X

Laboratory Column Test for Predicting Changes in Flow with Changes in Various Biofilter Mixture

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Bioretention systems are widely used in urban areas to reduce stormwater volume, peak flows and stormwater pollutant loads reaching receiving waters. However, the performances of bioretention systems, and other infiltration devices, are affected by factors such as texture, structure, and degree of compaction of the media during their construction. The soil/media mixture used in bioretention systems is central for determining water quality treatment and stormwater flow control performance. Premature clogging of filtration media by incoming sediment is a major problem affecting the performance of stormwater biofiltration systems in urban areas. Appropriate hydraulic characteristics of the filter media, including treatment flow rate, clogging capacity, and water contact time, are needed to select the media and drainage system.

This chapter describes a series of controlled laboratory column tests conducted using various media to predict changes in flow with changes in the mixture, focusing on media density associated with compaction, particle size distribution (and uniformity), and amount of organic material. The laboratory columns used in the tests have various mixtures of sand and peat. The results of the predicted performance of these mixtures were also verified using column tests (for different compaction conditions) of surface and subsurface soil samples obtained from Tuscaloosa, AL, infiltration test areas, along with bioretention media obtained from actual Kansas City biofilters and standard samples of North Carolina biofilter media. Three levels of compaction were used to modify the density of the media layer during the tests: hand compaction, standard proctor compaction, and modified proctor compaction.

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Statistical analyses were performed to determine the effects of media texture, uniformity of the media, organic content of the material, and compaction, plus their interactions on the flowrate through the bioretention media. Model fitting was performed on the time series plots to predict the flowrate through the mixture as a function these factors and their interactions.

X.1 Introduction

Understanding the physical and hydrologic properties of different bioretention media mixtures as well as their response to compaction may increase the functional predictability of bioretention systems and thus improve their design (Pitt et al., 2002 and 2008; Thompson et al., 2008). The usual effects of soil compaction results in increased bulk densities, decreased moisture holding capacities, restricted root penetration, impeded water infiltration, and fewer macropore spaces needed for adequate aeration, all often leading to a significant reduction in infiltration (Gregory et al., 2006; Pitt et al., 2008; Thompson et al., 2008; Sileshi et al., 2012a and b). Infiltration tests conducted on many different soils having a wide range of texture and representative of the great soil and parent –material group at 68 field sites throughout the United States indicated that the infiltration rate decreases with increasing clay content and increases with increasing noncapillary porosity (Free et al., 1940). Premature clogging by silt is usually responsible for early failures of infiltration devices, although compaction (during either construction or use) is also a recognized problem (Pitt et al., 2002 and 2008).

Substantial reductions in infiltration rates were noted due to soil compaction, especially for clayey soils, during prior research (Pitt et al., 1999b). Sandy soils are better able to withstand compaction, although their infiltration rates are still significantly reduced. Compaction was seen to have about the same effect as moisture saturation for clayey soils, with saturated and compacted clayey soils having very little effective infiltration rates (Pitt et al., 2008). Sandy soils can still provide substantial infiltration capacities, even when greatly compacted, in contrast to soils containing large amounts of clays that are very susceptible to compaction's detrimental effects. In a similar study that examined the effects of urban soil compaction on infiltration rates in north central Florida, Gregory et al. (2006) found a significant difference between the infiltration rates of a noncompacted pasture and wooded area, despite similar textural classification and mean bulk densities.

Soil amendments (such as organic composts) improve soil infiltration rates and water holding characteristics and add protection to groundwater resources, especially from heavy metal contamination in urban areas (Pitt et al., 1999a and 1999b). Groundwater contamination problems were noted more often in commercial and industrial areas that incorporated subsurface infiltration and less often in residential areas where infiltration occurred through surface soil (Pitt et al., 1999a and Clark et al., 2006). However, pretreatment of stormwater runoff before infiltration can reduce groundwater contamination of many pollutants and also prolong the life of the infiltration device.

Compost has significant pollutant sorption and ion exchange capacities that can also reduce groundwater contamination potential of the infiltrating water (Pitt et al., 1999b). However, newly placed compost amendments may cause increased nutrient discharges until the material is better stabilized (usually within a couple of years). In addition to flow control benefits, amended soils in urban lawns can also have the benefits of reduced fertilizer requirements and help control disease and pest infestation in plants (US EPA, 1997).

X.2 Methodology

X.2.1 Bioretention Media

Controlled laboratory column tests using various mixture media to predict changes in flow with changes in the mixture, focusing on media density associated with compaction, particle size distribution (and uniformity), and amount of organic material were conducted. The media examined included eight materials: four different sands, surface and subsurface soil from Tuscaloosa, AL bioinfiltration sites, actual Kansas City biofilter media, and standard biofilter samples from North Carolina. The sand media were obtained from local supplier in Tuscaloosa, AL and Atlanta, GA. The column tests examined the different sand media mixed with different percentages of peat and each of the other four materials separately. Figure X.1 shows four of the eight media, with the remaining four media being different filter sands.

Figure X.1 Media (from left to right): Tuscaloosa surface soil, Tuscaloosa subsurface soil, North Carolina biofilter media, Kansas City biofilter media from test sites 1 and 2.

The median size of the filter sand used in the sand-peat mixture ranged from 300 to 2,000 um and the uniformity coefficient ranged from 2 to 3.5. Figure X.2 shows the particle size distribution plots for the various media used for the tests. The plot shows that both the North Carolina and Kansas City biofilter materials are relatively coarse, but the Kansas City media has a larger uniformity coefficient (uniformity coefficient = D60/D10, where D60 is the particle size associated with the 60th percentile and the D10 is the particle size associated with the 10th percentile).

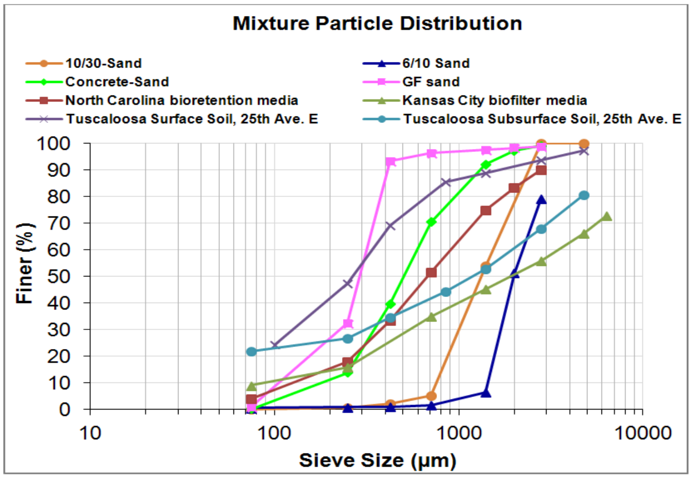

Figure X.2 Particle size distributions of filter sands, Tuscaloosa surface and subsurface soil, and bioretention media obtained from Kansas City and North Carolina.

X.2.2 Laboratory Column Tests

The effects of different compaction levels on the infiltration rates through the media described in section X.2.1 were examined during laboratory column testing in University of Alabama environmental engineering laboratories. A 100 mm diameter PVC pipe (Charlotte Pipe TrueFit 100 mm PVC Schedule 40 Foam-Core Pipe) purchased from a local building supply store in Tuscaloosa, AL was used to construct the columns for these tests. A total of sixty six columns, each 0.9 m long, were constructed as shown in Figure X.3. The columns were filled with about 5 cm of cleaned 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 and then filled with the different media listed in the previous section. The media layer was about 0.5 m thick. The bottom of the columns had a fiberglass window screen secured to contain the media.

Figure X.3 Lab column construction for infiltration tests (left to right): bottom of the columns secured with a fiberglass window screen (upper left), North Carolina bioretention media (lower left), and media compaction

Three levels of compaction were used to modify the density of the column's bioretention media during the test (Figure X.3): hand compaction, standard proctor compaction, and modified proctor compaction. Both standard and modified proctor compactions follow ASTM standard (D 1140-54). The standard proctor compaction hammer is 24.4 kN and has a drop height of 300 mm. The modified proctor hammer is 44.5 kN and has a drop height of 460 mm. For the standard proctor setup, the hammer is dropped on the test media 25 times on each of three media layers, while for the modified proctor test, the heavier hammer was also dropped 25 times, but on each of five thinner media layers. The modified proctor test therefore results in much more compacted media, and usually reflects the most compacted soil observed in the field. The hand compaction is done by gently hand pressing the media material to place it into the test columns with as little compaction as possible, but with no voids or channels. The hand compacted media specimens therefore have the least amount of compaction. The densities were directly determined by measuring the weights and volume of the media material added to each column.

The infiltration rates through the bioretention media were measured in each column using municipal tap water. The surface ponding depths in the columns ranged from 28 - 36 cm. The freeboard depth above the media to the top of the columns was about 50 - 75 mm. Infiltration rates in the bioretention media were determined by measuring the rates with time until apparent steady state rates were observed. The laboratory column setup for the infiltration measurements in the different media is shown in Figure X.4.

Figure X.4 Laboratory column setup for infiltration measurements.

X.3 Results and Discussions

X.3.1 Laboratory Infiltration Results Using Biofilter Media

Infiltration data for different test trials using bioretention media from North Carolina and Kansas City biofilter media were fitted to Horton's equation by using multiple nonlinear regressions to estimate f_c (the saturated soil infiltration rate) based on the observed data. The estimated infiltration rates of saturated North Carolina bioretention media ranged from 2.1 to 32.3 cm/h for the hand compaction tests and 4 to 5.6 cm/h for modified proctor compaction tests. The estimated infiltration rates of saturated soils ranged from 0.9 to 1.4 cm/h for the hand compaction tests and 0.1 to 0.9 cm/h for modified proctor compaction tests using Kansas City biofilter media. Horton's plots of the different test trials, comparing different compaction conditions using North Carolina and Kansas City media are shown in Figure X.5 and X.6 respectively.

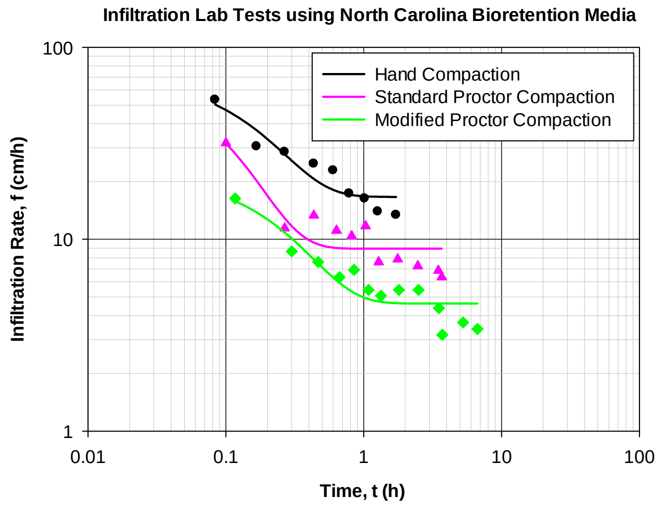

Figure X.5 Example of laboratory infiltration test results using North Carolina media

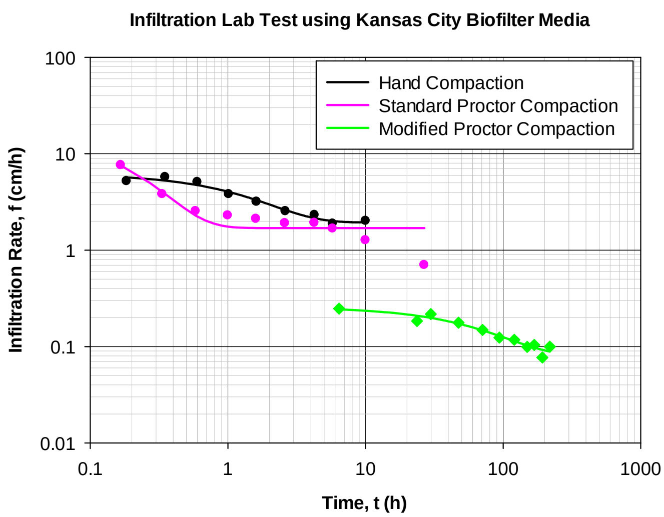

Figure X.6 Example of laboratory infiltration test results using Kansas City media

The saturated soil infiltration rates for hand, standard proctor and modified proctor compactions using North Carolina media are greater that the saturated soil infiltration rates through the Kansas City biofilter material for the three levels of compactions. Table X.1 summarizes the laboratory column infiltration test results and the biofilter material properties.

Table X.1 Laboratory column infiltration test results

	Hand compaction		Standard proctor compaction		Modified proctor compaction		
Bioretention media	F_c (cm/h and COV)	density (g/cm^3 and porosity)	F_c (cm/h and COV)	density (g/cm^3 and porosity)	F_c (cm/h and COV)	density (g/cm^3 and porosity)	D_{50} (mm and C_u)
Kansas City	1.40 (0.4)	1.0 (0.36)	1.61 (0.41)	1.13 (0.15)	0.34 (1.27)	1.12 (0.25)	1.9 (39)
North Carolina	18.8 (0.68)	1.24 (0.34)	10.2 (0.4)	1.34 (0.3)	5.1 (0.16)	1.36 (0.3)	0.7 (6)

X.3.2 Laboratory Infiltration Results Using Sand-peat Mixture

Infiltration data for different test trials using different sand-peat mixtures were fitted to the Horton equation by using multiple nonlinear regressions to estimate f_c (the saturated mixture infiltration rate) based on the observed data. The average infiltration rates of the saturated mixtures indicated that the infiltration rates through the mixtures increased with increases in the percentage of peat. Horton's plots of the different test trials are shown in Figures X.7 and X.8.

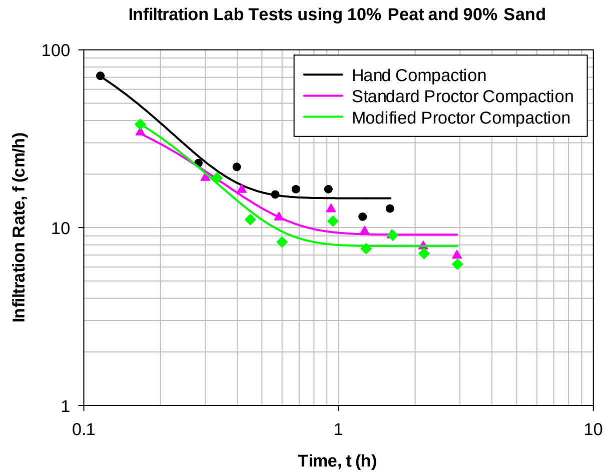

Figure X.7 Infiltration measurements for 10% peat and 90% sand

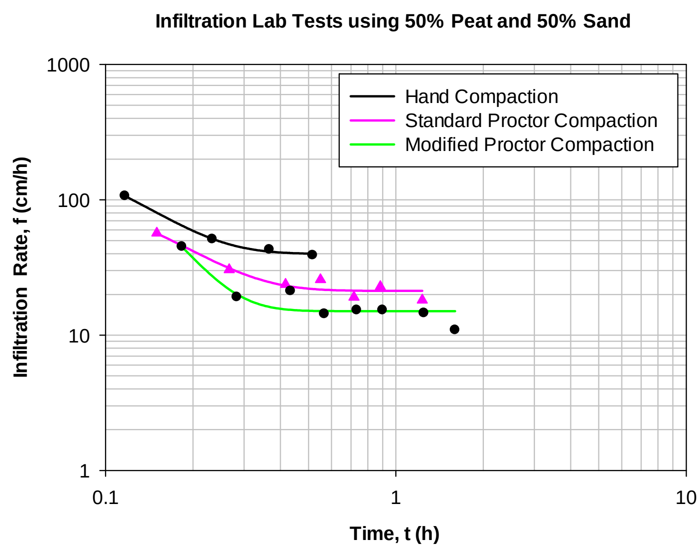

Figure X.8 Infiltration measurements for 50% peat and 50% sand

Figure X.9 shows the infiltration rates (cm/h) through the sand-peat mixtures. The rates appear to increase with increases in the percentage of peat. Compaction did not significantly affect the infiltration rates for the mixtures having large amounts of sand and little peat; however infiltration studies conducted previously indicated that compaction significantly affected typical soil infiltration rates having normal organic content, especially if high in fines (Sileshi et al., 2012a). Therefore, mixing the soil media with filter sand or peat improved the infiltration capacity of the media and also reduced the impact of compaction on the infiltration rates.

Four different sand media were used for the test series for full factorial tests and other analyses. Table X.2 shows the sand-peat mixtures used during the tests. Fifteen replicates are available for each test series. The median sizes of the sand-peat mixtures ranged from 300 to 1,875 μm and the uniformity coefficients ranged from 2 to 22.

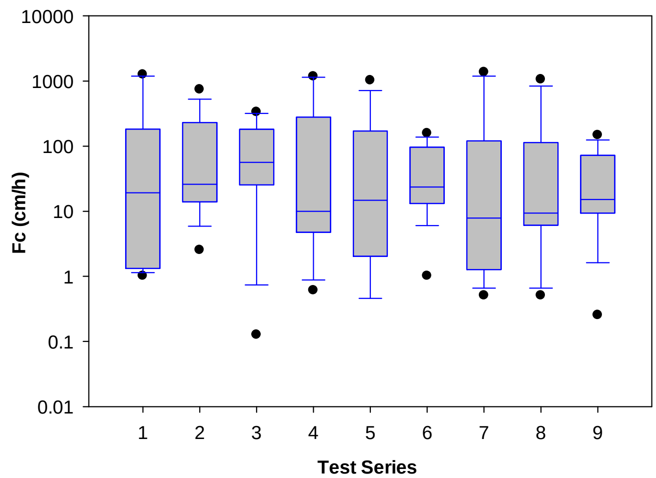

Figure X.9 Box and Whisker plots of the different test conditions, comparing different compaction conditions with varying amounts of peat amendments

Table X.2 Test mixture descriptions (fifteen replicates in each test series.

Data series	Mixture
1	10% peat and 90% sand with hand compaction
2	25% peat and 75% sand with hand compaction
3	50% peat and 50% sand with hand compaction
4	10% peat and 90% sand with standard proctor compaction
5	25% peat and 75% sand with standard proctor compaction

6	50% peat and 50% sand with standard proctor compaction
7	10% peat and 90% sand with modified proctor compaction
8	25% peat and 75% sand with modified proctor compaction
9	50% peat and 75% sand with modified proctor compaction

X.3.3 Statistical Analyses

Statistical analyses were conducted to determine the effects of texture, uniformity, amount of organic material, and compaction, plus their interactions, on the flowrate through the various mixtures of sand and peat to predict changes in flow, focusing on the media properties.

A complete two level and four factors (2^4, with varying texture, uniformity, organic content, and compaction) factorial experiment (Box et al. 1978) was conducted to examine the effects of those factors, plus their interactions, on the flowrate through the various sand-peat mixtures. The factors studied, and their low (-1) and high values (+1) used in the calculations, are shown in Table X.3. The complete data used in this factorial study is also summarized in Table X.4, showing the $\log_{10}$ transformed f_c rates for each experiment. Experiments were performed in replicates of 3 to 15 for each infiltration measurements. Statistical methods are used to summarize the data and to provide an efficient method to analyze factor interactions on the flowrate.

Table X.3 Laboratory column infiltration test results

Variable	Low value (-1)	High value (+1)
Median particle size of mixture (T), D_{50} (μm)	500	1000
Uniformity of the mixture (U)	4	6
Organic content of the mixture (O), %	10	25
Compaction level (C), hand/modified proctor	hand	modified proctor

The data analyses were performed using the statistical software package Minitab (version 16). Normal plots of the standardized effects, residual plots, main effects plots, and interaction plots were prepared to examine the effects of the factors and to compare the significance of each effect. An analysis of variance (ANOVA) table was constructed to determine the significant factors and their interactions needed to best predict media flow performance. Statistical hypothesis tests using a p-value of 0.05 (95% confidence) were used to determine whether the observed data were statistically significantly different from the null hypothesis.

Table X.4 Infiltration data used in Full 2^4 Factorial designs

Case	Texture (T)	Uniformity (U)	Organic (O)	Compaction (C)	Log (Fc) (cm/h)
1A	+	+	+	+	0.07
1B	+	+	+	+	0.40
1C	+	+	+	+	0.97
2A	+	+	+	-	1.60
2B	+	+	+	-	1.31
2C	+	+	+	-	0.33
3A	+	+	-	+	0.90
3B	+	+	-	+	0.71
3C	+	+	-	+	0.40
3D	+	+	-	+	-0.99
3E	+	+	-	+	-1.75
3F	+	+	-	+	-1.12
4A	+	+	-	-	1.17
4B	+	+	-	-	0.12
4C	+	+	-	-	0.09
4D	+	+	-	-	0.82
4E	+	+	-	-	0.91
4F	+	+	-	-	0.98
5A	+	-	+	+	2.17
5B	+	-	+	+	2.04
5C	+	-	+	+	1.86
6A	+	-	+	-	2.54
6B	+	-	+	-	2.57
6C	+	-	+	-	2.45
7A	+	-	-	+	3.10
7B	+	-	-	+	3.06
7C	+	-	-	+	2.78
8A	+	-	-	-	3.14
8B	+	-	-	-	2.81
8C	+	-	-	-	3.03
9A	-	+	+	+	1.03
9B	-	+	+	+	0.71
9C	-	+	+	+	0.68
10A	-	+	+	-	1.85
10B	-	+	+	-	1.44
10C	-	+	+	-	1.62
11A	-	+	-	+	0.55
11B	-	+	-	+	0.36
11C	-	+	-	+	0.40
11D	-	+	-	+	-0.69
11E	-	+	-	+	-0.90
11F	-	+	-	+	-1.12
11G	-	+	-	+	-0.76
11H	-	+	-	+	-0.68
11I	-	+	-	+	-1.03
11J	-	+	-	+	-0.71
11K	-	+	-	+	-1.16
11L	-	+	-	+	-1.29

Case	Texture (T)	Uniformity (U)	Organic (O)	Compaction (C)	Log (Fc) (cm/h)
11M	-	+	-	+	-0.06
11N	-	+	-	+	-0.08
11O	-	+	-	+	-0.52
12A	-	+	-	-	1.28
12B	-	+	-	-	1.08
12C	-	+	-	-	1.21
12D	-	+	-	-	0.84
12E	-	+	-	-	1.16
12F	-	+	-	-	0.78
12G	-	+	-	-	1.76
12H	-	+	-	-	1.47
12I	-	+	-	-	1.18
12J	-	+	-	-	0.58
12K	-	+	-	-	0.50
12L	-	+	-	-	0.42
12M	-	+	-	-	0.90
12N	-	+	-	-	0.91
12O	-	+	-	-	1.18
13A	-	-	+	+	1.06
13B	-	-	+	+	-0.60
13C	-	-	+	+	0.98
14A	-	-	+	-	1.86
14B	-	-	+	-	1.72
14C	-	-	+	-	-0.90
15A	-	-	-	+	1.01
15B	-	-	-	+	0.10
15C	-	-	-	+	0.71
16A	-	-	-	-	1.34
16B	-	-	-	-	0.10
16C	-	-	-	-	0.01

Normal probability plots of effects are used to compare the relative magnitudes and the statistical significance of both main and interaction effects. These plots also indicate the direction of the effect; in Figure X.10, the factors media texture and the interaction of uniformity and organic content of the material have positive effects because they appear on the right side of the plot, meaning that when the low level changes to the high level of the factor, the response increases. In Figure X.10, the interaction of texture and uniformity of the material; uniformity; compaction; and the interaction of uniformity and compaction appears on the left side of the plot, meaning that the factor has a negative effect. This indicates that when the low level changes to high, the response decreases.

Figure X.10 shows that media texture and the interaction of texture and uniformity have the highest effects on the measured infiltration rates followed by uniformity; interaction of uniformity and organic content; compaction; and interaction of uniformity and compaction. The results of the factorial analyses are summarized in Table X.5

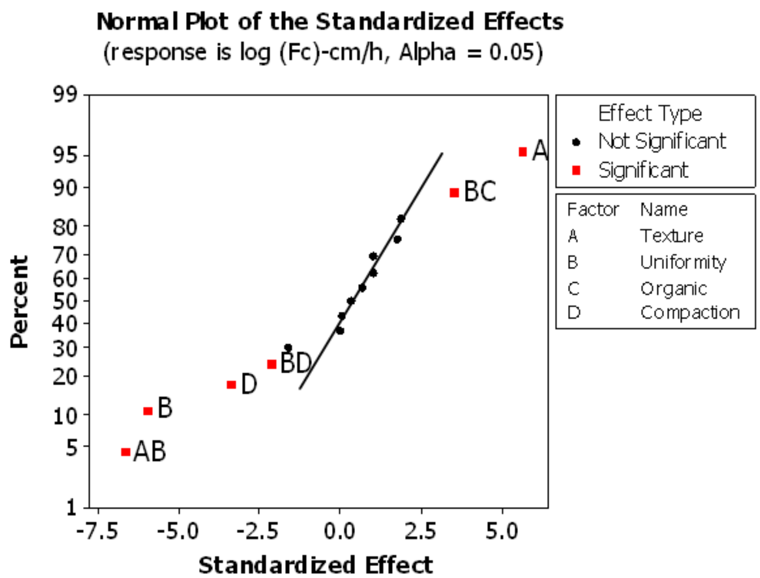

Figure X.10 Probability plot to identify important factors affecting the infiltration rate through a media mixture.

Table X.5 Estimated Effects and Coefficients for log (FC) -cm/hr (coded units).

Term	Effect	Effect/ Pooled SE		SE Coef	T	P
Constant			Coef	0.082	13.910	0.000
T	0.926	1.493	0.463	0.082	5.650	0.000
U	-0.966	-1.558	-0.483	0.082	-5.900	0.000
O	0.295	0.475	0.147	0.082	1.800	0.077
C	-0.547	-0.882	-0.273	0.082	-3.340	0.001
T*U	-1.085	-1.749	-0.542	0.082	-6.620	0.000
T*O	-0.261	-0.421	-0.131	0.082	-1.590	0.116
T*C	0.116	0.186	0.058	0.082	0.700	0.483
U*O	0.580	0.936	0.290	0.082	3.540	0.001
U*C	-0.347	-0.559	-0.173	0.082	-2.120	0.038
O*C	0.056	0.090	0.028	0.082	0.340	0.736
T*U*O	0.169	0.272	0.084	0.082	1.030	0.307
T*U*C	0.169	0.273	0.085	0.082	1.030	0.306
T*O*C	0.014	0.022	0.007	0.082	0.090	0.932
U*O*C	0.310	0.499	0.155	0.082	1.890	0.064

T*U*O*C	0.001	0.001	0.001	0.082	0.010	0.995

S = 0.620238 PRESS = 40.1298 Pooled SE = 0.62
R-Sq = 76.82% R-Sq(pred) = 61.00% R-Sq(adj) = 71.21%

T: texture, U: uniformity, O: organic content, and C: compaction.

According to Table X.5, the significant factors and interactions that affect the long-term infiltration rates are texture, uniformity of the mixture, and compaction, interactions of texture and uniformity, interactions of uniformity and organic content of the material, and interactions of uniformity and compaction. Texture and uniformity had the greatest effects, but all those listed above were significant. Table X.6 indicates that 3- way and 4- way interactions of the factors have no effect on the infiltration rates through the media.

Table X.6 Analysis of Variance for log (FC) -cm/hr (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	4	49.287	35.397	8.849	23.000	0.000
2-Way Interactions	6	27.430	23.233	3.872	10.070	0.000
3-Way Interactions	4	2.333	2.280	0.570	1.480	0.219
4-Way Interactions	1	0.000	0.000	0.000	0.000	0.995
Residual Error	62	23.851	23.851	0.385		
Pure Error	62	23.851	23.851	0.385		
Total	77	102.902				

Table X.6 Analysis of Variance for log (FC) -cm/hr (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	p
Main Effects	4	49.287	35.3973	8.8493	23	0.000
T	1	13.483	12.2785	12.2785	31.920	0.000
U	1	18.991	13.3735	13.3735	34.760	0.000
O	1	1.612	1.2439	1.2439	3.230	0.077
C	1	15.203	4.2854	4.285	11.140	0.001
2-Way Interactions	6	27.43	23.233	3.872	10.070	0.000
T*U	1	16.634	16.8568	16.856	43.820	0.000
T*O	1	1.002	0.9763	0.976	2.540	0.116
T*C	1	1.409	0.1912	0.191	0.500	0.483
U*O	1	4.711	4.8266	4.827	12.550	0.001
U*C	1	3.408	1.7237	1.724	4.480	0.038
O*C	1	0.267	0.0442	0.044	0.120	0.736
3-Way Interactions	4	2.333	2.2803	0.570	1.480	0.219
T*U*O	1	0.408	0.4077	0.408	1.060	0.307
T*U*C	1	0.55	0.4096	0.409	1.060	0.306
T*O*C	1	0.000	0.0028	0.003	0.010	0.932
U*O*C	1	1.375	1.373	1.373	3.570	0.064

4-Way Interactions	1	0.000	0.000	0.000	0.000	0.995
T*U*O*C	1	0.000	0.000	0.000	0.000	0.995
Residual Error	62	23.851	23.8511	0.3847		
Pure Error	62	23.851	23.8511	0.3847		
Total	77	102.902				

The main effects plots are useful to compare magnitudes of main effects. The main effect plots are obtained to examine the data means for the four factors. Figure X.11 shows increases in infiltration rates occurred with increases in media texture and organic content, whereas infiltration rates decreased with increasing uniformity and compaction of the mixture.

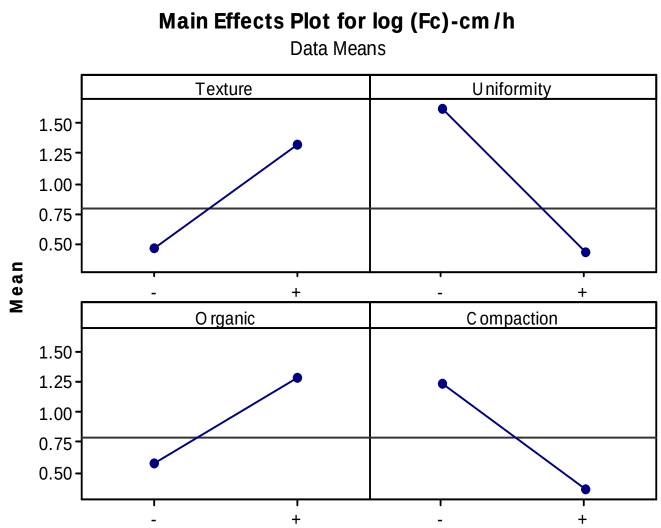

Figure X.11 Main effects plot for the four factors

Figure X.12 depicts interaction plots which are used to interpret significant interactions between the factors. In the interaction plot, the lines in texture vs. uniformity, uniformity vs. organic content cross each other, indicating there exists an interaction between these factors. Figure X.12 also shows texture vs. organic content, and texture vs. compaction, are approximately parallel, indicating a lack of interaction between the two factors. These interaction plots suggest that mutual interaction between these factors have negligible effect on the infiltration rates. The greater the departure of the lines from the parallel state, the higher the degree of interaction.

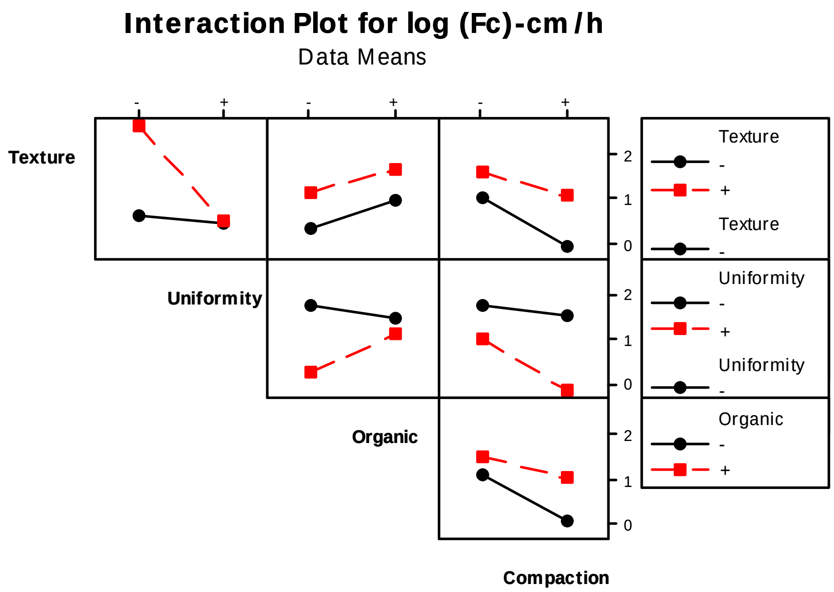

Figure X.12 Interaction plot between different factors

X.3.4 Model Fitting

The effects and half-effects of the significant effects (main effects and interactions) were used to predict the flowrate performance of various mixtures. Table X.7 shows the matrix (table of contrasts) representing factors (texture, uniformity, organic content, and compaction) and their interactions. The results of the effects and half-effect are also shown in the table.

Table X.7 shows the results of the effects and half-effects.

Main Effects	Two interactions

Case	T	U	O	C	TU	TO	TC	UO	UC	OC
1	+	+	+	+	+	+	+	+	+	+
2	+	+	+	-	+	+	-	+	-	-
3	+	+	-	+	+	-	+	-	+	-
4	+	+	-	-	+	-	-	-	-	+
5	+	-	+	+	-	+	+	-	-	+
6	+	-	+	-	-	+	-	-	+	-
7	+	-	-	+	-	-	+	+	-	-
8	+	-	-	-	-	-	-	+	+	+
9	-	+	+	+	-	-	-	+	+	+
10	-	+	+	-	-	-	+	+	-	-
11	-	+	-	+	-	+	-	-	+	-
12	-	+	-	-	-	+	+	-	-	+
13	-	-	+	+	+	-	-	-	-	+
14	-	-	+	-	+	-	+	-	+	-
15	-	-	-	+	+	+	-	+	-	-
16	-	-	-	-	+	+	+	+	+	+

	T	**U**	**O**	**C**	**TU**	**TO**	**TC**	**UO**	**UC**	**OC**
Avg Y @ -1	0.68	1.62	0.99	1.41	1.68	1.3	1.08	0.9	1.3	1.1
Avg Y @ +1	1.6	0.66	1.29	0.87	0.6	1.0	1.2	1.4	0.97	1.2
Δ	0.93	-0.97	0.29	-0.55	-1.08	-0.26	0.12	0.6	-0.35	0.06
Δ/2	0.46	-0.48	0.15	-0.27	-0.54	-0.13	0.06	0.29	-0.17	0.03

T: texture, U: uniformity, O: organic content, and C: compaction.

Table X.6 shows the results of the effects and half-effects.

	Three and four interactions					log (Fc) (cm/h)
Case	TUO	TUC	TOC	UOC	TUOC	
1	+	+	+	+	+	0.85
2	+	-	-	-	-	1.08
3	-	+	-	-	-	-0.31
4	-	-	+	+	+	0.68
5	-	-	+	-	-	2.02
6	-	+	-	+	+	2.52
7	+	-	-	+	+	2.98
8	+	+	+	-	-	2.99
9	-	-	-	+	-	0.81
10	-	+	+	-	+	1.63
11	+	-	+	-	+	-0.51
12	+	+	-	+	-	1.02
13	+	+	-	-	+	0.48

14	+	-	+	+	-	0.90
15	-	+	+	+	-	0.61
16	-	-	-	-	+	0.49
					Y (grand)	**1.14**
	TUO	**TUC**	**TOC**	**UOC**	**TUOC**	
Avg Y @ -1	1.06	1.05	1.13	0.98	1.14	
Avg Y @ +1	1.22	1.22	1.15	1.29	1.14	
Δ	0.17	0.17	0.014	0.31	0.001	
Δ/2	0.08	0.08	0.01	0.15	0.00	

T: texture, U: uniformity, O: organic content, and C: compaction

As noted previously, the significant factors and interactions that affect the responses are texture, uniformity, compaction, interactions of texture and uniformity, interactions of uniformity and organic content of the material, and interactions of uniformity and compaction. Those factors and interactions have to be included in the prediction equation. The parameters organic content, interactions of texture and organic content, interactions of texture and compaction, interactions of organic content and compaction, and all the three-way and four-way interactions of these factors, have negligible effect (p-values greater than the chosen value of $\alpha = 0.05$) on the flowrate and a reduced model was created wherein these factors are ignored.

The prediction equation can be written in terms of the grand mean and half-effects, excluding the non-significant factors.

$$\hat{y} = \bar{\bar{y}} + \left(\frac{\Delta_T}{2}\right)T + \left(\frac{\Delta_U}{2}\right)U + \left(\frac{\Delta_C}{2}\right)C + \left(\frac{\Delta_{TU}}{2}\right)TU + \left(\frac{\Delta_{UO}}{2}\right)UO + \left(\frac{\Delta_{UC}}{2}\right)UC \quad (X.1)$$

where:

$\hat{y}$ = predicted response (Y pred)
$\bar{\bar{y}}$ = grand mean (Y grand)
$\frac{\Delta}{2}$ = half-effects of each factor or interaction
T = texture
U = uniformity of the mixture
C = compaction
O = organic content of the material

The fial prediction equation is given as:

$$\widehat{\log(y)} = 1.14 + 0.46T - 0.48U - 0.27C - 0.54TU + 0.29UO - 0.17UC$$

An ANOVA test was used to test the significance of the regression coefficients, which highly depends on the number of data observations. When only few data observations are available, strong and important relationships may not be shown to be significant, or high R^2 values could occur with insignificant equation coefficients. The data was evaluated by using the p-value (the probability of obtaining a test statistic that is at least as extreme as the calculated value if there is actually no difference; the null hypothesis is true). The independent variable was used to predict the dependent variable when $p < 0.05$. A summary of statistical information about the model is also shown in Table X.5. R^2 is a statistical measure of goodness of fit of a model whereas adjusted R^2 is a statistic that is adjusted for the number of explanatory terms in a model. The value of R^2 and adjusted R^2 for the model are 76.8% and 71.2% respectively. Predicted R^2 is calculated from the PRESS (Prediction Error Sum of Squares) statistic. The predicted R^2 statistic is computed to be 61.0%. Larger values of predicted R^2 suggest models of greater predictive ability. This indicates that the model is expected to explain about 61.0% of the variability in new data. Figure X.13 shows a scatterplot of the observed and fitted log (Fc) values, indicating very good fits of the observed with the predicted log F_c values over a wide range of conditions.

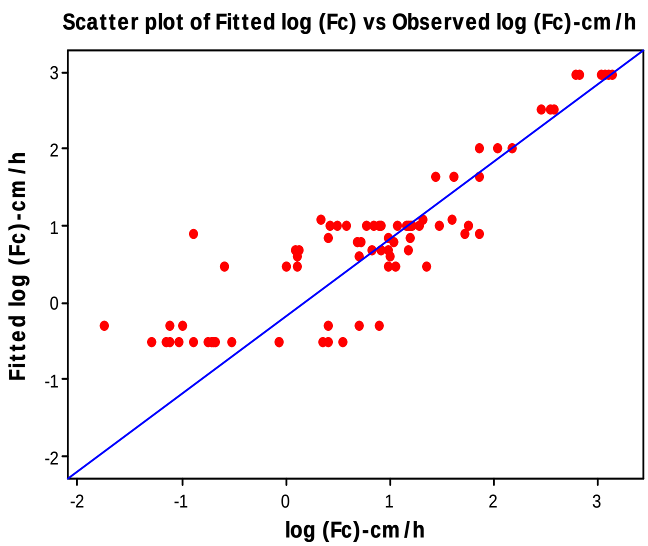

Figure X.13 Observed vs fitted log (Fc) values.

Residual analyses were conducted to investigate the goodness of model fit. Residual plots were inspected to determine if the error term in the regression model satisfies the four assumptions (they must be independent, zero mean, constant variance, and normally distributed). To check the constant variance assumptions, the plots of residuals vs. the fitted values were inspected. To evaluate the normality of the residuals, normal probability plots and histograms of the residuals were also constructed. Anderson-Darling test statistic was also calculated to check for normality. The normal probability plot of the residuals shown in Figure X.14 shows that the fitted data is normally distributed (Anderson-Darling test for normality has a p-value greater than 0.05, so the data are not significantly different from a normal distribution for the number of observations available). The zero mean of the residuals assumption was checked by examining the descriptive statistics and graphs of the residuals vs. fitted values and vs. the order of the observations. To determine if the residuals were independent of each other, graphs of the residuals vs. observation number were also examined.

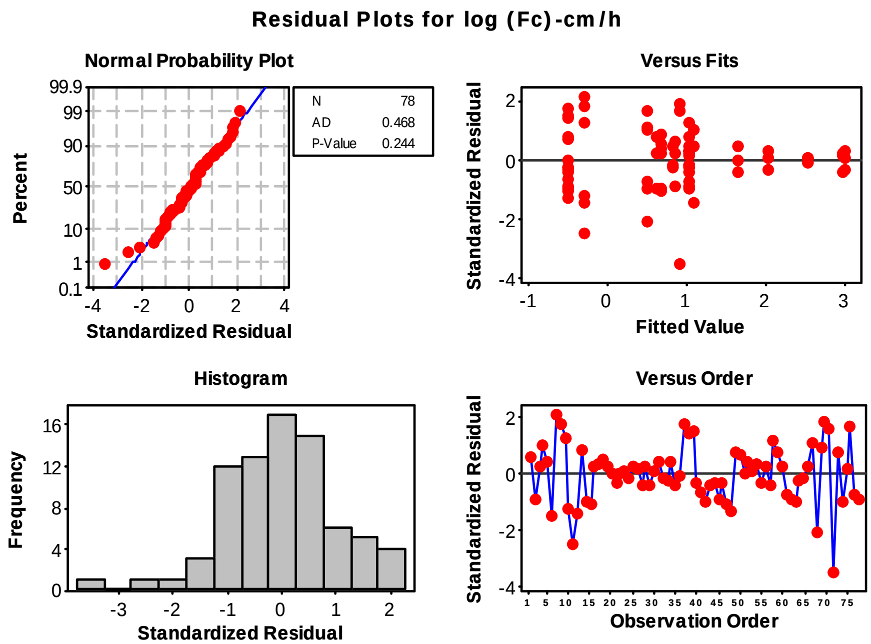

Figure X.14 Residuals analysis plot.

The examination of the residual values vs. fitted values of the data indicated that there was a greater spread in the residuals for the lower fitted values. The model residual histogram was approximately bell shaped; the residuals were normally distributed and had zero mean, and was independent of each other. Model improvements should therefore focus on conditions that had low infiltration conditions.

11.3 Conclusions

The laboratory compaction tests indicated that median particle size and media particle uniformity have the most significant effects on the infiltration rates; while the amounts of organic material had a smaller effect. Compaction did not significantly affect the infiltration rates for the media having large amounts of sand and few fines (silts and clays); compaction significantly affected typical soil infiltration rates, however, especially for material having large amounts clay.

The test results also indicated that the infiltration rates through all sand-peat mixtures columns were greater than the infiltration rates through only soil media for the three levels of compaction (modified proctor, standard proctor and hand compaction), however mixing the soil media with filter sand or peat improved the infiltration capacity of the media and also reduced the impact of compaction on the infiltration rates. Soil compaction has dramatic effects on the infiltration rates of most underlying soils; therefore care needs to be taken during stormwater treatment facilities construction in urban areas to reduce detrimental compaction effects.

The results of the four factor factorial analysis indicated that media texture and the interaction of texture and uniformity of the media mixture have the highest effect on the measured infiltration rate followed by uniformity; interaction of uniformity and organic content; compaction; and interaction of uniformity and compaction. The organic matter in the biofilter media does not have a significant effect on the infiltration rate compared to the other factors (texture, uniformity, and compaction). However the organic matter serves as a reservoir of nutrients and water in the biofilter media, aids in reducing compaction and increases water infiltration into the media.

References

Box, G.E.P., W.G. Hunter, and J.S. Hunter. Statistics for Experimenters. John Wiley and Sons. New York. 1978.

Clark, S.E., Baker, K.H., Mikula, J.B., Burkhardt, C.S., and Lalor, M.M. 2006. Infiltration vs. surface water discharge: Guidance for stormwater managers. Water Environment Research Foundation. Project No.03-SW-4. 220 pages.

Free, G. R., Browning, G. M., and Musgrave, G. W. 1940. Relative infiltration and related physical characteristics of certain soils. United State Department of Agriculture, Washington, D.C. Technical Bulletin No. 729.

Gregory, J. H., Dukes, M. D., Jones, P. H., and Miller, G. L. 2006. Effect of urban soil compaction on infiltration rate. J. Soil Water Conserv., 61(3), 117-123.

Pitt, R., S. Clark, and R. Field. 1999a. Groundwater Contamination Potential from Stormwater Infiltration Practices. Urban Water, 1(3), 217-236.

Pitt, R., J. Lantrip, R. Harrison, C. Henry, and D. Hue. 1999b. Infiltration through Disturbed Urban Soils and Compost-Amended Soil Effects on Runoff Quality and Quantity. EPA 600-R-00-016. U.S. Environmental Protection Agency. National Risk Management Research Laboratory. Office of Research and Development. Cincinnati, OH: 231 pp.

Pitt, R., Chen, S.-E., Clark, S.E. 2002. Compacted Urban Soils Effects on Infiltration and Bioretention Stormwater Control Designs. Proc., 9th Int. Conf. on Urban Drainage (9ICUD). Portland, Oregon.

Pitt, R., Chen, S-E., Clark, S., Swenson, J., and Ong, C.K. 2008. Compaction's Impacts on Urban Storm-Water Infiltration. J. Irrig. and Drain. Engrg., 134(5), 652-658.

Sileshi, R., R. Pitt, S. Clark, and C. Christian (2012a). Laboratory and Field Studies of Soil Characteristics of Proposed Stormwater Bioinfiltration Sites, Water Environment Federation (WEF) Stormwater Symposium 2012. July 18-20, 2012. Baltimore, Maryland.

Sileshi, R., Pitt, R., and Clark, S. (2012b) Assessing the Impact of Soil Media Characteristics on Stormwater Bioinfiltration Device Performance: Lab and Field Studies, ASCE/EWRI, Proceedings of the 2012. World Environmental and Water Resources Congress, May 2012, 3505-3516

Thompson, A.M., A.C. Paul, and N.J. Balster. 2008. Physical and Hydraulic Properties of Engineered Soil Media for Bioretention Basins. Transactions of the American Society of Agricultural Engineers, 51(2), 499-514.

United States Environmental Protection Agency (US EPA). 1997. Innovative Uses of Compost: Erosion Control, Turf Remediation, and Landscaping. US EPA Fact Sheet EPA 530-F-97-043.