Preliminary Study on the Impacts of Variation Engineered Soil Composition in Bioretention on Hydraulic Performance

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ABSTRACT
Engineered filter media are the main component in a bioretention system, which also influenced bioretention performance. Typically, the ranges of soil mixtures were 30-60% of sand, 20–40% of organic compost and 20–30% of topsoil. Hence, this paper aims to examine the hydraulic performance, mainly saturated hydraulic conductivity (K_{sat}) in variation engineered soil composition. The soil characteristics for sand and topsoil were examined. Then, standard permeability tests were conducted for each soil sample. K_{sat} was determined for each sample. These results were used as the benchmark for permeability test using column. A 74 mm diameter designated column was filled with engineered soil media with different soil composition variations. K_{sat} data were collected for 2 months to observe the profile of K_{sat}. The results indicated that there was a reduction in hydraulic K_{sat} with the variation in composition of engineered soil. The composition of 50% medium to fine sand, 30% topsoil and 20% organic leaf compost provides better K_{sat} range. The long-term K_{sat} was obtained from cylindrical cell test where significant declination in K_{sat} was found within 2 months. These data were useful to predict the design life of filter media by monitoring the permeability rates.

KEYWORDS
Hydraulic conductivity (K_{sat}), engineered soil composition, standard permeability test, laboratory cell test, bioretention

INTRODUCTION
Bioretention has rapidly become one of the most versatile and widely used storm-water best management practices (BMPs) throughout the United States and many parts of the world. It has recently become identified as a preferred site practice for green building design and leadership in energy and environmental design (LEED) certification. Despite the rapid acceptance of this BMP throughout the United States, detailed performance information and related design guidance are not currently available for many regions. Several state and local governments have adopted bioretention guidelines published by another state agency, often

without modifying the guidelines for local conditions, using out-of-date information, or without a good understanding of the range or limitations of these BMPs (Davis *et al.*, 2009).

Filter media zone is the main component in bioretention. It consists of mulch layer, planting soil or engineered soil media, and cleaning sand as transition layer (DID, 2012). Mulch layer or organic layer is filled at the top of fill media to allow some of biological processes to occur in the system. Typically, a specified range of sand (30–60%), compost (20–40%), and topsoil (20–30%) with several specifying additional soil composition details of the compost and topsoil including pH, specifications of clay content, or grain size distribution. The clay plays the role in the bioretention process because clay will greatly reduce the infiltration rate and also assist in filtering and adsorbing pollutants. The recommended clay content varies from content less than 5%, 10% and 25% (Carpenter and Hallam, 2010). Structurally, bioretention facilities consist of approximately 0.7–1.0 m of a porous media, composed of a sand/soil/organic matter mixture. This media layer was covered with a thin 2.5–8 cm layer of standard hardwood mulch (Davis, 2008).

Soil types also influenced the effectiveness of the reduction of peak flow and runoff volume in term of permeability rates. However, the soil selection for bioretention still be less understood. The presence of clay in soil media up to 30% might contribute to the failure of the system since the water infiltrates slowly due to its smaller pore sizes (Davis *et al*, 2009). Low infiltration may contribute to overflow and flooding issues. Conversely, sand also not suitable due to rapid permeability rate up to 21 cm/hr because it will release higher amount of stormwater volume with less treatment (Clar *et al.*, 2007). Hence, engineered soil mixtures have been recommended to cater this issue. In 2008, six (6) non-vegetated columns tested the influence of the variation of soil compositions consisting fine sand, sandy loam, synthetic soil, compost and mulch with different portion to the hydraulic behaviours mainly K_{sat} and runoff volume. It indicated that those parameters were reduced for soil-based media except sand media due to compaction of filter media with high correlation (r^2=0.96). High level compaction on soil filters may reduce their capability in discharging water unlike sand filter. Thus, compaction needs to be considered during construction work (Hatt *et al.*, 2008). Carpenter and Hallam (2010) proposed the use soil mixtures which consisted of 20% compost, 50% sand and 30% top soil. They carried out laboratory and field experiment to observe the effect of soil composition to the hydrologic and treatment performance. Conversely, they reported that this mixture at field contribute to the lower infiltration rate and higher field capacity as compared to laboratory result due to improper mixed by front-end loader(Carpenter and Hallam, 2010). Another study was conducted in the bench-scale (Stander and Borst, 2009). They tested the hydraulic characteristics of filter media in bioretention system by applying shredded newspaper layer as carbon sources and it was arranged with soil media layer separately. It showed that shredded newspaper did influence volume and flow rates. However, it was not major factor contribute to blocking drainage. But Coffman and Siviter (2007) argued on this implementation. They said if the system has wide variation of soil mix which present difference infiltration rate, it will lead to high cost of construction (Coffman and Siviter, 2007; Davis *et al.*, 2009). Based on previous literature, sandy loam or loamy sand types are the most preferable engineered soil that have been recommended for bioretention design by most of the researchers (Hatt *et al.*, 2008; Li *et al.*, 2009; Brown and Hunt, 2011) . Hence, this paper aims to determine the effects on hydraulic performance by having the variation composition of engineered soil media in bioretention system.

MATERIALS AND METHODS

Collection and Soil Preparation

There were three (3) main materials in engineered soil media as recommended in MSMA (2012) which are medium sand, topsoil (mainly sandy loam) and leaf compost. The sand was dried in the oven at 105°C for 24 hours and sieved it using sieve shaker using standard guidelines for dry sieving method as recommended in BS 1377 Part 2:1990(BSI, 1990). Besides, several tests were conducted for example hydrometer test, specific gravity test and proctor test to determine the soil classification for topsoil. All soil testing were conducted according to BS 1377 Part 2:1990. Table 1 listed the characteristics of soil materials used that have been used in the bioretention system.

Table 1. The characteristics of selected soil materials

Soil materials (Label)	Grain Size (mm)	pH	Moisture content (%)
Topsoil (TS)	<2	6.5	20
Fine sand (FS)	0.06 – 0.2		
Medium sand (MS)	0.2 – 0.6		
Coarse sand (CS)	0.6 – 2		
Leaf compost (LC)	0.001 – 2	5.5 - 6.5	45 - 55

Experimental Design and Procedures

Initially, the standard permeability test (contant head) was conducted in Geotechnical Laboratory, School of Civil Engineering, Universiti Sains Malaysia. There were fifteen (15) samples of engineered soil media were prepared with different composition as listed in Table 2. Permeameter cell with 72 mm diameter were filled with the estimated height of sample of 194 mm. The samples were compacted softly with rod at every 50 mm depth with 27 blows to minimize the voids in the samples. Compaction method needs to properly consider because its influence the reduction of infiltration rates mainly urban construction site (Brown and Hunt, 2010). The permeability test (constant head) was conducted according to BS 1377 Part 2:1990 for each engineered soil sample except for topsoil. The falling head test was used to determine the K_{sat} for topsoil.

Next, the experiment was continued using Perspex cylindrical cell test which was carried out at Physical Laboratory, River Engineering and Urban Drainage Centre (REDAC), Engineering Campus, Universiti Sains Malaysia The cylindrical cell was designed with the scale of 1:20 from the actual site with catchment area of 372 m^2 (4000 ft^2). The characteristics of the engineered soil media cell as tabulated in Table 2. The design of cell also considered the ration of the diameter of cylinder cell to the mean diameter of grain size (D_c/D_{50}) which greater than 50 as suggested by previous literature to obtain more realistic scale(Bright *et al.,* 2010; Le Coustumer *et al.,* 2012). The experimental setup for column test is illustrated in Figure 1. All cells were filled with gravel as underdrain, the net (to prevent the engineered soil media accumulate at underdrain layer and the outlet tube), and engineered soil media as filter layer. The engineered soil media were compacted softly using rod at every 50 mm depth to minimize compaction influence to K_{sat}. All three (3) cells were flushed with tap water through 6mm diameter transparent tubes with gravity flow. The flow was discharged until all cells were saturated and it was continued up to two (2) months in order to observe daily K_{sat} for each cell. It was also to minimize the possibility of the occurrence of preferential flow paths (Good *et al.,* 2012). Then, the inflow was controlled by valve to achieve constant depth at the water ponding layer in the cell. After the flow rates became steady within 24- 48 hours, the initial K_{sat} was measured. Then, it was continued collecting data for each cell in every three (3) times a week. K_{sat} values were calculated based on derivation of Darcy's Law as given in Equation 1 (Erickson *et al.,* 2012; Good *et al.,* 2012).

$$K_{sat} = \frac{QL}{A_c(L+H)} \qquad \text{(Equation 1)}$$

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)
H = Ponding depth at the top of engineered soil layer (m)

Table 2. Design and specifications of cell setup

Design characteristics	Specification
No. of columns monitored	3
Drainage area	0.04ha
Actual Peak Discharge	8.49L/s
Column diameter	74 mm
Column height	700 mm
Design Inflow	0.28 L/min
Filter media depth	500 mm
Fill media specifications:	
Cell 1	50% coarse sand:30% topsoil:20% leaf compost
Cell 2	50% medium sand:30% topsoil:20% leaf compost
Cell 3	50% fine sand:30% topsoil:20% leaf compost
Gravel	6-9 mm grain size at 30 mm depth

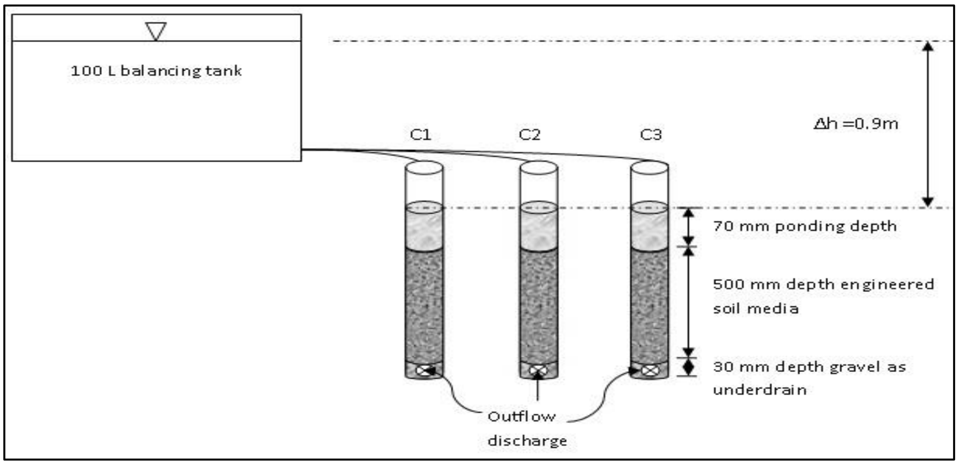

Figure 1. Schematic diagram for column testing

RESULT AND DISCUSSION

K_{sat} for Standard Permeability Test (Constant Head)

From sieve analysis curve, D_{50} and D_{10} were determined for each soil sample. D_{10} was the effective size and it was used to estimate permeability. Hazen's approximation (1893) is an empirical equation to establish relationship between grain size and K_{sat} as shown in equation 2.

$$K = 100(D_{10})^2 \qquad \text{(Equation 2)}$$

Where,
K = hydraulic conductivity (cm/s)
D_{10}=a grain diameter for which 10% of the sample will be finer than it (cm).
There were fifteen (15) samples of soil with five (5) measurements for each soil as listed in Table 3. The table also tabulated the K_{sat} (mean±standard deviation) which according to the mean grain size (D_{50}) and effective grain size (D_{10}). By comparing with the study by Carpenter and Hallam (2010), the soil composition in this study produced higher values of K_{sat} than their study.The relationship of K_{sat} and D_{10} is shown in Figure 2. This result indicates that the hydraulic conductivities of each engineered soil composition are rely on the effective grain size (D_{10}) by comparing the actual results of K_{sat} and the estimated value using Hazen's empirical equation.

Table 3. Summary of K_{sat} measurement according to grain size for each engineered soil sample.

Soil composition label	N	D_{50} (mm)	D_{10} (mm)	Hydraulic conductivity, K_{sat} (mm/hr)
90CS/10TS	5	0.8	0.49	5108.13±133.98
90MS/10TS	5	0.5	0.3	1751.64± 66.09
90FS/10TS	5	0.22	0.17	640.11±7.25
80CS/20TS	5	0.79	0.45	1316.27±69.91
80MS/20TS	5	0.52	0.26	969.39±21.54
80FS/20TS	5	0.24	0.16	363.18±2.10
70CS/30TS	5	0.8	0.6	868.72±6.51
70MS/30TS	5	0.5	0.34	578.70±3.43
70FS/30TS	5	0.26	0.17	325.63±4.78
60CS/30TS/10LC	5	0.8	0.45	704.03±26.05
60MS/30TS/10LC	5	0.55	0.3	515.20±17.11
60FS/30TS/10LC	5	0.28	0.17	483.04±22.55
50CS/30TS/20LC	5	0.71	0.2	386.25±12.23
50MS/30TS/20LC	5	0.5	0.25	311.45±4.06
50FS/30TS/20LC	5	0.25	0.17	163.49±4.44
20C/50S/30T*				46.7
80C/20S*				455.9

*Results carried out by Carpenter and Hallam (2010). (C=compost; S=sand; T=topsoil)

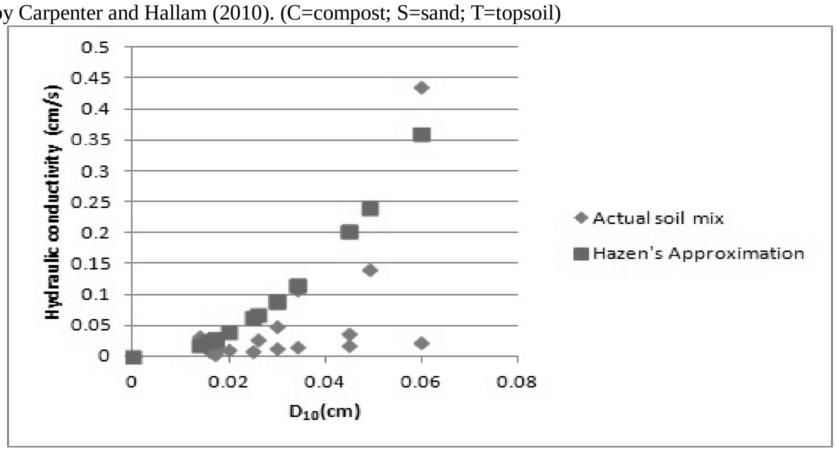

Figure 2. The relationship between K_{sat} and grain size of D_{10}.

Figure 3 illustrates the presence of top soil has affected the K_{sat}. In other words, higher percentage of topsoil can reduce the permeability rate. Typically, the recommended values of K_{sat} for bioretention is ranged between 50-200 mm/hr (DID, 2012).Thus, based on the figure, only 80FS/20TS and 70FS/30TS are suited with the recommendation which means its required more finer particles to achieve the recommended design value of K_{sat}. This study obtained higher K_{sat} by comparing to the results by Good *et al.* (2012) where they arranged the sand and topsoil by layer in the column, the initial and final of K_{sat} are 302±7 mm/hr and 290±5 mm/hr, respectively. Coarser particles in engineered soil media provide higher permeability coefficient which was indicate more untreated water discharge from filter media. In addition, the composition of engineered soil media was made based on the MSMA guidelines to have the ranged of 50- 60% of sand, 20-30% of top soil (sandy loam) and 10-12% organic leaf compost (DID, 2012). As demonstrated in Figure 4, the composition of 60% sand for all types of sand was not suitable to apply for bioretention purposes since it creates higher permeability rates. However, for the sample of 50MS/30TS/20LC and 50MS/30TS/20LC was possibly recommended because both results showed good ranges of K_{sat}. Besides, the comparative study was made between the result of this study and previous research that carried out by Hatt *et al*. (2008). This results of this study obtained slightly lower hydraulic conductivity as compared to soil composition (60% sandy loam, 20% compost and 20% mulch) that was used by Hatt et al. (2008) where initial and final K_{sat} of their result were 2329.2.mm/hr and 1152 mm/hr, respectively. Besides, it was found that the existence of organic compost assists the declination of K_{sat}. However, more organic leaf compost in the engineered soil composition will affect the quality of stormwater effluent and it also disturbs the growth of several vegetations.

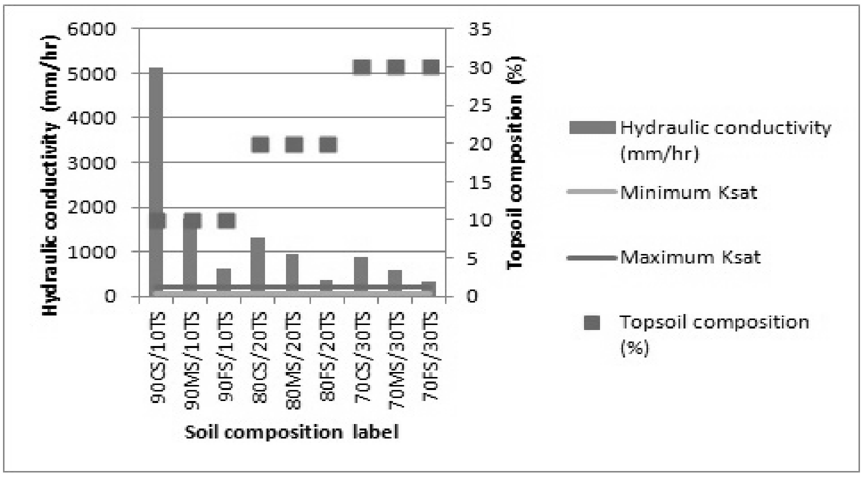

Figure 3. The influence of topsoil composition in engineered soil media

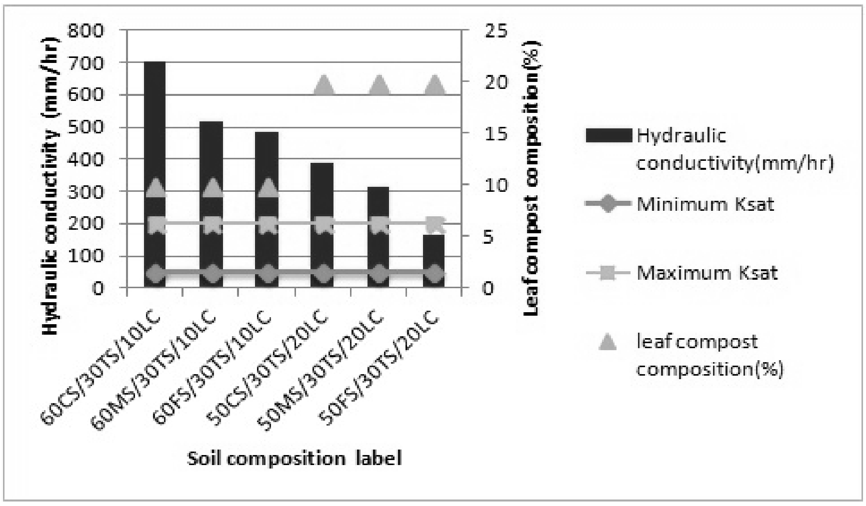

Figure 4. The influence of leaf compost on K_{sat} in engineered soil media.

Results of Laboratory Cell Test

Figure 5 represents K_{sat} in the cells decline significantly over time. The declination is very drastic during week 6 until week 9 for cell 1 which consist of 50% coarse sand, 30% topsoil and 20% organic leaf compost (50CS/30TS/20LC). It was observed that Cell 2 (50MS/30TS/20LC) had a leaking problem at the cell wall and at the outlet pipe for the first 3 week, thus there was a possibility to have a quick reduction of K_{sat} at the beginning of experiment. However, it started follow the trends in week 4 until week 9. The K_{sat} for cell 2 was slightly higher than the K_{sat} in cell 3 which consist of the composition of fine sand, topsoil and organic leaf compost. The overall reduction for each cell of K_{sat} were 55%, 78% and 44%, respectively as compared to the study by Le Coustumer *et al.*(2007) where the reduction was 66% (Figure 5). Both cells provide better ranges of K_{sat} as recommended in MSMA (2012) except cell 1 which consist of 50% coarse sand. It is noticed that coarse sand with greater particle size might allow larger pore size between them which can transmit more water quickly from the filter media.

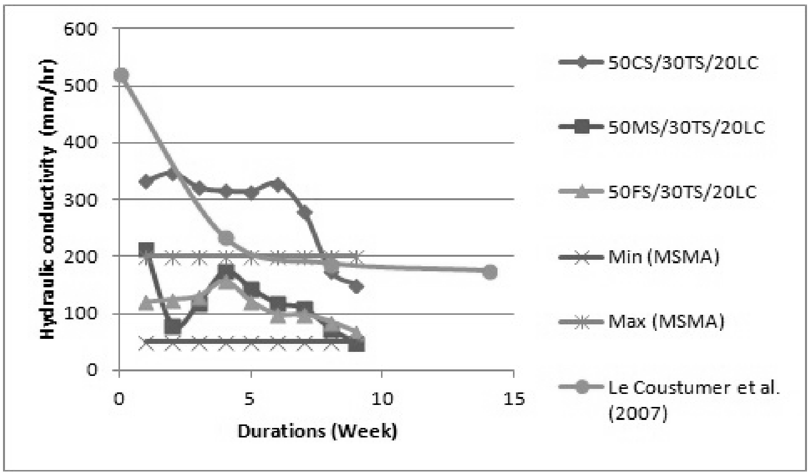

Figure 5. Mean K_{sat} for each soil sample within 9 weeks.

K_{sat} Standard Permeability Test versus K_{sat} Laboratory Cell Test

Figure 6 shows the results of K_{sat} using standard permeability test (constant head) and laboratory cylindrical cell test. It shows that the results obtained from standard permeability test were greater than the results from cell test. The mean ratio of K_{sat} using permeability test to the result from cell test is 1.25. This is probably due to the geometric design or scale defects of the cell might result the K_{sat} values. In addition, previous research highlighted that the small scale of bioretention cells which reflect to the catchment size will prone to the quick declination of K_{sat} due to high loading rates (Le Coustumer *et al.*, 2007).

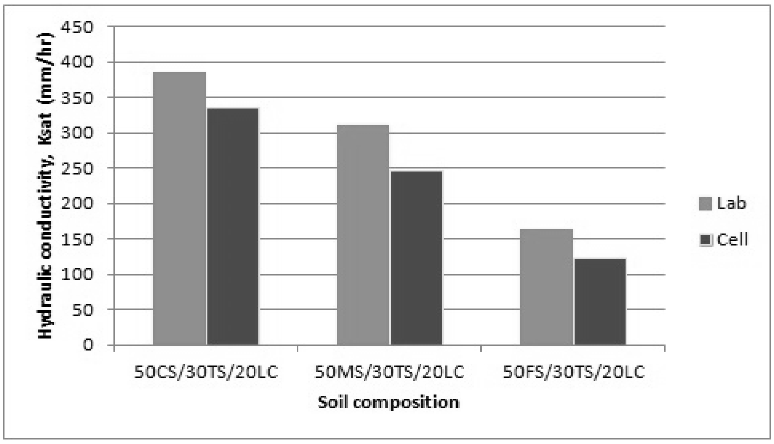

Figure 6. Comparison of K_{sat} between standard permeability test and using laboratory cell test.

CONCLUSION

The variation of engineered soil that have been applied in bioretention was influenced the declination of K_{sat}. The composition 50% medium to fine sand, 30% topsoil mainly sandy loam and 20% topsoil are suggested in this study because it providing better range of K_{sat} which was recommended in MSMA (2012) guidelines. However, the presence of coarse sand with the other two materials is not suitable to use for bioretention purposes due to its characteristics which providing larger pore sizes may lead to the greater permeability rates. The evolution of K_{sat} over time can be determined with long-term study using cylindrical cell test. This information can be used to predict the design life of bioretention by monitoring the permeability rates. Further study will be continued with larger scale of cylindrical cell to examine the impacts of K_{sat} on nutrient removals by having different compost materials and new types of underdrain layer.

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