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Variation of Infiltration Rates with Soil Texture. A Laboratory Study

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Abstract: The need for an efficient predictor of infiltration rate in agriculture and water resources project cannot be overemphasized. In this laboratory study, fine and coarse (F & C) fractions of a soil were mixed in seven ratios, Fine/Coarse, of 100/0, 80/20, 40/60, 50/50, 40/60, 20/80 and 01100. Water was allowed to infiltrate into each mixture and data on infiltration rate (f) and time (t) since infiltration started were subjected to a simple polynomial regression: f = at2 + t + y where a, 3 and y are infiltration coefficients and the polynomial in t accounts for not less than 95% of the variation in f. Each of a, f3 and y was regressed also as a polynomial in fine fraction (F) with more than 84% coefficient of determination (R2). The model obtained is:

$f=(38.941F^2 - 5298.8F + 158083)\ t^2+(3.4793F^2- 483.18F+ 15172)\ t +0.0877F^2 - 12.731F+ 488.24$

suggesting that with only the fine fraction content known, one can predict the infiltration rate at any given time or duration of the infiltration process other factors remaining constant Consequently, one can use the model to predict the total infiltration depth by integrating the infiltration rate curve over time.

I. INTRODUCTION

Infiltration rate, being a measure of how fast water enters the soil, influences the major mechanisms governing water availability to plants. It decreases with time from the onset of rainfall or irrigation. The rate of decrease depends on several environmental factors such as rainfall rates and pattern or head of water application, soil properties (including soil depth, texture, pore characteristics, organic matter content, and structure), vegetation, land use, and antecedent moisture. The measure of infiltration of water into the soil is an important indication concerning the efficiency of irrigation and drainage, optimizing the availability of water for plants, improving the yield of crops and minimizing erosion. Adequate knowledge of soil infiltration data is essential for reliable prediction and control of soil and water related environmental hazards [1]. As environmental impact assessments are concerned with long-term effects, it is essential that the infiltration data on which they are based should be reasonably stable over time. Earlier, Abdelwahab[2] established that the design, operation, management and hydraulic evaluation of on-farm water application rely heavily on the infiltration properties of the soil. This is because infiltration behavior of the soil directly determines the essential variables such as inflow rate, length of run, application time, depth of percolation and tail-water run-off in irrigation systems.

The inhabitants of the study area are dominantly farmers, relying heavily on rainfall. A significant number of them however practice irrigation, and it has become part of their lives [3]. Flood and soil erosion are the common hydrologic problems in this area, either in the rainy season or in irrigated farm during irrigation seasons [4]. Both the hazards exert a heavy toll on their victims, the consequences are obvious with a lot agronomic, economic, and health implications and they are on the increase. The assessment of runoff risk has therefore assumed an increased importance because of concerns about the associated environmental and social hazards [4]. Many efforts geared toward curbing the menace have been projected but with little success. It has been believed that additional information on the hydraulic properties of the soil need to be considered in modeling environmental problems. Jianfeng and Kenneth [5] provide a summary of infiltration models.

Proper environmental impact assessments are concerned with long-term effects, it is therefore essential that the infiltration data on which they are based should be reasonably stable over decades and under various soil characteristics.

Jianfeng and Kenneth [5] indicate infiltration rates are influenced by the initial moisture content, condition of the surface, hydraulic conductivity of the soil profile, texture, porosity, degree of swelling of soil colloids, organic matter, vegetative cover, duration of irrigation or rainfall and viscosity of water. Of these, soil texture, however, play predominant role [6]. Management practices such as tillage, by its ability to vary the composition of top soil, also influences infiltration.

Irrigation systems should be designed and managed so that the application rate of water does not exceed the infiltrability of the soil (Khatri and Smith, 2005).

The objective of this study is to investigate the variation of infiltration rate with changes in the soil texture, with a particular reference to the soil fine fraction. Specifically it is to: Determine a model that can be used to estimate the infiltration rate of a soil at any time, given the fine fraction and (2) determine the most suitable ratio of coarse and fine aggregates combination for good infiltration.

II. MATERIALS AND METHODS

A. Study Site

The study was carried out in the Agricultural and Environmental Resources Engineering laboratory at the University of Maiduguri. Maiduguri is located at 130°5E and 11 0°5E, 345m above mean sea level with the mean annual rainfall of about 625mm and annual temperature of 28 - 32°C. Maiduguri, the capital of Borno State, lies between latitudes 110 45'N and110 51'N longitudes 130 2'E and 130 9'E. It is located in the Ngadda Basin, a seasonal stream that flows through Maiduguri. Land use at the site is characterized by permanent rain fed cultivation of grain crops such as sorghum and millet. Dry season Fadama (Market gardening) cultivation is practiced at some points, using small horse power pumps. Other land use activities include sand mining, grazing, urban house construction, garden and orchards. The climate of Maiduguri is generally semi-arid, with moderate variations in temperatures; the mean monthly minimum temperature is lowest (13.5°C) during the period of strongest and most constant northeast winds (Harmattan) in December and January; and highest (24.7°C) in April. The mean monthly maximum temperature is highest (40.2°C) prior to and during the onset of the rains in April and the lowest (31.3°C) during the peak rained period of August.

B. Sample Collection and Preparation.

The soil sample was collected near River Ngadda, a river flowing through Maiduguri metropolis behind the Maiduguri water treatment plant located at the 202 housing estate opposite the University of Maiduguri depth of between 0 - 15cm from the soil surface of undisturbed land at five (5) locations space 250 -500 m apart. The sample was air dried; all clumps and aggregates were broken in the laboratory and subjected to particle size analysis using dry sieving method. Using 500 µm below as fine textured soil the method as described by ASTM D 422 - Standard Test Method for Particle-Size, the sample was separated into fine and coarse fractions. The samples were then mixed again in seven (7) predetermined fine: Coarse fractions ratios of 100/0, 80/20, 60/40, 50/50, 40/60, 20/80, and 0/1 00. The ratios were labeled 1-7 respectively.

Table 1 Particle Size Distribution Analysis

MESH DIAMETER	SAMPLE WEIGHT RETAINED (g)	PERCENTAGE RETAINED (%)	PERCENTAGE PASSING (%)	COARSE AND FINE PERCENTAGE (%)
4mm	5.01	5.01	94.99	
2mm	11.35	11.35	83.64	
1mm	17.70	17.70	65.94	
850µm	5.43	5.43	60.51	55.20%
710µm	5.08	5.08	55.43	Coarse
>425µm	9.58	9.58	45.85	particles
<500µm	4.27	4.27	41.58	
300µm	5.07	5.07	36.51	
250µm	10.15	10.15	26.36	
150µm	15.18	15.18	11.18	44.80%
63µm	9.08	9.08	2.10	Fine
Pan	1.05	1.05	0	Particles
TOTAL	100	100	-	100

C. Experimental Set up and Procedure

Plastic buckets (infiltrometers) were perforated at the bottom using a heated metal to a diameter 4 mm (Figure 1). Nylon material was then placed on the perforated base of the buckets to keep soil samples in place and a manometer was attached to the buckets. The manometers were held upright by a clamp mounted on a tripod stand. All connections were checked for leakages. About 20 Kg of the mixed samples were loading in turn starting with sample 1 and ending with sample 7 into the "infiltrometer" cylinder, saturated with water, and allowed to drain. Soft foam was put on top of the soil sample so as to avoid re-stratifying of the soil due to action of falling water and the resulting compaction. Particle and bulk densities were determined each time from which porosity and pore volume were calculated. Water was then poured into the bucket and the time taken for the water to fall through a height of 5 cm (50 mm) in the manometer was recorded. This was done continually until a nearly constant time for a drop in the water head by 5cm was obtained. At this point, it is assumed that a nearly constant time between 2-3 subsequent readings indicates the infiltration rate of the soil and the experiment terminated.

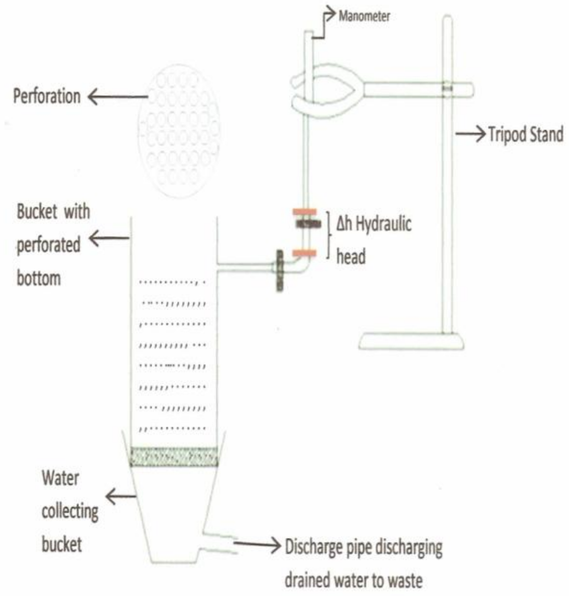

Fig. 1: Schematic diagram of experimental setup

D. Regression Analyses

For each test data, infiltration rate, (f) was regressed on time (t) since infiltration started, to obtain the best fit. A polynomial of second order was found to be the best fit with a high coefficient of determination, R2 of more than 95% in all the seven tests. The infiltration coefficients α, β, and γ in Eqn, 1 which were found to be different from one test to another, were assumed as to be functions of either the fine fraction (**F**) contents or the Fine/Coarse (**F/C**) ratio.

$$f = \alpha t^2 \div \beta t + \gamma \qquad (1)$$

Therefore, α was regressed separately on F and FIC and the other two infiltration coefficients (β, and γ) were likewise regressed on F first, and then on **F/C** to result in another set of polynomials (Eqns. 2-4).

$$\alpha = \alpha_1 F^2 + \mathbf{b_1}F + \mathbf{c_1} \qquad (2)$$

$$\beta = \alpha_1 F^2 + \mathbf{b_2}F + \mathbf{c_2} \qquad (3)$$

$$\gamma = \alpha_3 F^2 + \mathbf{b_3}F + \mathbf{c_3} \qquad (4)$$

The above procedure was repeated for each of the seven soil mixtures and the values obtained were tabulated.

III. RESULTS AND DISCUSSION

Table 2 contains all the essential infiltration test variables as well as the results of all the regression analyses carried out. Figures 2 - 4 are graphical representations of the regression analysis of the infiltration rate — time data. The data in the Table and the Figures shows that Eqn.1 fits the *f* - t relationship excellently as R^2 varied from 95.3% in the seventh mix of zero fine fraction to 100% in the mix of 20% fine fraction.

$$\boldsymbol{f} = \boldsymbol{\alpha} t^2 + \boldsymbol{\beta} t + \gamma \qquad (1)$$

The polynomials maintain a well-known relationship between ***f*** and ***t***, namely

f decreases with ***t*** as ***f*** approaches a constant low value that is said to approximate saturated hydraulic conductivity, ***K***. Table 2 and 3 are shown in Appendix.

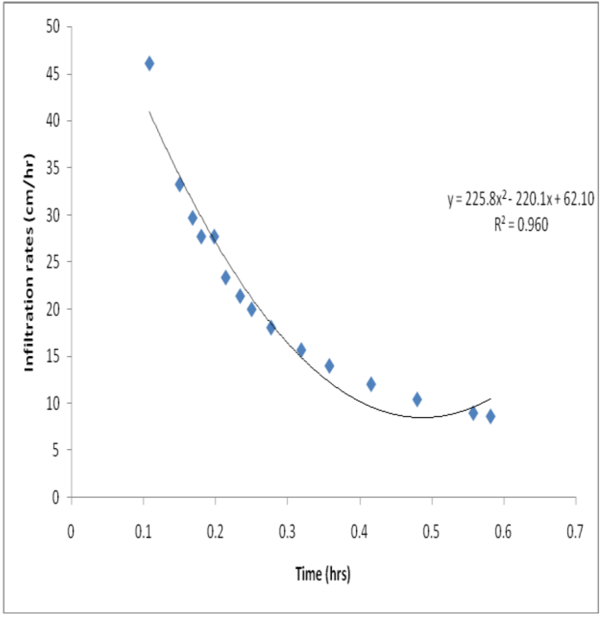

Fig 2: Graph of infiltration rates versus time for sample No. 1: (100% Fine, 0% Coarse)

From the graph above, it can be seen that the time taken for a drop in head of 5 cm differs greatly from the preceding value as the soil gets more saturated, hence the points can be observed to be more clustered at the beginning. The regression analysis yielded a polynomial (Eqn. 2)

$$f = 226.61t^2 - 220.8t + 62.233 \qquad (2)$$

Where *f* is the infiltration rate and t is the time taken for the water to infiltrate into the soil. The intercept of the graph is 62.233, and the coefficient of determination R^2 is 0.9605. This means that about 96% of the variation in infiltration rate can be explained by variation in fine fraction content of the soil. In other words, the regression equation can predict infiltration rate with 96% certainty. Similar results was observed for sample No. 2 through 7. Their regression equations are presented below.

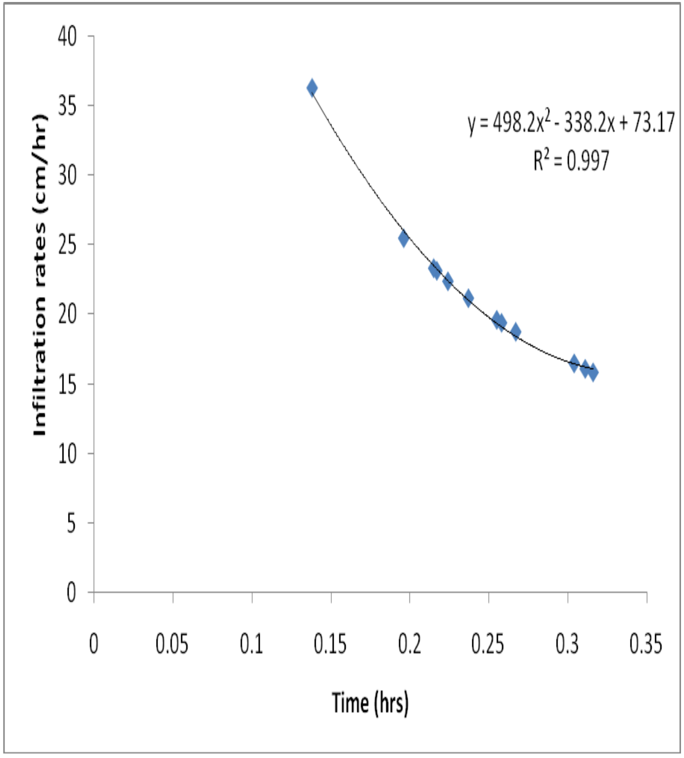

Fig 3 Graph of infiltration rates versus time for sample No. 1: (80% Fine, 20% Coarse)

Sample No. 2: $f = 499.98t^2 - 338.8\ \mathrm{It} + 73.205$, R^2 is 0.9977 (3)

Sample No. 3: $f = 257.99t^2 - 219t + 58.806$, R^2 is 0.9962 (4)

Sample No. 4: $f = 536.97t^2 - 355.38t + 74.861$, R^2 is 0.9918 (5)

Sample No. 5: $f = 1197.9t^2 - 610.33t + 98833$, R^2 is 0.9982 (6)

Sample No. 6: $f = 15889t^2 - 3273.9t + 222.76$, R^2 is 0.9997 (7)

Unlike the other graphs, Fig. 4 shows values clustered at the beginning of the graph and there was sudden sharp increase in time taken for the required water to infiltrate into the soil. This might be due to be absence of fine aggregates in the soil sample, creating room for easy movement of water through the soil.

The equation and R^2 for this sample are:

$$f = 142393t^2 – 14881t + 489.18,\ R^2 = 0.9522 \qquad (8)$$

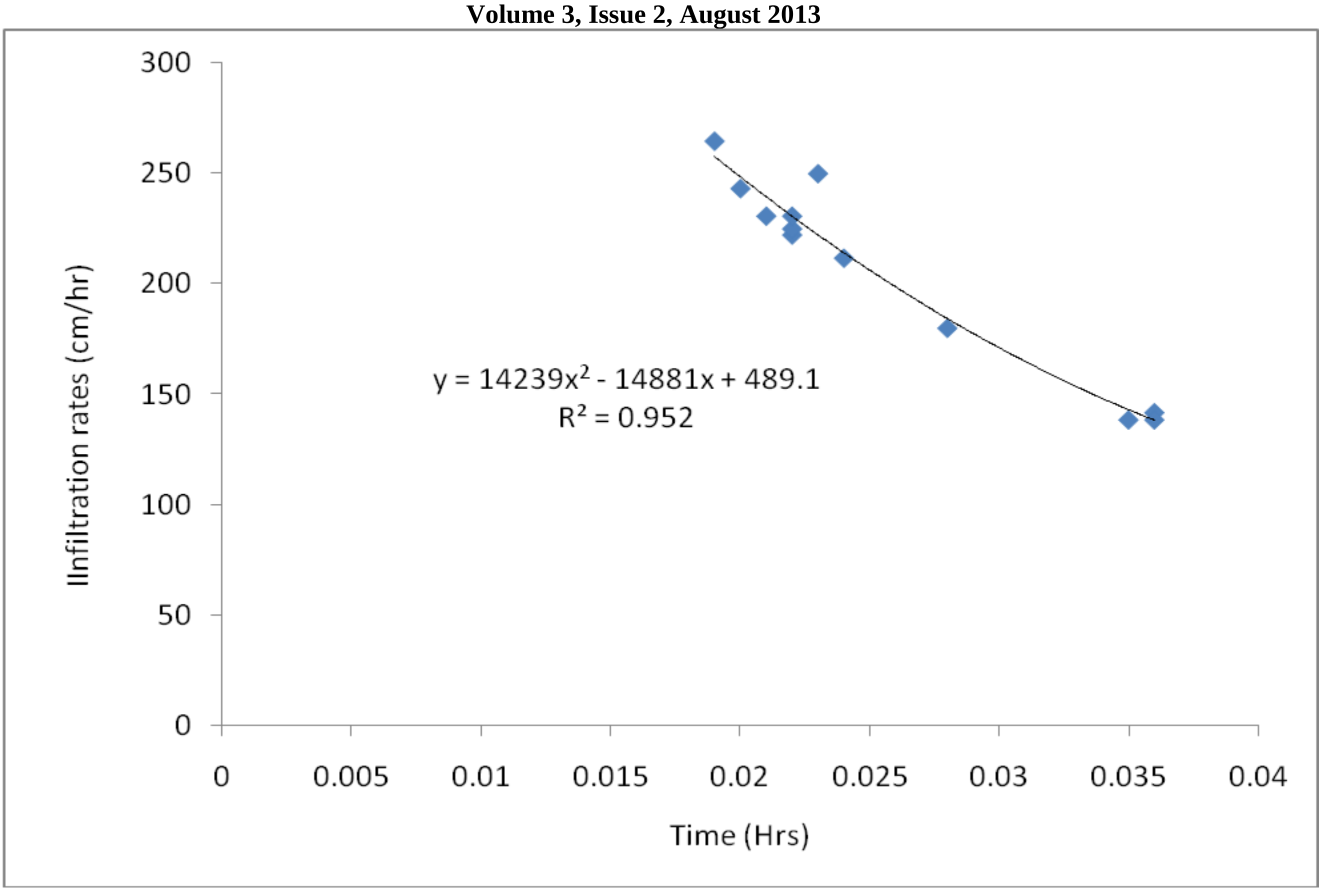

Fig 4 Graph of infiltration rates versus time for sample No. 1: (0% Fine, 100% Coarse)

IV. VARIABILITY OF INFILTRATION COEFFICIENTS α, β AND γ

Table 4 contains the data on infiltration coefficients, and it shows that the infiltration coefficients α, β and γ, which are assumed to be functions of the soil texture among other factors, were better predicted by the Fine Fraction Content (F) than the mix ratio (F/C) in polynomial fits. While the R^2 value in the Infiltration Coefficient - Fine Fraction regression varied from 84% to 96%, the corresponding R^2 values in the Infiltration Coefficient - Mix Ratio varied from 23.6% to 35.5%.

Table 4: Goodness of Fit of infiltration Coefficients by polynomial in Fine Fraction Content F and in Fine/Coarse Ratio (F/C)

(i)	Infiltration Coefficient = $aF^2 + bF + c$			
	A	B	C	R^2,%
α	38.941	-5298.8	158083	84.0
β	-3 .4793	483.18	-15172	89.4
γ	0.0877	-1 2.731	488.24	96.2

(ii)	Infiltration Coefficient = $aF^2 + bF + c$			
	E	G	H	R^2,%
α	240.4	-24678	64027	23.6
β	-23.426	24062	-6583.5	27.8
γ	0.6971	-71	260.98	35.5
		.693		

It is obvious therefore that using the fine fraction (100% - 0%) is more suitable than the mix ratio due to a higher R^2 value implying a high level of certainty (good fit) between the coefficients and the fine fraction. Hence the mix ratio does not fit very well into the polynomial function and is not reliable.

Therefore, a generalized model was deduced for estimating the infiltration rate (*f*) of any soil with known fine fraction at any time (*t*) with a reasonable degree of certainty. The model is capable of predicting infiltration rate with a high degree of certainty by fitting in Eqns. 9-11 into Eqn. 1.The three regression equations obtained are shown below.

$$\alpha = 38.941\mathbf{F}^2 - 5298.8\mathbf{F} + 158308 \qquad (9)$$

$$\beta = 34793\mathbf{F}^2 + 483.18\mathbf{F} - 15172 \qquad (10)$$

$$\gamma = 0.0877\mathbf{F}^2\ 12.731\mathbf{F} + 488.24 \qquad (11)$$

where F = fine fraction.

Substituting the three regression equations of the coefficients as function of the fine fraction into the infiltration equation (Eqn. 1) produces:

$$\boldsymbol{f}=(38.941F^2 - 5298.8F + 158083)\boldsymbol{t}^2+(3.4793F^2\_ 483.18F+ 15172)\boldsymbol{t}+ 0.0877F^2 - 12.731F + 488.24 \qquad (12)$$

This implies that if the fine fraction of any soil is known, the above equation can be used to estimate the infiltration rate at any time t, all other factors remaining constant.

V. CONCLUSION

There exists a high level of dependence of infiltration rate on the soil fine fraction. This was observed in the high R^2 value obtained from the regression analyses. The infiltration equation as obtained using the regression analysis is of a polynomial function with three coefficients believed to be functions of soil fine fraction, also in polynomial best fits.

A model was generated that could be used to estimate the infiltration rate of any soil at a time, t, if the fine fraction of the soil is known, all other factors remaining constant.

For a more elaborate understanding on the subject matter of variation of infiltration rate with soil texture with a particular reference to fine fraction content, the study recommends further research on this topic to separate the other soil constituent’s such as organic matter in the soil so as to have a clean soil sample ready for use. Also attempts should be made to separate the soil sample into sand, silt and clay and used to run the experiment. It is noteworthy that not only texture as a soil property affect infiltration rate. Hence a better result can be obtained if attempts are made to eliminate all the other soil factors such as soil structure, moisture content etc.

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[8]

APPENDIX

TABLE 2: Infiltration rate- time relationship obtained for different fine fractions

Sample	Fine*	Infiltration Rate *f* (cm/hr) and Time t (hrs) since infiltration started									
NO.	(%)										
1	100%	F(cm/hr)	46.116	33.264	29.699	27.72	27.72	23.364	21.384	19.98	18.036
		T(hrs)	0.108	0.15	0.168	0.18	0.198	0.214	0.234	0.25	0.277
2	80%	F(cmfhr)	36.252	25.452	21.132	23.112	23.292	22.356	19.584	19.368	18.72
		T(hrs)	0.138	0.196	0.237	0.217	0.215	0.224	0.255	0.258	0.267
3	60%	F(cm/hr)	29.952	22.788	21.672	20.808	20.556	19.62	18.324	17.676	16. 380
		T(hrs)	0.167	0.22	0.231	0.24	0.24	0.255	0.273	0.283	0.305
4	50%	F(cm/hr)	34.549	26.208	23.292	21.378	19.822	17.561	17.579	16.394	16.07
		T(hrs)	0.1447	0.198	0.215	0.234	0.234	0.285	0.284	0.305	0.311
5	40%	F(cm/hr)	50.004	32.076	28.584	28.836	26.712	26.316	25.344	24.588	23.724
		T(hrs)	0.1	0.156	0.175	0.173	0.187	0.19	0.197	0.203	0.211
6	20%	F(cm/hr)	91.836	83.736	80.712	73.764	72	71.712	69.228	68.976	68.436
		T(hrs)	0.054	0.059	0.062	0.068	0.069	0.07	0.073	0.073	0.073
7	0%	F(cm/hr)	264.7	249.98	243.25	230.76	222.23	225	230.76	211.75	180
		T(hrs)	0.019	0,023	0.02	0.021	0.022	0.022	0.022	0.024	0.028

Table 3: Infiltration Test variables and regression results for the Seven Mixtures (Ratios) of Fine and Coarse Fractions

Variables		**Values**						
TestNo.		1	2	3	4	5	6	7
Fine Fraction, %		100	80	60	50	40	20	0
Fine:Coarse Ratio		100:0	80:20	60:40	50:50	40:60	20:80	0:100
p * g/m3		2.56	2.62	2.57	2.63	2.61	2.60	2.59
Pb * g/cm3		145	153	t46	1.63	1.63	1.52	1.46
Porosity, p		0.43	0.42	0.43	0.38	0.38	0.42	0.44
Soil Volume, V* cm^3		13396.7	12758.8	13396.7	11993.3	11993.3	12758.8	13396.7
Pore Volume, cm^3		5818.6	5316.0	5809.2	4678.8	4552.0	5297.3	5829.1
Infiltration rate, (f)					$f = \alpha t^2 + \beta t + \gamma$			
Infiltration Coeff.	**α**	226.61	499.98	257.99	536.97	1197.9	15889	187458
	β	-220.80	-338.81	-219.00	-355.38	-610.33	-	-
	γ	62.233	73.205	58.806	74.861	98.833	3273.9	17316
Coeff. of Det., R^2,’%		96.1	99.8	99.6	99.2	99.8	222.76	519.32
							100.0	95.3

*ρ_s = Particle density, ρ_b = bulk density, p = I (ρ_s/ ρ_b),
Pore Volume = pV,
R^2 = Coefficient of Determination, %