Assessing the Impact of Soil Media Characteristics on Stormwater Bioinfiltration Device Performance: Lab and Field Studies

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ABSTRACT

Bioinfiltration devices are a potentially effective option for the treatment and discharge of stormwater runoff from urban areas. However, the performance of these systems and other infiltration devices can be affected by factors such as texture, structure and degree of compaction of the media during their construction. The main goal of this study is to provide insight on media characteristics of a poorly operating biofilter facility located in Tuscaloosa, AL. Double ring infiltrometer tests and soil compaction measurements were conducted along a large biofilter to determine the in-situ characteristics of the media. Infiltration observations were also made during actual rain events. The effects of different compaction levels on the infiltration rates through the soil media were examined during laboratory column tests. Similar tests were also conducted examining compaction effects of the media after mixing with varying amounts of filter sand to investigate restoration options. These results indicate that soil compaction has dramatic effects on the infiltration rates; therefore care needs to be taken during stormwater treatment facilities construction to minimize detrimental compaction effects.

INTRODUCTION

Biofilters are widely used in urban areas to reduce runoff volume, peak flows and stormwater pollutants impact on receiving waters. Most of the removal benefits of stromwater biofilter devices are through physical removal as the particulate-bound pollutants are trapped in the media, and through water infiltration into the natural soil surrounding the device. The rate of infiltration depends on a number of factors, including the condition of the soil surface and its vegetative cover, the properties of the soil, such as its porosity and hydraulic conductivity, and the current moisture content of the soil (Chow, et al. 1988). The infiltration rate in a soil typically decreases during periods of rainfall as the soil becomes saturated. Infiltration practices have the greatest runoff reduction capability of any stormwater practice and are suitable for use in residential and other urban areas where measured soil permeability rates exceed 1/2 inch per hour (VA DCR, 2010).

Understanding the physical and hydrologic properties of different bioretention mixtures, as well as their response to compaction, may increase the functional predictability of bioretention systems and thus improve their design (Pitt et al. 2008, and Thompson et al. 2008). The usual effect of compaction are increased bulk density and soil strength , reduces the porosity, damages soil structure, reduces the air available to plant roots and other soil organisms and reduces infiltration rates. Soil compaction that occurs in stormwater treatment facilities during construction can cause significant reductions in infiltration capacities of the soils. Pitt, et al. (2008) noted large detrimental effects of compaction on infiltration rates in both sandy and clayey soils. Infiltration rates were reduced to near zero values in soils having even small amounts of clay, if compacted. Large reductions in the infiltration rates in sandy soils with compaction were also reported, but several inches per hour rates were usually still observed (down from tens of inches per hour), even with severe compaction. The poorly operating biofilter facility selected for this study is about 300ft (92m) long and 30ft (9m) wide (0.21 acres (850 m^2), or about 14% of the paved/roofed source area) is located in Shelby Park, adjacent to the University of Alabama, rental car parking lot, from which it receives flow (Figure 1).

Figure 1. Drainage areas tributary to the biofilter

Infiltration rate and soil density measurements in Shelby Park Biofilter

TURF-TEC Infiltrometers (Turf Tec 1989) were used to measure the infiltration rates at 12 test locations along the biofilter. These small devices have an inner ring about 64 mm (2.5 in.) in diameter and an outer ring about 114 mm (4.5 in.) in diameter. The infiltrometers were gently driven into the surface of the biofilter soil (having poor vegetation cover) until the “saturn” ring was against the soil surface (see Figure 2). Relatively flat areas were selected in the biofilter to install the Turf-Tec infiltrometers and small obstacles such as stones and twigs were removed. Each cluster of three infiltrometers were inserted within about a meter from each other to best measure the variability of the infiltration rates of the soil media in close proximity.

Four clusters of three infiltrometer tests were conducted along the biofilter to examine variations along the biofilter length. The tests were conducted for a period of one to two hours, until the infiltration rate become relatively constant.

After the soil was inspected and sealed around each ring to make sure that it was even and smooth, clean water was poured into the inner ring and allowed to overflow and fill up the outer ring. The rate of decline in the water level was measured by starting the timer immediately when the pointer reached the beginning of the depth scale. Additional water was added to both rings when the level in the inner ring dropped a measurable amount. The change in water level and elapsed time were recorded since the beginning of the first measurement. The measurements were taken every five minutes at the beginning of the test and less frequently as the test progressed until the rate of infiltration was considered constant.

Figure 2. Photographs showing the infiltration measurement setup and in-situ soil density measurement at Shelby park biofilter.

In-situ soil density measurements were also made in the same locations of the infiltration measurements. A small hole six inch deep and six inch wide was hand dug very careful to avoid disturbance of the soil that would bound the hole. The hole's side and bottom were also carefully smoothed. All of the soil excavated from each hole was placed into four separate zip lock plastic bags in order that the soil did not lose moisture. Sand was then poured into the hole from a graduated cylinder to measure the volume of the holes, up to the top of the soil that was removed from the biofilter. The excavated soil media was then transported to the university of Alabama geotechnical lab for further analyses. The soil media was weighed, dried at 105^{o}C, and weighed again. The density (dry) and moisture content (%) of the soil media collected from each test locations were determined. The density of the soil was determined by dividing the mass of oven-dried soil by the sand volume used to re-fill the hole. The soil moisture content (%) was determined from the ratio of the mass of water to the mass of oven-dried soil media. The mass of water was obtained from the difference between the mass of the moist soil and the oven dried soil.

Soil samples extracted from the surface of the biofilter were also delivered to the Auburn University Soil Testing Laboratory where soil texture (% sand, % silt, and % clay), organic matter, and general nutrients were also analyzed. Soil test data report and summary is shown in table 1. The critical soil test values as used by the Auburn University Soil Testing Laboratory vary from soil to soil and from crop to crop. As a general rule, no increased yield response is expected to a nutrient above its critical value. The biofilter soil is sand clay loam, with an average of 79% sand, 20% clay, and 1% silt. The organic matter content of the biofilter soil is 3.1%.Organic matter improves soil structure and soil tilth, and helps to provide a favorable medium for plant growth. Soils with large amounts of clay generally require large amounts or organic matter. Soils with a higher organic matter content will have a higher cation exchange capacity (CEC), higher water holding capacity, and better tilth than soils with a lower organic matter content. Soils in the Central Great Plains have organic contents ranging between 1 and 2% for cultivated soils, and about 1.5 to 3.0% for native grasslands (Bowman, 1996). Generally, healthy soil has between 3% and 5% organic material.

The cation exchange capacity (CEC) of a soil is a measurement of its ability to bind or hold exchangeable cations. The biofilter soil had CEC value 4.0 meq/100g and a pH value of 6.8. The CEC values as used by the Auburn University Soil Testing Laboratory (Mitchell and Huluka, 2011) vary from soil to soil, sandy soils have CEC values 0 to 4.6 and loam soils have CEC values 4.6 to 9.0. According to the Alabama Cooperative Extension System the ideal soil pH value for most crops ranges between 5.8 and 6.5 and for acid loving plants ranges between 5.0 and 5.7. When soil pH is outside of these optimal ranges nutrients can be less available to plants, potentially resulting in deficiencies. The biofilter soil had a phosphorus concentration value 12 Parts per million (ppm).The critical phosphorus concentration for crops (peanuts, pine trees, blueberries and centipedegrass) grown in sandy soil in Alabama is 9.5ppm whereas for all other crops is 25 ppm. The biofilter soil had a potassium, magnesium, and calcium concentration values 30, 137, and 525ppm respectively. The critical magnesium level for all crops grown in sandy soil in Alabama as used by the Auburn University Soil Testing Laboratory is about

13ppm. Whereas the critical calcium level for crops such as tomatoes, peppers, fruits and nuts grown in sandy soils is 250ppm .The biofilter soil had higher concentration of calcium for most crops grown in sandy and loam soils in Alabama.

Table 1 . Summary of the soil nutrient report for ShelbyPark biofilter soil.

Nutrient	ppm	Nutrient	ppm
Calcium(Ca)	525	Copper(Cu)	<0.1
Potassium(K)	30	Iron(Fe)	34
Magnesium(Mg)	137	Manganese(Mn)	31
Phosphorus(P)	12	Molybdenum(Mo)	<0.1
Aluminum(Al)	70	Sodium(Na)	31
Arsenic(As)	<0.1	Nickel(Ni)	<0.1
Boron(B)	0.2	Lead(Pb)	1
Barium(Ba)	9	Zinc(Zn)	6
Cadmium(Cd)	<0.1	Total Phosphorus(P)	149
Chromium(Cr)	<0.1		

Nutrient	%
Nitrogen(N)	0.06
Carbon(C)	1.79
Organic Matter(OM)	3.1
Sodium Adsorption Ratio(SAR)	0.3
pH	6.81
H_2O availability (cm^3/cm^3)	0.08
Cation Exchange Capacity (CEC) (meq/100g)	4

Biofilter surface ponding

During rainfall events, if the runoff rate entering the biofilter is greater than the infiltration capacity of the soil, water will pond on the biofilter surface. Biofilter surface ponding was often observed following heavy rainfall events on the test site. Infiltration rate measurements were manually recorded from biofilter ponded areas after five rainfall events between July 2010 and April 2011. Depth indicator rules were placed at 3 to 5 different locations along the biofilter at surface ponding areas. The decrease in the depth of water was measured every 30min at the beginning of the observations for each event and less frequently as the test progressed, until the water completely infiltrated. The change in water level and elapsed time were recorded since the beginning of the first measurement. Measurements were taken only during the day light hours and it was therefore difficult to accurately predict the total drainage time. This method is time consuming, labor intensive, and greatly depends on operator care for accuracy, but was needed to verify the infiltrometer measurements using the Turf-Tec units during dry weather. These measurements were taken after the runoff ceased and the biofilter was fully saturated.

Figure3. Ponded water on the biofilter surface observed after rainfall events and double ring infiltration measurement installations.

Laboratory column tests

The effects of different compaction levels on the infiltration rates through the biofilter soil media (extracted from the biofilter) when mixed with varying amounts of filter sand was also examined using laboratory column experiments. Four-inch (100mm) diameter PVC pipes (Charlotte Pipe TrueFit 4 in. PVC Schedule 40 Foam-Core Pipe) 3 ft (0.9 m) long, purchased from a local building supply store in Tuscaloosa, AL were used for these test. Nine columns were used for each test series and were setup as shown in Figure 4. The bottom of the columns had a fiberglass window screen secured to contain the media and were placed in funnels. The columns were first filled with about 2 inches of pea gravel purchased from a local supplier. To separate the gravel layer from the media layer, a permeable fiberglass screen was placed over the gravel layer. The column was then filled with the biofilter media obtained through excavating it from the biofilter. The columns had various mixtures of media and filter sand; they are listed in Table 2. The filter sand was purchased from a local supplier in Tuscaloosa, Alabama. It has a median particle size (D_{50}) of about 700 µm and a uniformity coefficient (*Cu*) of 3.3.The media layer was about 1.5 ft (0.5 m) thick. Each filter media was filled in roughly 4.5 inch lifts for the modified proctor compaction, 4.5 inch lifts for the standard proctor compaction, and about 18inch for hand compaction, and suitably compacted after each lift. The infiltration rates were measured in each column with clean water. The surface ponding depths ranged between 11 in. (28 cm) and 14 in. (36 cm) to correspond to the approximate maximum ponding depth at the site biofilter. The free board depth above the media to the top of the columns was about 2 to 3 in. (50-75 mm). Infiltration rates in the media mixtures were determined by measuring the rates with time until apparent steady state rates were observed.

Figure 4. Laboratory column setup.

Table 2. Various Mixtures of Media and Filter Sand Used for Laboratory Infiltration Measurements

Column No.	Compaction method	Density(g/cc) before test	Mixture
1	Hand	1.54	Only biofilter media
2	Standard	1.66	
3	Modified	1.94	
4	Hand	1.63	50% biofilter media and 50% filter sand
5	Standard	1.70	
6	Modified	1.77	
7	Hand	1.52	75% biofilter media and 25% filter sand
8	Standard	1.71	
9	Modified	1.76	
10	Hand	N/A	90% biofilter media and 10% filter sand
11	Standard		
12	Modified		

RESULTS

In-situ biofilter infiltration results

The average initial infiltration rate for the field test was about 11 in/hr (280 mm/hr), and ranged from 3 to 28 in/hr (76 to 710 mm/hr). The final rates had an average value of about 4.6 in/hr (115 mm/hr), and ranged from 1.5 to 10.5 in/hr (38 to 270 mm/hr). Variations of infiltration rates (about a factor of 2) were also observed along the biofilter, as shown on Figure 5. The actual rain event ponded infiltration rates were about ten times less than these values, being somewhat less than the lowest infiltrometer measurements observed, indicating fully saturated conditions. These low rates corresponded to the standard to modified compacted soil rates observed during the column tests. The average initial and final infiltration rates from the ponded locations did not very significantly and were about 0.5 in/hr (12mm/hr) and 0.55 in/hr (14 mm/hr) respectively. These very low values were about equal to the observed laboratory tests conducted under the most severe compaction conditions (the modified Proctor compaction tests).

Table 3. Field Infiltration Tests

Test site location	Horton's parameters						Dry density (g/cc)	Initial moisture content (%)
	f_o (in/hr)		f_c (in/hr)		k (1/min)			
	mean	range	mean	range	mean	range		
1	6.5	(4.5-9.0)	2.0	(1.5-3.0)	0.07	(0.03-0.15)	2.2	9.2
2	16.6	(2.9-27.8)	6.0	(2.2-10.0)	0.07	(0.06-0.1)	2.3	5.6
3	12.5	(8.1-14.8)	4.5	(4.4-4.49)	0.09	(0.06-0.11)	1.8	8
4	9.0	(7.4-11.0)	6.0	(3.0-10.5)	0.045	(0.001-0.07)	2.1	8.2

Laboratory infiltration results:

For the laboratory tests, the median initial infiltration rates through the mixture with increasing degrees of compaction were 18, 6, 3 in/hr (460, 150 and 75 mm/hr) using hand compaction, standard proctor compaction and modified proctor compaction methods, respectively. The initial median infiltration rates of the hand compacted mixture were reduced by 66 and 83 percent using the standard proctor compaction and modified proctor compaction methods. Table 4, through 7 summarizes the column test results for the biofilter soil alone and with varying amounts of added sand, and for different compaction values.

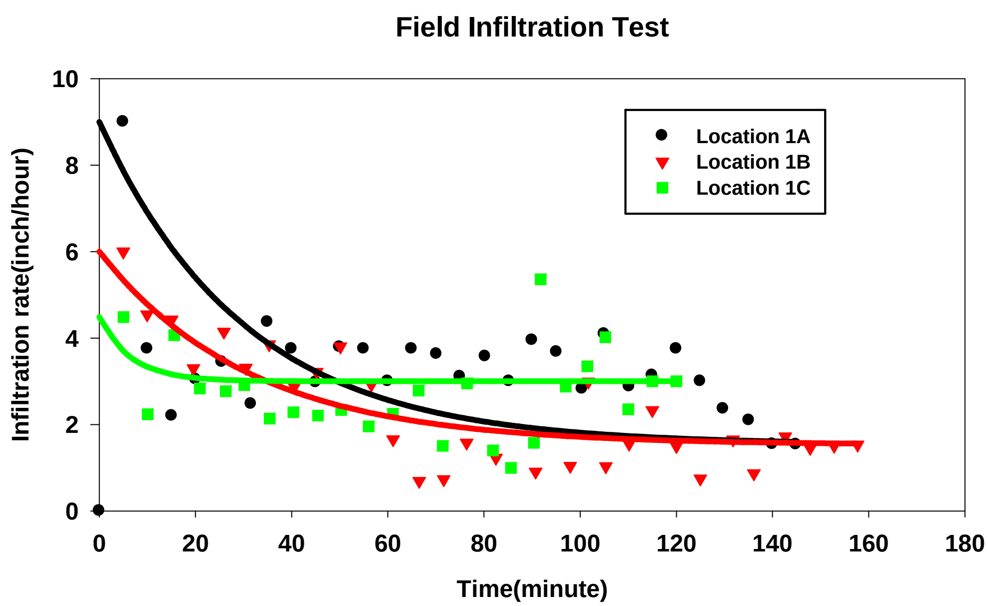

Figure 5. Example field infiltration measurements fitted with Horton equations.

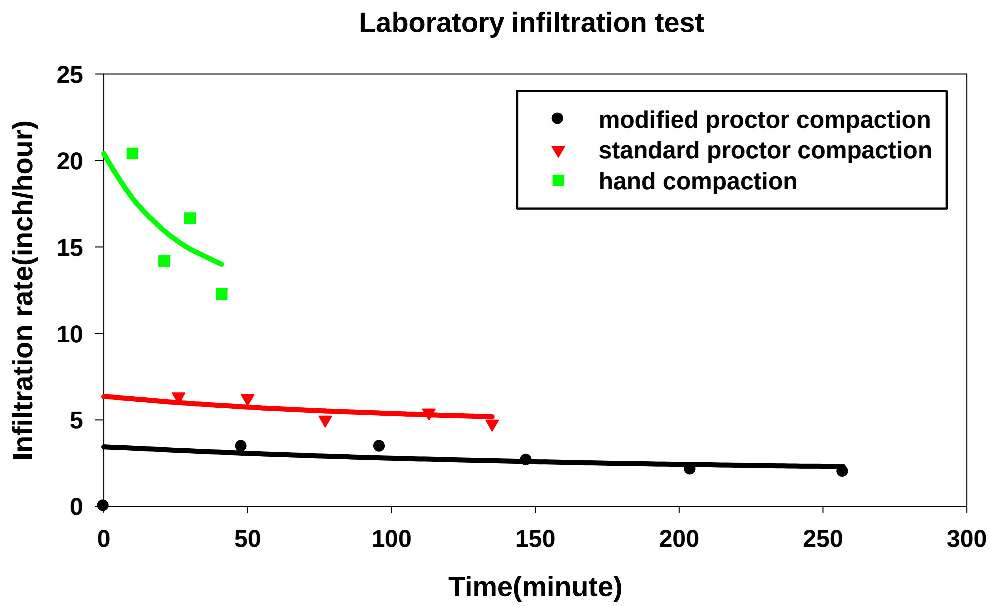

Figure 6. Example laboratory infiltration measurements fitted with Horton equations. Mixture of 50% biofilter soil and 50% filter sand was used for the lab-test.

Table 4. Laboratory Infiltration Tests Using Biofilter Soil Only.

only biofilter soil				
Compaction method	Day	f_o (in/hr)	f_c (in/hr)	k (1/min)
modified (density =1.94g/cc)	1	0.54	0.34	0.002
	2	0.44	0.33	0.001
	3	0.19	0.12	0.001
	mean	0.39	0.26	0.001
	range	(0.19-0.54)	(0.12-0.34)	(0.001-0.002)
standard (density = 1.66g/cc)	Day	f_o (in/hr)	f_c (in/hr)	k (1/min)
	1	1.13	0.97	0.010
	2	1.05	0.94	0.010
	3	0.79	0.50	0.010
	mean	0.99	0.81	0.010
	range	(0.79-1.13)	(0.5-0.97)	
hand (density = 1.54g/cc)	Day	f_o (in/hr)	f_c (in/hr)	k (1/min)
	1	5.00	3.14	0.025
	2	3.91	3.19	0.039
	3	9.69	5.95	0.045
	mean	6.20	4.09	0.036
	range	(3.9 - 9.7)	(3.1 - 6.0)	(0.025 - 0.05)

Table 5. Laboratory Infiltration Tests Using a Mixture of 50% Biofilter Soil and 50% Filter Sand.

a mixture of 50 % biofilter soil and 50% filter sand				
Compaction method	Day	f_o (in/hr)	f_c (in/hr)	k (1/min)
modified (density =1.77g/cc)	1	6.58	4.50	0.018
	2	3.44	1.98	0.009
	3	2.02	1.97	0.010
	mean	4.01	2.82	0.012
	range	(2.0-6.6)	(2.0-4.5)	(0.009-0.02)
standard (density =1.70g/cc)		f_o (in/hr)	f_c (in/hr)	k (1/min)
	1	12.19	5.29	0.019
	2	6.35	4.77	0.010
	3	6.32	4.64	0.009
	mean	8.28	4.90	0.013
	range	(6.3-12.2)	(4.64-5.3)	(0.009-0.02)
hand (density =1.63g/cc)		f_o (in/hr)	f_c (in/hr)	k (1/min)
	1	30.00	19.71	0.045
	2	20.40	12.27	0.038
	3	24.00	15.00	0.065
	mean	24.80	15.66	0.049
	range	(20.4-30.0)	(12.3-19.7)	(0.038-0.065)

Table 6. Laboratory Infiltration Tests Using a Mixture of 75% Biofilter Soil and 25 % Filter Sand.

a mixture of 75 % biofilter soil and 25% filter sand				
Compaction method	Day	f_o (in/hr)	f_c (in/hr)	k (1/min)
modified (density =1.76g/cc)	1	4.50	1.50	0.005
	2	3.46	1.70	0.010
	3	3.75	1.25	0.005
	mean	3.90	1.48	0.007
	range	(3.5-4.5)	(1.25-1.7)	
standard (density =1.71g/cc)	Day	f_o (in/hr)	f_c (in/hr)	k (1/min)
	1	9.60	4.69	0.009
	2	6.43	3.00	0.013
	3	6.00	3.16	0.010
	mean	7.34	3.62	0.011
	range	(6.0-9.6)	(3.0-4.7)	
hand (density =1.52g/cc)	Day	f_o (in/hr)	f_c (in/hr)	k (1/min)
	1	28.93	2.14	0.031
	2	15.00	8.18	0.047
	3	17.14	8.33	0.047
	mean	20.36	6.22	0.042
	range	(15-29)	(2.1-8.3)	(0.03-0.05)

Table 7. Laboratory Infiltration Tests Using a Mixture of 90% Biofilter Soil and 10% Filter Sand.

a mixture of 90 % biofilter soil and 10% filter sand				
Compaction method	Day	f_o (in/hr)	f_c (in/hr)	k (1/min)
modified	1	6.64	1.13	0.020
	2	1.58	0.50	0.003
	3	1.15	1.25	0.500
	mean	3.12	0.96	0.174
	range	(1.2-6.6)	(0.5-1.3)	(0.003-0.5)
standard	Day	f_o (in/hr)	f_c (in/hr)	k (1/min)
	1	8.00	0.75	0.019
	2	2.73	0.63	0.010
	3	1.88	1.02	0.006
	mean	4.20	0.80	0.01
	range	(1.9-8.0)	(0.6-1.0)	(0.006-0.02)
hand	Day	f_o (in/hr)	f_c (in/hr)	k (1/min)
	1	18.46	5.00	0.034
	2	9.00	3.33	0.015
	3	8.63	6.75	0.040
	mean	12.03	5.03	0.030
	range	(8.6-18.5)	(3.3-6.8)	(0.015-0.04)

CONCLUSIONS

The laboratory column test results indicated that, the infiltration rates through all mixtures of media and filter sand are greater than the infiltration rates through only biofilter soil media for the three levels of compactions (modified proctor, standard proctor and hand compaction). Mixing the biofiter media with filter sand improved the infiltration capacity of the media and also reduced the impact of compactions on the infiltration rates. The mixture containing 50% biofilter media and 50% filter sand exhibited the highest infiltration rates. The laboratory test results demonstrate that soil compaction has dramatic effects on the infiltration rates; therefore care needs to be taken during stormwater treatment facilities construction in urban areas to reduce detrimental compaction effects. The infiltration values from the ponded locations are very small compared to the laboratory and field test infiltration values indicating fully saturated conditions and moderately to severely compacted conditions.

The in-situ infiltration measurements need to be evaluated cautiously. The ponded water measurements in the biofilter were obtained after complete saturation. Also, ponding was not even throughout the biofilter, and preferentially pooled in areas having depressions and with low infiltration capacities. Because they were in depressions, silting may have also occurred in those areas. Long-term and continuous monitoring in a biofilter during rains is the best indication of performance, and these spot checks likely indicate the lowest values to occur. In fact, they were similar to the lowest infiltration rates observed with the infiltrometers and also corresponded to the compacted media column tests. Data from the infiltrometers also need to be cautiously evaluated as they also show very high rates that only occur during the initial portion of the event. Most of the infiltration in biofilters likely occurs after saturated conditions and the lowest rates observed may be most representative of actual rain-runoff conditions.

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