Infiltration Through Disturbed Urban Soils

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Abstract

This research examined a common, but poorly understood, problem associated with land development, namely the modifications made to soil structure and the associated reduced rainfall infiltration and increased runoff. More than 150 infiltration tests were conducted in disturbed urban soils and the data was compared with the site conditions. A complete factorial experiment fully examined the effects, and interactions, of soil texture, soil moisture, and compaction. Age since development was also briefly examined. The major finding was that compaction had dramatic effects on infiltration rates through sandy soils, while compaction was generally just as important as soil moisture at sites with predominately clay rich soils. Moisture levels had little effect on infiltration rates at sandy sites. Because of the large amounts of variability in the infiltration rates found, it is important that engineers obtain local data to estimate the infiltration rates associated with local development practices.

Introduction

Unpublished double-ring infiltration tests conducted by the Wisconsin Department of Natural Resources (DNR) in Oconomowoc, Wisconsin, indicated highly variable infiltration rates for soils that were generally sandy (Natural Resources Conservation Service (NRCS) A/B hydrologic group soils) and dry. The median initial rate was about 75 mm/hr (3 in/hr), but ranged from 0 to 640 mm/hr (0 to 25 in/hr). The final rates also had a median value of about 75 mm/hr (3 in/hr) after at least 2 hr of testing, but ranged from 0 to 380 mm/hr (0 to 15 in/hr). Many infiltration rates actually increased with time during these tests. In about 1/3 of the cases, the infiltration rates remained very close to zero, even for these sandy soils. Areas that experienced substantial disturbances or traffic (e.g., school playing fields), and siltation (e.g. some grass swales) had the lowest infiltration rates.

This paper attempts to explain much of the variation observed in earlier infiltration tests of disturbed urban soils. During recent tests conducted in the Birmingham, Alabama area, 153 double-ring infiltration tests were conducted. These tests were separated into eight categories of soil conditions (comprising a full factorial experiment). Factors typically considered to cause infiltration rate variations are texture and moisture. These tests examined texture and moisture, plus soil compaction. It was also hoped that age since disturbance and cover condition could be used to explain some of the variation, but these conditions were unevenly represented at the test sites and complete statistical examinations of these additional factors could not be performed.

Infiltration Mechanisms

Rainfall losses on pervious surfaces are controlled by three mechanisms, the initial entry of the water through the soil/plant surface (infiltration), followed by movement of the water laterally (interflow) or vertically (percolation) through the vadose (unsaturated) zone, and finally, the rate of depletion of the soil water storage capacity. Infiltration is the least of these three rates, and the surface runoff rate is assumed to be the excess of the rainfall intensity greater than the infiltration rate. Infiltration rates typically decrease during the rain. Storage capacity is recovered when the movement of the water through the soil is faster than the interflow or percolation rate, which usually takes place after the rainfall has ended.

The surface entry rate of water may be affected by the presence of a thin layer of silt and clay particles at the surface of the soil and vegetation. These particles may cause a surface seal that would decrease a normally high infiltration rate. The movement of water through the soil depends on the characteristics of the underlying soil. Water cannot enter soil faster than it is being transmitted away, so interflow or percolation rates affect the infiltration rate. The depletion of available storage capacity in the soil also affects the infiltration rate. The storage capacity depends on thickness, moisture content, and porosity of the soil. Many factors, i.e., texture, root development, structure, and presence of organic matter, affect the porosity of soil.

The infiltration of water into the surface soil is responsible for the largest abstraction (loss) of rainwater in natural areas. The infiltration rate of most soils allows low intensity rainfall to totally infiltrate, unless the soil voids become saturated or the underlying soil is much more compact than the top layer (Morel-Seytoux 1978). High intensity rainfalls generate substantial runoff because the infiltration rate of the upper soil layer is surpassed, even though the underlying soil might be very dry.

The classical assumption is that the soil's infiltration rate is highest at the beginning of a storm and decreases with time (Willeke 1966). The moisture content of the soil, whether it was initially dry or still wet from a recent storm, has a great effect on the infiltration rate of certain soils (Morel-Seytoux 1978). Horton (1939) is credited with defining infiltration rate and deriving an appropriate working equation which is still the most widely used infiltration equation. Horton defined infiltration as "...the maximum rate at which water can enter the soil at a particular point under a given set of conditions" (Morel-Seytoux 1978).

This study used the Horton equation to compare the measured equation parameters with published literature values. The equation is as follows:

$f = f_c + (f_o - f_c)e^{-kt}$ where:

f= infiltration rate (in/hr),
f_o = initial infiltration rate (in/hr),
f_c = final infiltration rate (in/hr),
k = empirical constant (hr^{-1})

The Horton equation assumes rainfall intensity is greater than the infiltration rate at all times and that infiltration decreases with time. The storage capacity of the soil decreases as the length of the storm increases because the pores in the soil become saturated with water and no longer allows water to continuously infiltrate through the surface (Bedient and Huber 1992). A major drawback of the Horton equation is that it does not consider storage capacity in the soil after varying amounts of infiltration have occurred, but only considers infiltration as a function of time (Akan 1993).

The parameters f_c, f_o, and k should be obtained through field test, but are rarely measured locally. More commonly, they are determined through calibration of relatively complex stormwater drainage models, or by using published values (Table 1). The use of published values in place of reliable field data is the cause of much concern (Akan 1993).

Table 1. Commonly used Horton infiltration parameters

Soil Type	f_o mm/hr	(in/hr)
Dry sandy soils with little to no vegetation	130	(5)
Dry loam soils with little to no vegetation	80	(3)
Dry clay soils with little to no vegetation	30	(1)
Dry sandy soils with dense vegetation	250	(10)
Dry loam soils with dense vegetation	150	(6)
Dry clay soils with dense vegetation	50	(2)
Moist sandy soils with little to no vegetation	44	(1.7)
Moist loam soils with little to no vegetation	30	(1)
Moist clay soils with little to no vegetation	8	(0.3)
Moist sandy soils with dense vegetation	84	(3.3)
Moist loam soils with dense vegetation	50	(2)
Moist clay soils with dense vegetation	20	(0.7)

Soil Type	f_c mm/hr	(in/hr)	k (min^{-1})
Clay loam, silty clay loams	0—1.3	(0—0.05)	0.069
Sandy clay loam	1.3—3.8	(0.05—0.15)	0.069
Silt loam, loam	3.8—7.6	(0.15—0.30)	0.069
Sand, loamy sand, sandy loams	7.6—11.4	(0.30—0.45)	0.069

Source: Akan 1993.

The above k values are not divided into categories, with only a single value used for all conditions (Akan 1993). The units of the k value are listed as min^{-1} instead of hr^{-1} because the time steps commonly used in urban hydrology are measured in minutes, while the infiltration rates are commonly measured in units of mm/hr or in/hr. These values will be compared to the measured values obtained during this study by calibrating the Horton equation.

Methods

Sampling and Test Site Descriptions

Birmingham, Alabama, the location of many of the test sites for disturbed urban soils, receives about 1400 mm (54 in.) of rain and about 110 separate rain events per year. Typical antecedent dry periods range from about 2 to 5 days and it is unusual to go more than 10 days without recorded rainfall. The driest months are October and November, averaging 66 and 91 mm (2.6 and 3.6 in.), respectively, while March is the wettest month averaging 160 mm (6.3 in.) of rainfall. The growing season (> 28° F) is at least 243 days per year in 5 out of 10 years. Average daily maximum temperatures are about 90° F from June through August and about 55° F from December through February. Average daily minimum temperatures are about 65 to 70° F in the summer and about 34° F in the winter. Many of the sandy soil tests were located near Mobile, Alabama, where the rainfall is about 250 mm (10 in.) more than in Birmingham, and the summers are hotter and more humid. Table 2 briefly describes the test locations and site conditions.

Measurement of Site Parameters

A series of 153 double-ring infiltrometer tests were conducted in disturbed urban soils in the Birmingham, and Mobile, Alabama, areas. The tests were organized in a complete 2^3 factorial design (Box, *et al*. 1978) to examine the effects of soil moisture, soil texture, and soil compaction on water infiltration through historically disturbed urban soils. Ten sites were selected representing a variety of desired conditions (compaction and texture). Soil moisture and texture were determined by standard laboratory soil analyses. Compaction was measured in the field using a cone penetrometer and confirmed by the site history. Moisture levels were increased using long-duration surface irrigation before most of the saturated soil tests. From 12 to 27 replicates were conducted in each of the eight experimental categories in order to measure the variations within each category for comparison to the variation between the categories.

Table 2. Infiltration test site locations and conditions

Site #	Location	Land Use	Age (years)	Texture	Compaction (psi)
1a	Homewood Park	Recreational	>40	Clayey	100-200
1b					>300
2a	Chadwich, Helena	Medium density residential	<1	Clayey	150
2b				Clayey	>300
3a	South Lakeshore Drive	Commercial	>25	Sandy	>300
3b				Sandy	225
3c				Clayey	280
4a	Private Residence Backyard (West Jefferson)	Low density residential	>30	Clayey	200
4b				Clayey	>300
4c				Sandy	200-250
5a	Private Residence Backyard (Trussville)	Medium density residential	>30	Clayey	150-200
5b				Sandy	>300
6	Littlefield Farms	Agricultural	>10	Sandy	>300
7a	Wildwood Apartment Complex (Homewood)	High density residential	<1	Clayey	>300
7b					<150
8	Private Residence Backyard (Birmingham)	Medium density residential	>30	Clayey	>300
9a	Jasper Golf Course (Walker County)	Recreational	<5	Sandy	150-175
9b			<5	Sandy	>300
9c			>10	Sandy	100
10	Private Residence Backyard (Gulf Shores)	Medium density residential	>20	Sandy	100

A relationship between soil infiltration rates and the time since the soil was disturbed by construction or grading operations (turf age) was anticipated. In most new developments, compact soils with reduced infiltration compared to pre-construction conditions are expected. In older areas, the soil may have recovered its infiltration rate due to root development and soil insects or other digging animals. Soils with a variety of times since development, ranging from current developments to about 50 years old, were included in the sampling program. However, these sites were poorly distributed in their representation of the other primary test conditions and the effects of time since development could not be statistically validated.

Infiltration Rate Measurements. TURF-TEC Infiltrometers were used to measure the soil infiltration rates. These small devices have an inner ring about 64 mm (2.5 in.) in diameter and an outer ring of about 110 mm (4.25 in.). The water depth in the inner compartment starts at 125 mm (5 in.) at the beginning of the test, and the device is pushed into the ground 50 mm (2 in.). The rings are secured in a frame with a float in the inner chamber and a pointer next to a stop watch. These units are smaller than standard double-ring infiltrometers, but their ease of use allowed many tests under a variety of conditions. The use of three infiltrometers placed within one meter of each other enabled better determination of site variability than if only one larger unit was used.

The inner and outer compartments of the infiltrometer were filled with clean water by first filling the inner compartment and allowing it to overflow into the outer compartment. When the measuring pointer reached the beginning of the scale, the timer was started. Readings were taken every 5 min for 2 hr. The two hour test replicated the typical rain duration and the expected time needed to reach saturation. Instantaneous infiltration rates were calculated by noting the drop of water level in the inner compartment over the five-minute time period.

Soil Moisture Measurements. The weather during the testing enabled most site locations to produce paired sets of dry and wet tests. Moisture values are highly dependent on soil texture and were mostly determined by the length of antecedent dry period before the test. Dry tests tok place during periods of little or no rain, which typically extended as long as two weeks. Saturated tests were conducted through artificial soaking of the ground or after prolonged rain.

Soil moisture was measured in the field using a portable moisture meter (for some tests) and in the laboratory using standard soil moisture methods (for all tests). The moisture content is the percent of the weight of water to the weight of solids in a given volume of soil. Soil moisture was determined in the laboratory using the ASTM D 2974-87 method, by weighing the soil sample with its natural moisture content and recording the mass. The sample was then oven dried and its dry weight recorded. For typical sandy and clayey soils at the test areas, the dry soils had moisture contents ranging from 5 to 20% (averaging 13%) water, while wet soils had moisture contents ranging from 20 to 40% (averaging 27%) water.

Soil Texture Measurements. The texture of the samples was determined by ASTM standard sieve analyses to verify the soil texture estimated in the field and for comparison to the NRCS soil maps. The sieve analysis used was the ASTM D 422-63 *Standard Test Method For Particle Size Analysis of Soils* for the particles larger than the No. 200 sieve (75 ℓm +/- 5 ℓm), along with ASTM D 2488-93 *Standard Practice for Description and Identification of Soils (Visual - Manual Procedure).* The sample was prepared based on ASTM 421 *Practice for Dry Preparation of Soil Samples for Particle Size Analysis and Determination of Soil Constants.* The designation for the sand or clay categories follows the *Unified Soil Classification System*, ASTM D 2487. Sandy soils required that more than half of the material be larger than the No. 200 sieve, and more than half of that fraction be smaller than the No. 4 sieve (4.75 mm +/- 0.15mm). Similarly, for clayey soils, more than half of the material is required to be smaller than the No. 200 sieve.

Soil Compaction Measurements. Before infiltration testing, the compaction of the test areas was measured by pushing a DlCKEYjohn Soil Compaction Tester Pentrometer (cone pentrometer) into the ground and recording the readings from the gauge. Compact soils were defined as a reading of greater than 300 psi at a depth of 80 mm (3 in.), while noncompacted soils had readings of less than 300 psi. Compaction was confirmed based on historical use of the test site location (especially the presence of parked vehicles, unpaved lanes, well-used walkways, etc.). Because the cone pentrometer measurements were sensitive to moisture, measurements were not made for saturated conditions and the degree of soil compaction was also determined based on the history of the specific site. Other factors that were beyond the control of the experiments, but also affected infiltration rates, included bioturbation by ants, gophers and other small burrowing animals, worms, and plant roots.

Results of Infiltration Tests in Disturbed Urban Soils

As an initial analysis, three-D plots (Figures 1 and 2) of the infiltration data were prepared for the compaction and moisture factors for each major soil texture (sandy and clayey) in order to observe major trends. Four general categories were observed to be unique:

- Noncompacted-sandy soils
- Compacted-sandy soils
- Dry-noncompacted-clayey soils
- All other clayey soils (compacted and dry, plus all saturated conditions)

These analyses show that compaction had the greatest effect on infiltration rates in sandy soils, with little effects associated with soil moisture. Compaction and moisture affected clayey soils. Compaction had about the same effect as moisture on clayey soils, with saturated-compacted-clayey soils having the lowest infiltration rate.

Calculated Infiltration Rates and Fitted Models

Fitting Observed Data to the Horton Infiltration Equation. Data from each site test was fitted to the Horton infiltration equation and the equation coefficients were statistically analyzed using factorial analysis procedures. Table 3 summarizes the observed Horton equation parameter values, compared to the typical published parameter values, for sandy and clayey soils and for the four general categories, as found in the three dimensional plots of Figure 1 and 2.

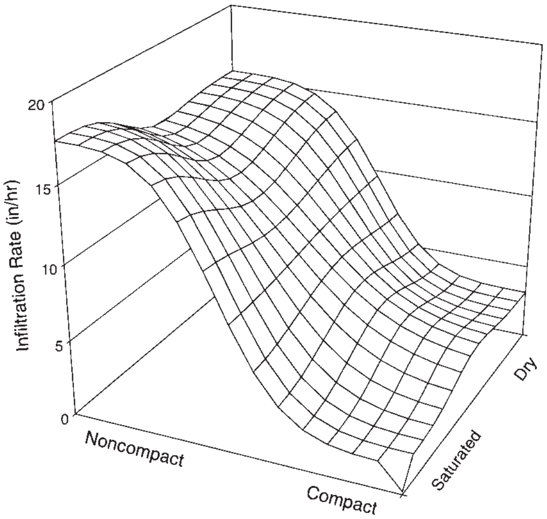

Figure 1. Three dimensional plot of infiltration rates for sandy soils.

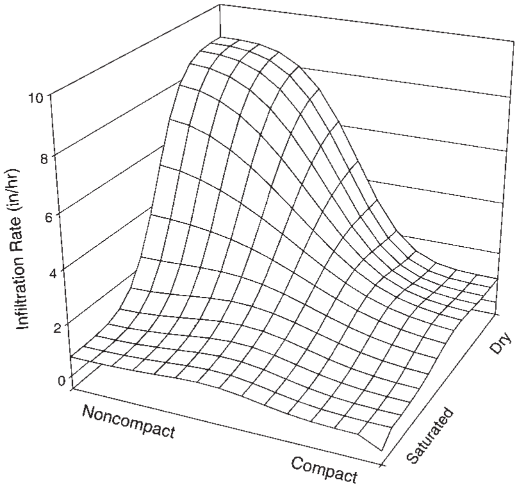

Figure 2. Three dimensional plot of infiltration rates for clayey soils.

Noncompacted sand was the urban soil category with the greatest infiltration potential. In addition, this was the only one of the four major categories that had an obvious decrease in infiltration with time during the tests. The observed infiltration rates occurred in a relatively even, but broad, band. Three of the 36 tests had very low initial rates, but were within the typical band of observations after about 10 min. Some initial wetting, or destruction of a surface crust, was apparently necessary before the site infiltration rate stabilized in these sites.

Observed infiltration rates differed greatly from published values. Typically, published values reflected moisture effects to the Horton infiltration equation and the equation coefficients, while the observations indicated very small effects associated with moisture for sandy soils, and very large effects associated with compaction. The constant-final-infiltration rates were larger than published values, with infiltration rates for noncompacted, sandy soils of about 350 mm/hr (14 in/hr), ranging from about 125 to 635 mm/hr (5 to 25 in/hr) during the tests. The comparable published rates were less than 25 mm/hr (1 in/hr). The infiltration rates leveled-off to the constant-final values after about 30 to 45 min.

Observed infiltration rates for compacted-sandy soils were significantly less than for non-compacted-sandy soils, reducing the infiltration rates between 5 and 10 times. Some initial rates were very large, but decreased quickly with time. After 20 to 30 min, all were within 0 to 500 mm/hr (0 to 20 in/hr), with most of the 39 observations less than 125 mm/hr (5 in/hr).

Table 3. Observed and published Horton equation parameter values

	f_o mm/hr (in/hr)		f_c mm/hr (in/hr)		k (min^{-1})	
	mean	range	mean	range	mean	Range
Observed noncompacted-sandy soils	990 (39)	110–3710 (4.2–146)	380 (15)	10–640 (0.4–25)	9.6	1.0–33
Observed compacted-sandy soils	380 (15)	3–2200 (0.1–86)	46 (1.8)	3–240 (0.1–9.5)	11	1.8–37
Published values for sandy soils		43–250 (1.7–10)		7.6–11 (0.30–0.45)	0.069	
Observed dry-noncompacted-clayey soils	460 (18)	64–1500 (2.5–58)	170 (6.6)	3–610 (0.1–24)	8.8	-6.2–19
Published values for dry-clayey soils		30–50 1–2		0–1 0–0.05	0.069	
Observed for all other clayey soils (compacted and dry, plus all saturated conditions)	86 (3.4)	0–1200 (0–48)	10 (0.4)	-15–170 (-0.6–6.7)	5.6	0–46
Published values for saturated-clayey soils		8–18 (0.3–0.7)		0–1 (0–0.05)	0.069	

Dry-noncompacted-clayey soils had the highest infiltration rate for clayey soils. No significant change in infiltration rates were seen as a function of time, with all test average values within the range of 8 to 500 mm/hr (0.3 to 20 in/hr) and a mean rate of about 230 mm/hr (9 in/hr) for all 18 tests. The test results for the other clayey soils (dry and compact, and all saturated conditions) were the lowest observed. Some test in clayey soils exhibited infiltration rates that decreased with time. Most of the 60 sets of test data indicated infiltration rates were within a relatively narrow range of less than 125 mm/hr (5 in/hr). The mean clayey-soil infiltration rates were all greater than the published values, although the compacted and saturated clays were much closer to the published values than the observed rates of dry clayey soil.

Time-Averaged Infiltration Rates

Because of the wide range in observed infiltration rates for each of the major categories, it may not matter which infiltration rate equation is used. The residuals are all relatively large and it may be more important to consider the random nature of infiltration rate about any fitted model and to address the considerable effect that soil compaction has on infiltration. A Monte Carlo stochastic component may be necessary in runoff models to describe this variation.

Table 4 shows the measured infiltration rates for each of the four major soil categories, averaged for different storm durations (15, 30, 60, and 120 min). Also shown are the ranges and coefficient of variation (COV) values for each duration and condition. As an example of a Monte Carlo type approach, a routine in a model could select an infiltration rate, associated with the appropriate soil category, based on the storm duration. The selection of a storm-averaged rate would be from a random distribution (likely a log-normal distribution) using the mean and standard deviation values shown on this table.

Factorial Analyses of Infiltration Measurements

A factorial analysis was performed on the infiltration parameters calculated from the observed field data to determine the importance of the different site characteristics. First, a 2^3 factorial design was used to evaluate all data for the effects of soil moisture, soil texture and soil compactness on each of the infiltration parameters, f_o, f_c, k, and on the time-averaged infiltration rates for 15, 30, 60 and 120 min. These analyses identified the significant site factors needed to best predict the infiltration parameters.

Table 4. Soil infiltration rates for different categories and storm durations

Sandy, Noncompacted (in/hr)

	15 min	30 min	60 min	120 min
mean	22.9	19.5	16.9	15.0
median	25.0	19.7	17.4	15.7
std. dev.	10.6	9.1	8.0	7.2
min	1.3	0.8	0.6	0.5
max	43.0	38.0	32.4	28.6
COV	0.5	0.5	0.5	0.5
number	36	36	36	36

Sandy, Compacted

	15 min	30 min	60 min	120 min
mean	6.7	4.9	3.8	3.0
median	4.3	2.9	1.9	1.3
std. dev.	8.8	6.9	5.4	4.4
min	0.1	0.2	0.2	0.2
max	36.5	29.1	23.8	21.3
COV	1.3	1.4	1.4	1.5
number	39	39	39	39

Clayey, Dry, Noncompacted

	15 min	30 min	60 min	120 min
mean	12.7	10.8	9.6	8.8
median	7.6	6.3	5.8	5.4
std. dev.	10.8	9.5	8.9	8.5
min	1.0	0.5	.5	0.3
max	32.0	29.0	26.5	25.3
COV	0.9	0.9	0.9	1.0
number	18	18	18	18

All Other Clayey Soils
(compacted and dry, plus all saturated conditions)

	15 min	30 min	60 min	120 min
mean	1.8	1.3	1.0	0.7
median	1.3	1.0	0.8	0.6
std. dev.	2.3	1.7	1.3	1.1
min	0.0	0.0	0.0	0.0
max	13.5	11.4	9.4	7.5
COV	1.3	1.3	1.4	1.5
number	60	60	60	60

The full factorial analysis showed that soil texture had a significant effect for all parameters. Therefore, to produce a model that is more sensitive and accurate, the data was separated into two groups according to texture, clayey or sandy, for a 2^2 factorial analysis. Results for the sandy-texture soil are shown on Table 5. Compaction of the sandy soil has the greatest effect on the infiltration parameters. This analysis shows that this infiltration model is acceptable for approximately 80% of the data. Table 6 shows the results for the factorial analysis for the data corresponding to the clay texture. The effects of moisture combined with compaction have the greatest effect on the clay soils. The results show the model is good for about 80% of the data.

More detailed analyses are provided in the full report (Pitt et al. 2000), along with possible corrective actions.

Conclusions

The initial analyses of the data showed that the infiltration rate of sandy soil was most affected by compaction, with little change due to moisture levels. However, the clayey soils were affected by a strong interaction of compaction and moisture. The variations of the observed infiltration rates in each category were relatively large but four soil conditions were found to be distinct. The data from each individual test were fitted to the Horton equation, but the resulting equation coefficients were relatively imprecise. It may not matter which infiltration equation is used, as long as the uncertainty is considered in the evaluation. Therefore, when modeling runoff from urban soils, it may be best to assume relatively constant infiltration rates throughout an event, and to utilize Monte Carlo procedures to describe the observed random variations about the predicted mean value, possibly using the time-averaged infiltration rates and COV values.

Very large errors in soil infiltration rates can easily be made if published soil maps and most available models are used for typically disturbed urban soils, as these tools ignore

Table 5. Sand texture soil results of the factorial analysis effects for each parameter.

Parameter	Average Value	Important Effects/ Model Equation	Compaction (C)	Model Value
f_o (in/hr)	24.63	Compaction (C) $f_o = 24.63 \pm (C/2)$ $f_c = 24.63 \pm (-4.11/2)$	+ -	22.57 26.68
f_c (in/hr)	6.67	Compaction $f_c = 6.67 \pm (C/2)$ $f_c = 6.67 \pm (-13.01/2)$	+ -	0.16 13.17
k (min^{-1})	10.42	Average k = 10.42	+ -	10.42 10.42
15 min (in/hr)	15.01	Compaction $f_{15\ min} = 15.01 \pm (C/2)$ $f_{15\ min} = 15.01 \pm (-16.75/2)$	+ -	6.63 23.38
30 min (in/hr)	12.43	Compaction $f_{30\ min} = 12.43 \pm (C/2)$ $f_{30\ min} = 12.43 \pm (-15.10/2)$	+ -	4.88 19.98
60 min (in/hr)	10.64	Compaction $f_{60\ min} = 10.64 \pm (C/2)$ $f_{60\ min} = 10.64 \pm (-13.65/2)$	+ -	3.81 17.46
120 min (in/hr)	9.35	Compaction $f_{120\ min} = 9.35 \pm (C/2)$ $f_{120\ min} = 9.35 \pm (-12.69/2)$	+ -	3.01 15.70

Table 6. Clay texture soil results of the factorial analysis effects for each parameter.

Parameter	Average Value	Important Effects/ Model Equation	Moisture x Compaction (MC)	Model Value
f_o (in/hr)	7.25	Moisture x Compaction (MC) $f_o = 7.25 \pm (MC/2)$ $f_o = 7.25 \pm (5.85/2)$	+ -	10.18 4.33
f_c (in/hr)	2.26	Moisture x Compaction $f_c = 2.26 \pm (MC/2)$ $f_c = 2.26 \pm (3.49/2)$	+ -	4.00 0.51
k (min^{-1})	5.96	Moisture x Compaction $k = 5.96 \pm (MC/2)$ $k = 5.96 \pm (0.43/2)$	+ -	6.17 5.74
15 min (in/hr)	4.22	Moisture x Compaction $f_{15\ min} = 4.22 \pm (MC/2)$ $f_{15\ min} = 4.22 + (3.84/2)$	+ -	6.14 2.30
30 min (in/hr)	3.45	Moisture x Compaction $f_{30\ min} = 3.45 \pm (MC/2)$ $f_{30\ min} = 3.45 + (3.41/2)$	+ -	5.15 1.74
60 min (in/hr)	2.97	Moisture x Compaction $f_{60\ min} = 2.97 \pm (MC/2)$ $f_{15\ min} = 2.97 + (3.29/2)$	+ -	4.62 1.33
120 min (in/hr)	2.60	Moisture x Compaction $f_{120\ min} = 2.60 \pm (MC/2)$ $f_{120\ min} = 2.60 \pm (3.25/2)$	+ -	4.22 0.97

compaction. Knowledge of compaction (which can be mapped using a cone penetrometer or estimated based on expected activity on grassed areas) can be used to more accurately predict stormwater runoff quantity.

In most cases, the mapped soil textures were similar to what was actually measured in the field. However, important differences were found during many of the tests. The averaged infiltration rates in Table 3 ranged from 0.5 to 1.5 for four major groupings, these COV values are much less than if compaction was ignored. The results of the factorial analysis indicated that the best models were separated by the soil texture. For more accurate modeling, it is recommended that site specific data be obtained. Once the texture, moisture and compaction of the soil are known, the models based on the factorial analysis can be used. The high variations within each category makes it difficult to statistically identify patterns, implying that average infiltration rates may be most suitable for predictive purposes. The remaining uncertainty can probably best be described using Monte Carlo components in runoff models.

The measured infiltration rates during these tests were all substantially larger than published values, but comparable to previous standard double-ring infiltrometer tests in urban soils. Other researchers have noted that infiltrometers generally over predict ponding in comparison to actual rainfall observations. In all cases, these measurements are suitable to indicate the relative effects of soil texture, compaction, and moisture on infiltration rates. The measured values can be directly used to predict the infiltration rates that may be expected from stormwater infiltration controls that utilize ponding. Additional research is needed in other locations to measure site specific effects of urban soil conditions on infiltration rates.

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