.

This study attempts to propose a modified permeable pavement as an alternative to improve the conventional permeable pavement which is widely used nowadays. To serve the purpose, a StormPav system is designed and its performance is evaluated through the laboratory works. The hollow cylinder structure within the system can provide an advantage in terms of storing capacity as it has a bigger space to detent the water. The StormPav provides detention storage of 190 L/m^2 with a void ratio of 70%. The system can manage continuous rainfall for the worst-case scenario, particularly for flood control of rainfall event with a return period of 10 years for less than or equal to 20 minutes duration. In addition, the inflow and outflow relationships of the system are presented and a minimal storage change of about than 7% is noticed. This is because the system can release the storage immediately to the underground, and thereby neither depression storage filling up nor runoff generation can be seen.

Furthermore, the designed StormPav can provide detention storage of continuous 3-hours storm events with an intensity of 170 mm/hr and 6-hours storm events with an intensity of 80 mm/hr (equivalent to 1 in 100 years return period) for a coverage area which is larger or equal to 7 m^2. Additionally, it is proven that, with an increase of area, the detention storage of the StormPav system shows an increasing trend.

Overall, the experimental investigations show good and promising results in terms of hydrological perspectives with the modified StormPav system. It is recommended that to investigate the full performance of the system through the field pilot study. In addition, to function optimally, the void capacity and structure thickness of the StormPav system should be designed appropriately. A design reference is proposed in this study to ease the user while dealing with various types of storm events.

Acknowledgement

The authors wish to thank the hydraulic laboratory of Faculty of Engineering Universiti Malaysia Sarawak for the facilities provided for the experiments. The authors acknowledged the financial support from the VC Impact Grant, UNIMAS UNI/F02/VC-HIRG-2/86056/2023.

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