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THE INFLUENCE OF SOIL CHARACTERISTICS ON HYDRAULIC PERFORMANCE IN BIORETENTION SYSTEM

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ABSTRACT

This study examined the influence of soil properties on the hydraulic performance of bioretention system on a different configuration of soil mix design. Proportions of 50–90% sand and 10–50% topsoil of soil configurations were selected for this study. Standard constant head permeability test was conducted in the laboratory. It was found that Ksat increases as the proportion of the topsoil reduce in the soil configuration. It was found that the plotted data are fitted well to the best–fit line by using Breyer empirical formula which indicates a strong relationship between Ksat, effective grain size (D10), n and Coefficient of Uniformity (CU). It was observed that 50–60% sand and 40–50% topsoil of soil configuration for the bioretention design having the Ksat between 14–150 mm/hr met the parameter required by local guidelines.

Keywords: bioretention, soil mixtures, hydraulic conductivity, empirical formula

INTRODUCTION

Rapid urbanisation will often result in an increase of the quantity of stormwater in a catchment [1-3]. This leads to a disconnection between the surface and the subsurface water or reduced infiltration hence creating significant stormwater and runoff peaks leading to floods [4-8]. The Best Management Practices (BMPs) is a treatment technique accepted globally to tackle the challenge of runoff increment and water contamination [9-11]. Bioretention system is one of the initiatives of low–impact development (LID) and function as one of the BMPs for stormwater management to accommodate solutions for the impact of urban development [8, 12-14]. The main concern in bioretention is engineered soil media, which significantly influence hydraulic characteristics [8]. Studies on a distinct composition of soil media used in the bioretention design found that the combination of topsoil and sand provide an adequate K_{sat} (290 – 302 mm/hr) to release the treated water to the receiving watercourse [15]. The range of recommended K_{sat} for different regions is presented in Table 1.

The bioretention systems are in different design with mostly several layers of soil media, shallow depressed sites for stormwater infiltration and storage [16]. In the bioretention system, soil serves as the natural filter to reduce the quantity of runoff through processes like evapotranspiration and water retention. It also uses physical and chemical retardation methods to promote pollutant retention. The design of the system usually has a layer of topsoil of 10 – 20 cm having adequate organic matter for vegetation root space and microorganism which use the biological, chemical and mechanical means to promote pollution removal in the system [17]. To reduce the migration of fine soil particles and promote draining of the infiltrated stormwater, a porous layer is provided at the bottom with average grain sizes [16].

compost and 10% of organic matter by weight [20]. Stormwater Biofiltration System Guidelines suggested that the clay content and organic matter must be less than 6% and 5% respectively, a maximum of 10% vermiculite or perlite to be incorporated and no natural topsoil in the system design [21]. Department of Irrigation and Drainage (DID) outlined that the engineered soil media composition contents by volume should contain: topsoil that may be classified as sandy loam or silty loam (20 – 25%); medium sand (50 – 60%) and organic compost leaf (12 – 20%) [22].

Table 1 The Required K_{sat} based on several Guidelines [15]

Stormwater Guidelines	Country	Range of K_{sat} (mm/hr)
California Stormwater Quality Association (CASQA) [4],Prince George's County (PGC) [18, 19]	United States	12.5–12.7
Washington State University and Puget Sound Partnership [20]	United States	25.4–305
Facility for Advancing Water Biofiltration (FAWB) [21]	Australia	100 –300 (Temperate Climate) 100–500 (Tropical Climate)
Stormwater Management Manual for Malaysia (MSMA) [22]	Malaysia	13–200

LITERATURE REVIEW

Soil Composition in Bioretention system

The soil configuration is significant to the performance of retaining the capacity and hydraulic conductivity performance of the bioretention system. The sand was the main media added into a bioretention system to enhance K_{sat} [23]. The sand filter is good for the enhancement of water quality. Mathematical models were developed to design the hydraulic characteristics of sand filter, i.e. depth and velocity since the physical model was not sufficient to determine the design parameter [24].

The common range of soil mixtures are 30 – 60% of sand, 20 – 40% of compost and 20 – 30% of topsoil. North Carolina soil configuration for the bioretention soil media suggest a range of 3 to 5% organic matter where peat moss performed well in their system; 8 to 12% of fines consist of both clay and silt; and 85 to 88% of washed sand where medium sand is sufficient for the soil mix design [25]. The Washington State recommended the soil mix of 60% of loamy sand; 40%

Interaction between K_{sat} and Grain Sizes

Physical characteristics of soil, mainly grain size, is the most important feature that enhances the infiltration process. Particle size in the range of 0.075 – 2 mm was recommended as an inappropriate selection of grain size particle might lead the BMPs system under or over design, which contributes to the ineffective cost [26]. The accumulation of fine sediments may limit the rain garden's design life [27]. Besides, particle size distribution (PSD) was less uniform, and the particle size range was more extensive, as reflected by the more significant Coefficient of Uniformity (CU) [28]. Carpenter and Hallam [29] analysed the PSD and permeability and identified the relationship between

D_{10} and the permeability of finer particle soils having lower rates of permeability. The empirical equations that can be used to estimate the hydraulic conductivity of the soil and sufficient size, d_{10} was established as listed in Table 2.

Malaysia. The selected soil mixtures were used in the bioretention system as an engineered soil media. Sand and topsoil were used as the main component in engineered soil media. Both materials were mixed based on the selected proportions varied within the

Table 2 The Established Relationship (Empirical Formulae) Between K_{sat} And D10 [30]

Developer	Equations*	Remark
Hazen (1892)	$K_{sat} = \frac{g}{u} \times 6 \times 10^{-4} [1+10(n-0.26)]d_{10}^2$	Applicable for fine sand to gravel
Kozeny–Carman (1937, 1956)	$K_{sat} = \frac{g}{u} \times 8.3 \times 10^{-3} \left(\frac{\boldsymbol{n}^3}{(1 - \boldsymbol{n})^2} \right) d_{10}^2$	It is widely used. Not suitable for clayey soils
Breyer	$K_{sat} = \frac{g}{u} \times 6 \times 10^{-4} \log \frac{500}{C_u} d_{10}^2$	Neglect porosity values
Slitcher	$K_{sat} = \frac{g}{u} \times 1 \times 10^{-2} n^{3.287} d_{10}^2$	Applicable for grain size between 0.01 – 5mm

**n* is porosity; *g* is gravitational acceleration (m/s^2); ʋ is dynamic viscosity (m^2/s); C_U is uniformity coefficient (D_{60}/D_{10})

Therefore, this study aims to evaluate the soil characteristics mainly particle size, bulk density, porosity and hydraulic conductivity of selected soil media used in the bioretention system and examine their influences on the hydrologic performance of bioretention system with a different configuration of soil mix design.

MATERIALS AND METHODS

This study was conducted in the Geotechnical Laboratory of Universiti Teknologi PETRONAS, range of 50 – 90% of sand and 10 – 50% of topsoil. A total number of 5 mixtures (M_1, M_2, M_3, M_4, and M_5) were used in this study. Table 3 shows the percentage of sand and topsoil for the different soil mixtures. Basic soil properties such as particle–size distribution (PSD), specific gravity (SG), moisture content, dry density and saturated hydraulic conductivity (K_{sat}) were tested for each mixture. Then, the mixtures were characterised based on basic soil properties. Table 4 presents the standard laboratory tests for basic soil properties.

Table 3 The percentage of sand and topsoil for soil mixtures

Soil Mixtures	Sand (%)	Topsoil (%)
M_1	50	50
M_2	60	40
M_3	70	30
M_4	80	20
M_5	90	10

Table 4 Brief descriptions on standard laboratory test

Parameters	Standard Laboratory Tests	Reference
SG	15g dry soil samples were weighed and transferred into pycnometer bottles.	BS 1377–4: 1990 (BSI, 1990)
PSD	Sieve analysis test was carried for sand and the mixtures to obtain the grain size. Hydrometer test was conducted for finer particles, e.g. topsoil.	BS 1377–4: 1990 (BSI, 1990)
Moisture content and dry density	Standard Proctor test was conducted using 2.5 kg hammer by applying 27 blows for each soil sample	BS 1377–4: 1990 (BSI, 1990)
Parameters	Standard Laboratory Tests	Reference
K_{sat}	Standard constant head method (permeability test) was carried out for each soil sample except for topsoil by using falling head method due to very fine particles.	BS 1377–5: 1990 (BSI, 1990)

Permeability Test on Variation Soil Composition

Permeameter cell with a diameter of 90.3 mm was filled with the mean height of soil sample of 170 mm. The sample was compacted gently using the rod with 27 blows for three (3) layers to minimise the voids in the samples. The K_{sat} of the constant head test was calculated based on the derivation of Darcy's Law, as given in Equation (1) [15, 31]. Falling head test was used to determine K_{sat} for topsoil. It was computed using Equation (2).

$$K_{sat} = \frac{QL}{Ac\,(L + P\,)}$$

Where; K_{sat} = Saturated hydraulic conductivity (mm/hr); Q = Outflow rate (m^3/s); L = Length of soil sample (m); A_c = Cross sectional area of the cell (m^2); P = Ponding depth at the top of engineered soil layer (m).

$$K_{sat} = \frac{a}{A}\,\frac{L}{\Delta t}\,1\text{n}\left(\frac{h_1}{h_2}\right)$$

Where; K_{sat} = Saturated hydraulic conductivity (mm/hr); a = area of standpipe (mm^2); A = Area of soil sample (mm^2); L = Soil Sample Length (mm); Δt = Duration of test (s); h_1 = Initial head of water (mm); h_2 = Final head of water (mm).

The measured data from each soil mixtures samples are compared with several established empirical formulae, as listed in Table 4 [30]. The K_{sat} can be estimated by using these equations by relating some physical properties of soil and water mainly gravitational acceleration (g) = 9.81 m/s^2, the dynamic viscosity of water, υ = 0.893 x 10^{-6} m^2/s (This is assumed at the temperature of 25°), D_{10} and *n*.

RESULTS AND DISCUSSION

The soil properties are presented in Table 5. Based on the results obtained, both soil samples (sand and topsoil) had consistent values of specific gravity (SG) with typical values of sand ranges 2.65 – 2.67 which is less than 2.6 for topsoil respectively. The porosity of soil was determined by calculating the ratio between the pore volume and the total volume of the soil.

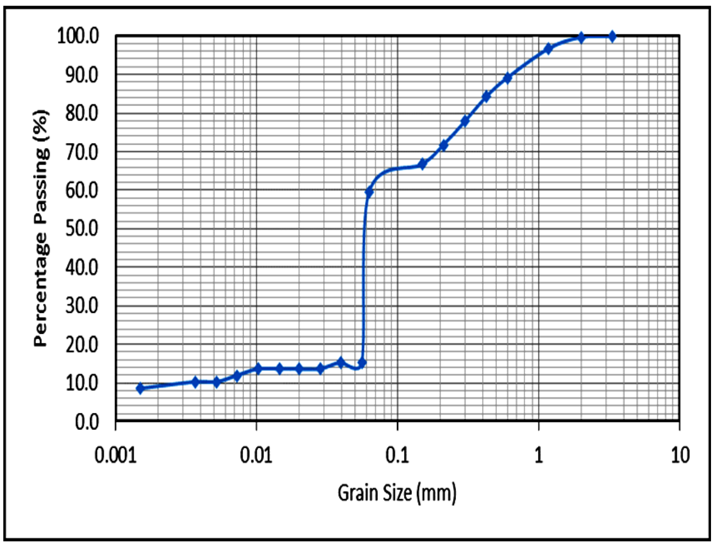
Morris and Johnson [32] recorded in their study that unconsolidated sedimentary materials that have smaller particle sizes tend to have a larger porosity compared to larger particle size soil. Also, Heath [33] addressed that porosity plays a crucial role in retaining the water by the capillary soil forces during gravity drainage, and this is known as specific retention. Specific retention increases with increasing porosity of the soil. In this study, therefore, the retaining capability is portrayed by the moisture content result in Table 5, where the decreasing porosity reduces the moisture content in different soil configurations.

The result of dry sieving and hydrometer test of 100 g of topsoil sample consist of a percentage of particles passing, and grain size is plotted as in Figure 1(a) while the PSD graph for different soil configurations is plotted in Figure 1(b). The topsoil with 40.32% of sand, 51.23% of silt and 8.45% of clay is classified into

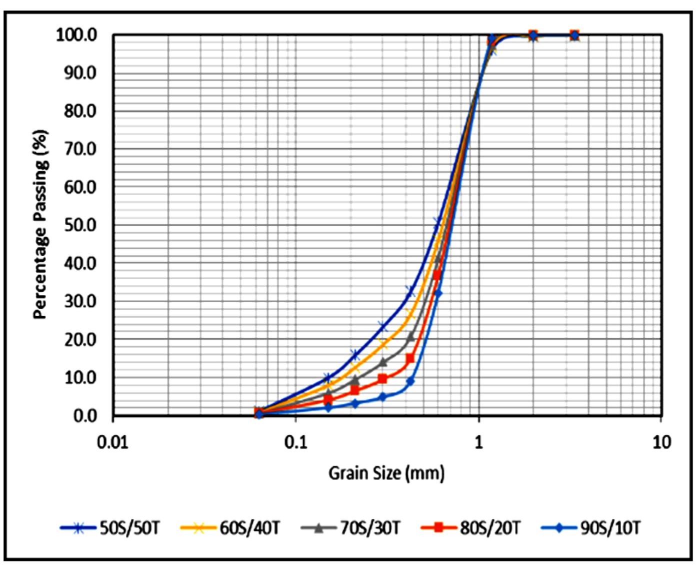
Table 5 Soil properties for each soil mixtures

Soil mixtures	Parameters										
	S_G	Moisture content (%)	Dry density, ρ_d (g/cm^3)	Porosity, *n* (%)	K_{sat} (mm/hr)	C_U	C_C	D_{10} (mm)	D_{50} (mm)	C_U	C_C
Sand	2.63	–	1.35	49.0	18612	1.47	1.14	0.470	0.750	1.47	1.14
Topsoil	2.53	4.30	1.362	60.7	3.32	17.14	17.42	0.004	0.058	17.14	17.42
M_1		26.44	1.010	26.62	107.2	4.53	1.57	0.150	0.400	4.53	1.57
M_2		24.83	1.030	25.57	244.8	4.24	1.06	0.170	0.450	4.24	1.06
M_3		22.53	1.030	23.14	569.67	3.29	1.62	0.225	0.490	3.29	1.62
M_4		19.53	1.050	20.53	765.36	2.38	1.24	0.320	0.525	2.38	1.24
M_5		15.47	1.050	16.29	1751.64	1.77	0.98	0.440	0.550	1.77	0.98

silty loam soil. The soil configurations have all the particle sizes ranging between 0.075 – 4.75 mm, as recommended by [6]. The most efficient soil media is the one that consists of particle sizes which are not dominated by fine particle size ranges and no gap in gradation. This is significant to prevent particle migration that leads to the structural collapse of engineered soil media in the bioretention system. The summary of mean particle diameter and effective finer diameter of the soil configurations are as in Table 4. The gradation of the particle size distribution is evaluated from the coefficient of curvature and uniformity to assess whether the gradation is well–graded or poorly graded (Table 5). The consistency of particle size ranges is portrayed by the coefficient of uniformity where value less than 3 have small sizes, and larger amounts imply a broader range of particle sizes. However, it was shown that all the soil configurations are poorly–graded and the uniformity of particle sizes narrows down with the increasing proportion of sand in the configuration. The soil mixtures with ranges of 50–60% of sand offer adequate K_{sat}, which are in agreement with the local requirement [22].



(a)



(b)

Figure 1 PSD for (a) topsoil sample (b) soil mixtures

The interrelationships among soil properties were investigated, as demonstrated in Figure 1. Only soil mixture samples were analysed since there was a large gap of K_{sat} values between soil mixtures and sand sample. The soil mixtures were compared with the results of Fassman–Beck et al. [34] using the established empirical formula (Table 2). Based on the results, good interaction between K_{sat} and the soil properties mainly D_{10}, n and C_U were determined. The good prediction was performed by using Breyer equation as the data plotted near to the fit–line was compared to Hazen and Kozeny–Carman formula, as shown in Figure 2. In summary, the soil characteristics significantly changed by having a different portion of soil composition, which also affected the K_{sat} values.

CONCLUSION

Engineered soil media is the main component in the retention system, which plays significant roles in the hydraulic performance of this BMP system. The soil media composed of sand and topsoil were mixed in five different proportions varied within the range of 50 – 90% of sand and 10 – 50% of topsoil. The ranges of K_{sat} and other basic soil properties such as PSD, SG, moisture content and dry density were determined for each composition. These soil properties were tested to obtain the interaction between both soil and hydraulic parameters. It was found that the increment of sand and reduction of topsoil had significantly affected the K_{sat}. This study revealed that the physical

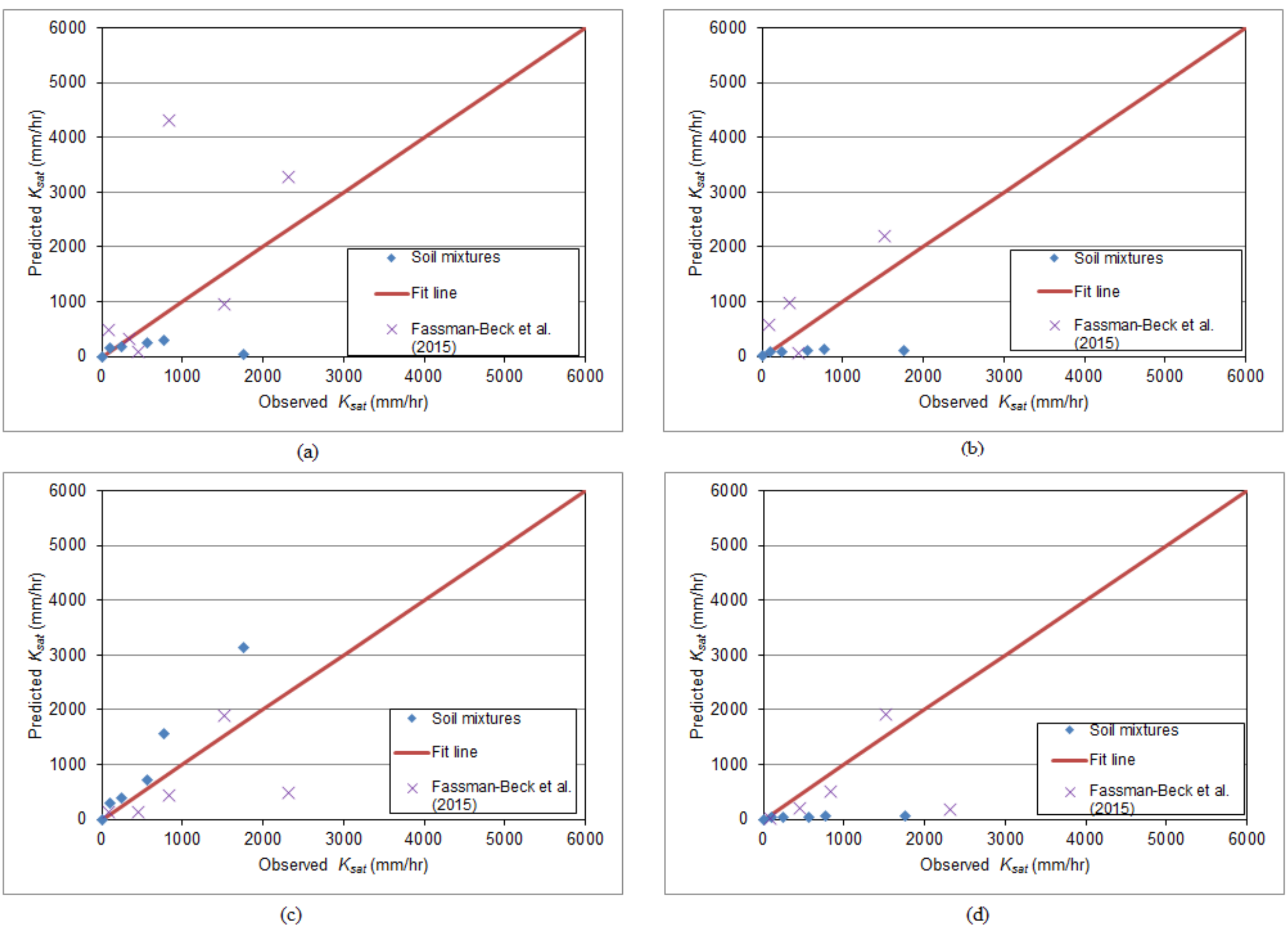


Figure 2 Relationship between measured K_{sat} and computed K_{sat} based on well–known empirical equations. (a) Hazen's approximation (b) Kozeny–Carman formula (c) Breyer formula (d) Slitcher formula

soil properties had more considerable influences on the K_{sat}. This can be used to predict the performance of bioretention media in the early stage due to the difficulties in direct K_{sat} measurement, which difficult and time consuming as reporting in several previous studies.

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