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Laboratory Modelling of Permeability Characterization of Clay under Different Hydraulic Gradient

[1]Alabi O.O., [2]Akinluyi F.O. and [1]Olatona G. I.

[1]Solid Earth Research Laboratory,
College of Science, Engineering and Technology,
Osun State University, Osogbo, Nigeria.
[2]Department of Remote Sensing and Geo-science Information System,
School of Earth and Mineral Sciences,
Federal University of Technology, Akure, Nigeria.

Abstract

This paper presents the laboratory test results of vertical infiltration on clay of different particle sizes under different hydraulic gradient. The aim of the study is to establish a model to determine the saturated hydraulic conductivity vis-à-vis permeability of soils as a function of time, for accurate estimate of volume of water available for plant growth in surface irrigation. The equation obtained from the hydraulic conductivity – time (K – t) curve is simple and practically useful for the determination of permeability at a particular time. This equation shows that permeability decreases with increase in time and yields zero only when there is no infiltration process.

Keywords: Infiltration, permeability, hydraulic gradient, volume flux, time.

1.0 Introduction

Soil as a vital natural resource which provides food, fodder, fuel wood, reduces flood risk, and protects water supplies.Soils also have a crucial role in climate change adaptation and mitigation polices. They are the basis for sustainable development and food security. Land productivity is fundamental to reaching many of the Millennium Development Goals.

Deserts and dry lands comprise 60% of the land surface of the African continent, populated by over one billion people. Much of the remaining land shows old, highly weathered soils which require special attention to be of use for agriculture.

Infiltration of water into soils is an important phenomenon affecting much of agricultural production. Water is a necessary input for crop production. In most agricultural production, water is supplied to the plant from the soil water reservoir. The recharge or refilling of this reservoir occurs as water infiltrates through the soil surface and percolates into the soil profile. Localized excesses and shortage of water can decrease production in both irrigated and dry land agriculture. Dry land agriculture is the descriptive term used to imply the irrigation water is not applied to supplement precipitation.

One of the most important considerations in the design and management of surface irrigation is the rate at which water infiltrates into the soil. Infiltration affects the advance of the irrigation stream, the rate of flow and flow depth within the field, the recession of water from the soil surface, and the total amount of water that enters the soil. In addition, the water flow on the surface can change soil surface conditions, which can change infiltration

A considerable amount of research has been conducted on the infiltration of water into (and through) soils. The basic principles of soil-water flow are well understood. However, several problems arise when trying to apply infiltration theory to field conditions. First, infiltration is greatly affected by the conditions at the soil parameters such as permeability, porosity, surface moisture content, and bulk density are changing, when assumed constant during irrigation [1].It is necessary to measure all the soil physical properties prior to an irrigation, to determine how these properties will change during the subsequent irrigation, to determine how these properties distributed over the irrigation rate-time relationship from which to make meaningful management decisions [2]. The aim of this study is to determine a simple and more efficient equation to represent the change in separated hydraulic conductivity or permeability with time for accurate estimation of volume of water for plant.

Time- Variant Crust (permeability)

Many soil physicist and hydrologist have attempted to find certain relationship between permeability and time of infiltration. One reason for searching for such relationship is that infiltration decreases with increase in time is as a result of

Corresponding author: ***Alabi O. O.,*** E-mail: -, Tel.: +2348035028760

reduction in permeability formed by the clogging of pores with fines deposited by the infiltration water.

[3,4] proposed the following exponential decay function to represent the change in saturated hydraulic conductivity of the surface seal with time,

$$k(t) = k_f + (k_i - k_f)e^{-at}$$

Where

$k(t)$ = saturated hydraulic conductivity of the surface soil at time t

k_i = initial saturated hydraulic conductivity

k_f = final saturated hydraulic conductivity of a well-established stable surface seal and a is a constant.

Concept of Clogging effect and action Mechanics

'Clogging effect' is caused by infiltration with the soil body pore being jam and permeability decreasing under seeping gradually [5]. The clogging effect is the result of internal and external factors combined action [6].In finely ground particles and the fluid state of motion in the infiltration process, are intrinsic factor to produce clogging effect [6,7,8].

The infiltration clogging effect is divided into four types according to the action mechanism, namely mechanical clogging, chemical clogging, biological clogging and comprehensive clogging [9]. It has been observed that the influence of chemical clogging and biological clogging is small, so the principal one is mechanical clogging [5]. It is found that mechanical clogging can also be divided into the following.

a. Clogging with silt refers to a phenomenon, when small soil particles enter the loose medium pore, reduce area of flow section, and decrease the permeability of soil.

b. Blocking, refers to a phenomenon that the particles are not easy to enter into the pore if they are of similar size of pores in loose medium, but they can still block partially the pass of water and therefore reduce the water cross sectional area, and decrease soil permeability.

c. Occluding, refers to a phenomenon that the tiny clay will gather on the surface pore and form mud pie to seal up the pore water cross section and reduce the soil permeability.

The above three types are not mutually independent since clogging effect is the result of the combined action synthesis [5].

2.0 Theoretical Background

Darcy's law [10] for homogeneous fluid generalized is gives as

$$v_s = -k/\eta\left(\frac{\partial p}{\partial s} - \gamma g cos\theta\right) \quad (1)$$

Where

v_s = rate of flow through the unit of area in the directions

θ = angle between the line of the vertical and the direction of flows

η = viscosity of fluid

γ = density of fluid

g = acceleration of gravity

p = pressure of the fluid

k = coefficient of permeability

In reference to the present study, the experimental set up used was in the form of vertical flow of water through sand in the permeameter.

Thus, equation (1) reduced to a simple equation

$$v_s = ki \quad (2)$$

Where

k = hydraulic conductivity (ms^{-1})

$i = \frac{\partial p}{\partial s}$ = one dimensional flow of water through sand (dimensionless)

v_s = volume of water flowing across a area per unit time or volume flux (ms^{-1})

and by using Hubert King [11] relation,

$$k = \frac{\gamma_g}{\eta}\kappa \quad (3)$$

Equation (2) is generally used to determine the hydraulic conductivity vis-à-vis the permeability of the sands. This can be done by plotting v_s against i and the slope of the curve gives hydraulic conductivity of the sand. Permeability is obtained from the hydraulic conductivity by using equation (3).

The Darcy flux is defined as

$$q = Q/A \quad (4)$$

Where, q = Darcy flux (ms^{-1}), Q = Volumetric flow rate (m^3s^{-1}), and A = Cross-sectional area (m^2)

The Darcy flux is the volumetric flow rate per unit area.
Then

$$q = -K\,\frac{dh}{dl} \qquad (5)$$

3.0 Experimental study and data analysis

Based on the Darcy's law an instrument for infiltration of water into soils, called permeameter was designed (Fig.1). The clay samples of different sizes were subjected to water infiltration. Seepage process was conducted for different hydraulic head within the same regular time interval to obtain the variation of soil permeability with time. The volume flux at different hydraulic head is plotted against hydraulic head. The slope of volume flux-hydraulic gradient gives permeability at various time intervals. The hydraulic conductivity/permeability time curve (that is k-t curve) was obtained for three clay samples of different particles sizes. The relationship between permeability and time were obtained by best fitting curve. The analysis indicates that the permeability reduces gradually with increase in time, which proves the existing of clogging effect as the time of flowing through soil increases.

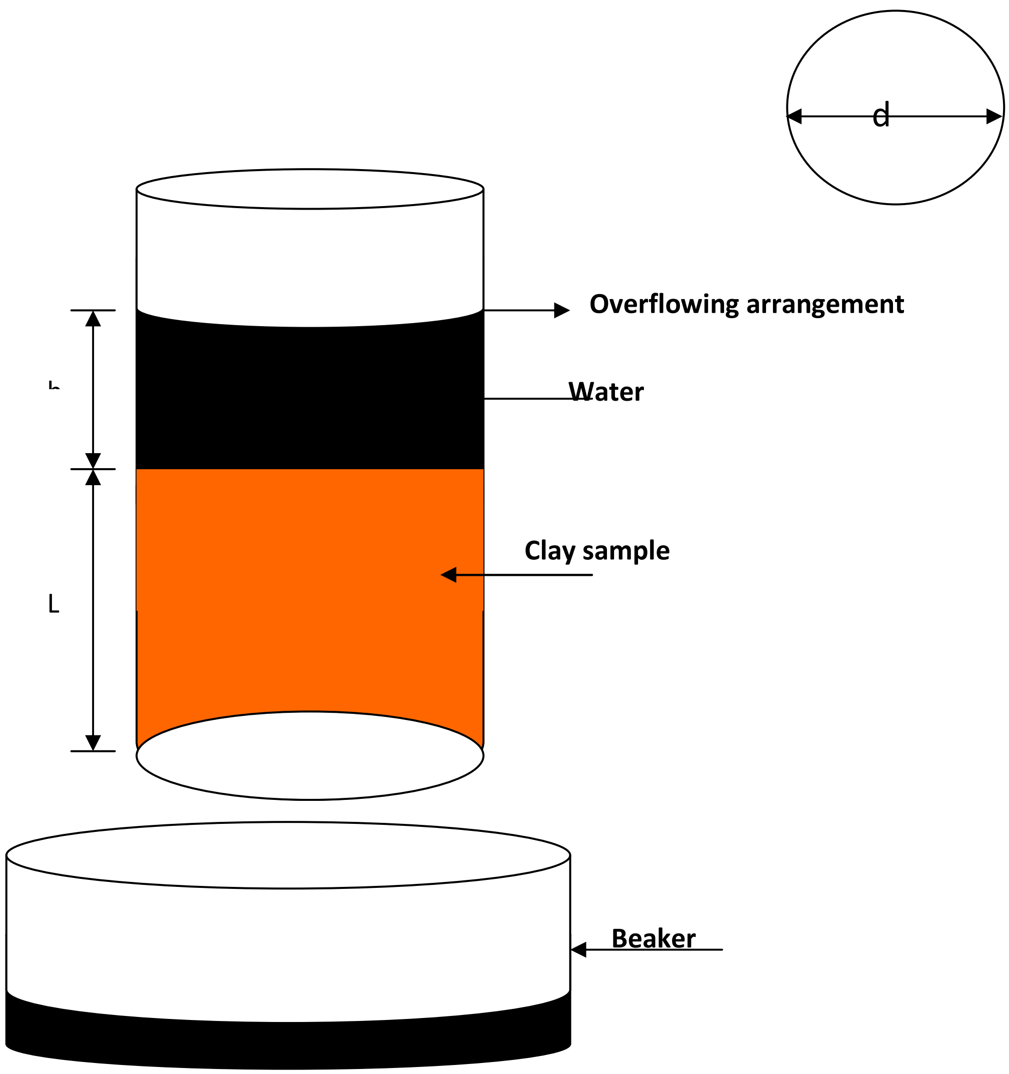

FIG. 1: Sand Model for Vertical Flow under hydraulic head [12]

4.0 Result and Discussion

A range of hydraulic gradient was achieved by varying the soil sample length in permeameter. The outflow from the permeameter for each gradient was measured by graduated measuring cylinder at interval of minutes. The volume flux, which is the rate of volume of water discharge per unit time per unit area were determined and presented in Tables 1, 2 and 3 for samples A,B and C respectively. The results show that volume flux increases with hydraulic gradient. This is to be so because hydraulic gradient acts as a 'driving force' and the higher the driving force, the more the volume flux (or volume of water discharge). This is in support of Darcy's law experiment and other previous investigations. All the samples exhibited a marked increase in volume flux as the hydraulic gradient increased from 5.67 to 19.00.

Table 1: discharge volume, volumetric flow rate and volume flux at different hydraulic head (SAMPLE A)

i	V x 10^{-6} (m^3)	Q x 10^{-8}(m^3/s)	q x 10^{-5}(ms^{-1})
Time 1mins			
5.67	0.30	0.05	0.41
7.00	1.10	1.80	1.50
9.00	1.60	2.70	2.20
12.33	1.30	2.20	1.80
19.00	5.50	9.20	7.40
Time 2mins			
5.67	0.80	0.67	0.54
7.00	1.80	1.50	1.20
9.00	2.80	2.33	1.90
12.33	3.10	2.60	2.10
19.00	9.25	7.70	6.30
Time 3mins			
5.67	1.00	0.56	0.45
7.00	2.60	1.44	1.20
9.00	3.60	2.10	1.70
12.33	4.60	2.50	2.00
19.00	13.50	7.50	6.10

Time 4mins

i	V x 10^{-6} (m^3)	Q x 10^{-8}(m^3/s)	q x 10^{-5}(ms^{-1})
5.67	1.00	0.42	0.34
7.00	3.50	1.50	1.20
9.00	5.00	2.10	1.70
12.33	6.30	2.60	2.10
19.00	17.00	7.10	5.80
Time 5mins			
5.67	1.60	0.53	0.43
7.00	4.20	4.00	1.10
9.00	6.50	2.20	1.80
12.33	7.90	2.60	2.10
19.00	20.75	6.90	5.60

Table 2: discharge volume, volumetric flow rate and volume flux at different hydraulic head (SAMPLE B)

i	V x 10^{-6} (m^3)	Q x 10^{-7}(m^3/s)	q x 10^{-4}(ms^{-1})
Time: 1min			
5.67	4.95	0.83	0.67
7.00	8.6	1.4	1.2
9.00	12.25	2.4	1.7
12.33	19.5	3.3	2.6
19.00	59	9.8	8.0
Time: 2mins			
5.67	19	1.6	1.3
7.00	24	2.0	1.7
9.00	31	2.6	2.1
12.33	54	4.5	3.7
19.00	156.5	13	11
Time: 3mins			
5.67	13.25	7.4	0.60
7.00	17.75	0.94	0.77
9.00	22.25	1.24	1.0
12.33	37.5	2.1	1.7
19.00	103.75	5.8	4.7

i	V x 10^{-6} (m^3)	Q x 10^{-7}(m^3/s)	q x 10^{-4}(ms^{-1})
Time: 4mins			
5.67	20	0.83	0.68
7.00	30.5	1.3	1.0
9.00	41	1.7	1.4
12.33	51	2.1	1.7
19.00	204.75	8.5	6.9
Time: 5mins			
5.67	35.5	1.2	0.96
7.00	42.5	1.42	1.2
9.00	49.5	1.7	1.34
12.33	87	2.9	2.4
19.00	262.75	8.8	7.1

Table 3: discharge volume, volumetric flow rate and volume flux at different hydraulic head (SAMPLE C)

i	V x 10^{-6} (m^3)	Q x 10^{-7}(m^3/s)	q x 10^{-4}(ms^{-1})
Time: 1min			
5.67	15.45	2.60	2.10
7.00	24.00	4.00	3.30
9.00	35.5	5.90	4.80
12.33	37.50	6.30	5.10
19.00	57.00	9.50	7.70
Time: 2mins			
5.67	26.50	2.21	1.80
7.0	47.00	3.92	3.20
9.00	65.50	5.50	4.40
12.33	70.00	5.80	4.70
19.00	99.00	8.30	6.70

Time: 3mins			
5.67	40.00	2.22	1.80
7.00	64.00	3.56	2.90
9.00	88.50	4.92	4.00
12.33	97.75	5.40	4.40
19.00	136.0	7.56	6.10

Time: 4mins

i	V x 10^{-6} (m^3)	Q x 10^{-7}(m^3/s)	q x 10^{-4}(ms^{-1})
5.67	54.50	2.30	1.80
7.00	81.00	3.40	2.70
9.00	105.2	54.4	3.60
12.33	117.0	4.61	4.00
19.00	177.0	7.00	6.00

Time: 5mins			
5.67	63.5	2.12	1.70
7.00	96.5	3.22	2.60
9.00	135.5	4.40	3.60
12.33	142.5	4.61	3.70
19.00	206.0	7.00	5.60

Hydraulic conductivity for each of the samples at an interval of 1minute were obtained from the volume flux-hydraulic gradient curve (q- i curves) which are the gradient of the curves (Figs. 2-16). Permeabilities were determined by Hubert King's relation. Hydraulic conductivity and permeability at different time were presented in table 4. Both hydraulic conductivity and permeability were found to be declined as the time increased. This pattern of declination was exhibited by all the samples. Hydraulic conductivity was found to be ranging from 0.48×10^{-5} to 0.36×10^{-5} ms^{-1}, 5.42×10^{-5} to $4.65\times10^{-5}ms^{-1}$, and 3.87×10^{-5} to $2.66\times10^{-5}ms^{-1}$ for samples A,B, and C respectively. This shows that irrespective of the grain size, the highest permeability for each was obtained for the first 1 minute.

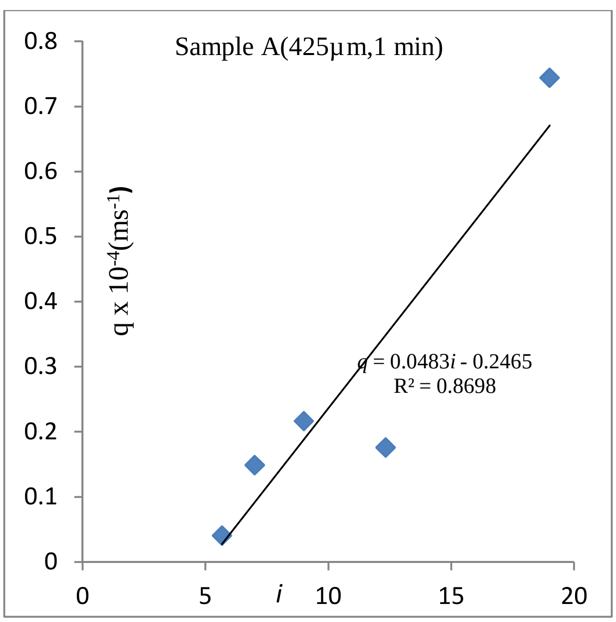

Fig. 2: Volume flux against hydraulic gradient (sample A, 1min.)

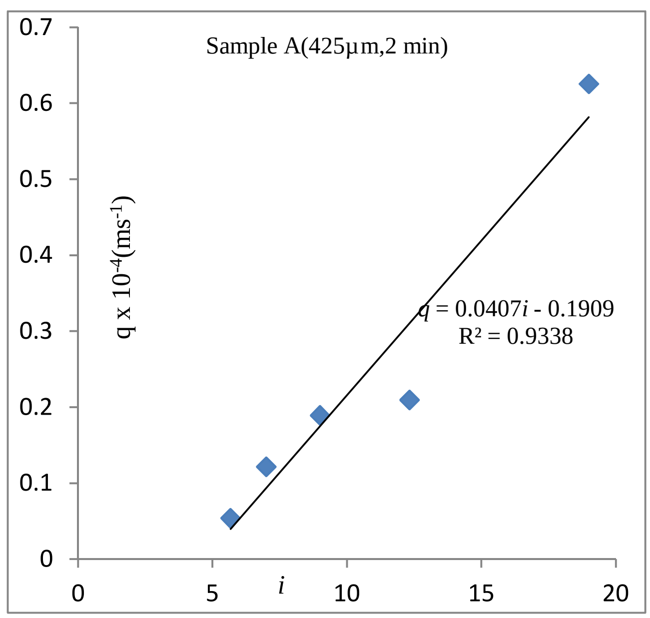

Fig. 3: Volume flux against hydraulic gradient (sample A, 2 min.)

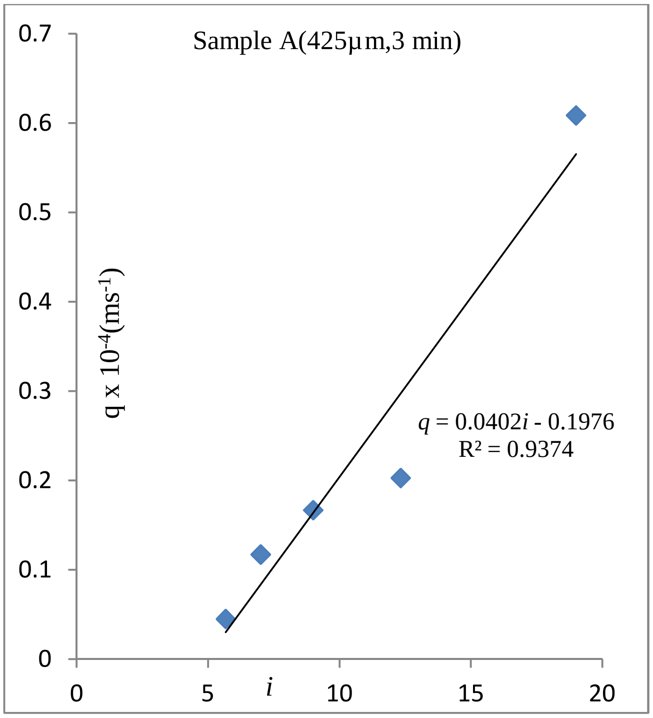

Fig. 4: Volume flux against hydraulic gradient (sample A, 3 min.)

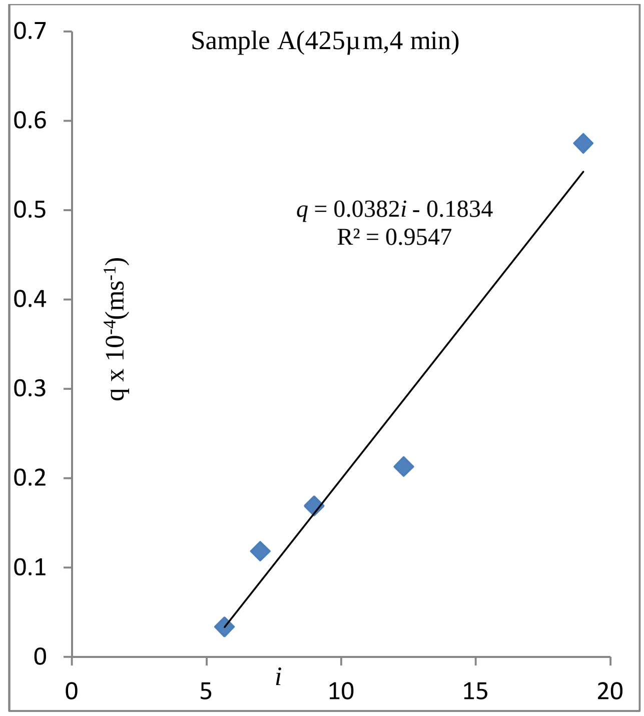

Fig. 5: Volume flux against hydraulic gradient (sample A, 4 min.)

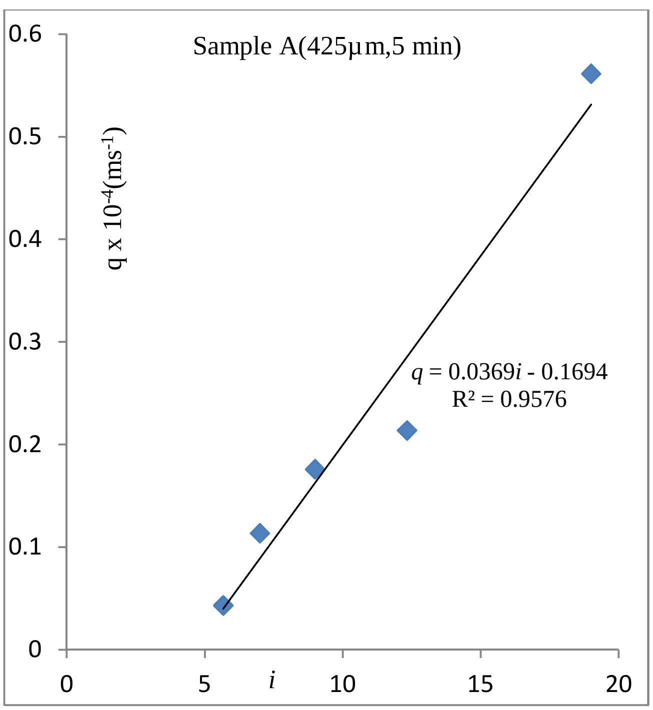

Fig. 6: Volume flux against hydraulic gradient (sample A, 5 min.)

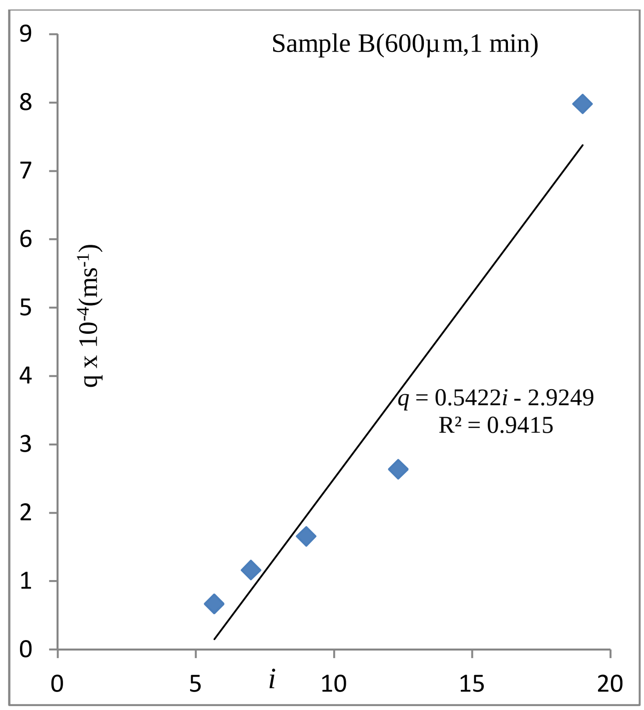

Fig. 7: Volume flux against hydraulic gradient (sample B, 1 min.)

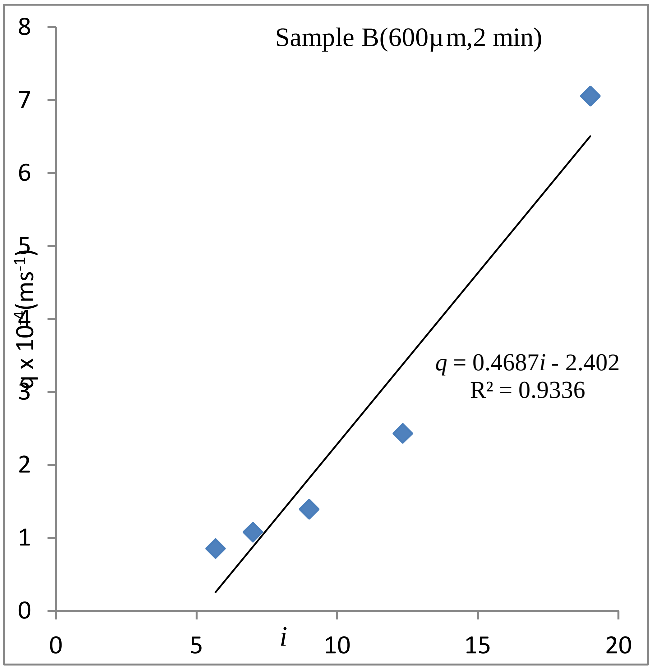

Fig. 8: Volume flux against hydraulic gradient (sample B, 2 min.)

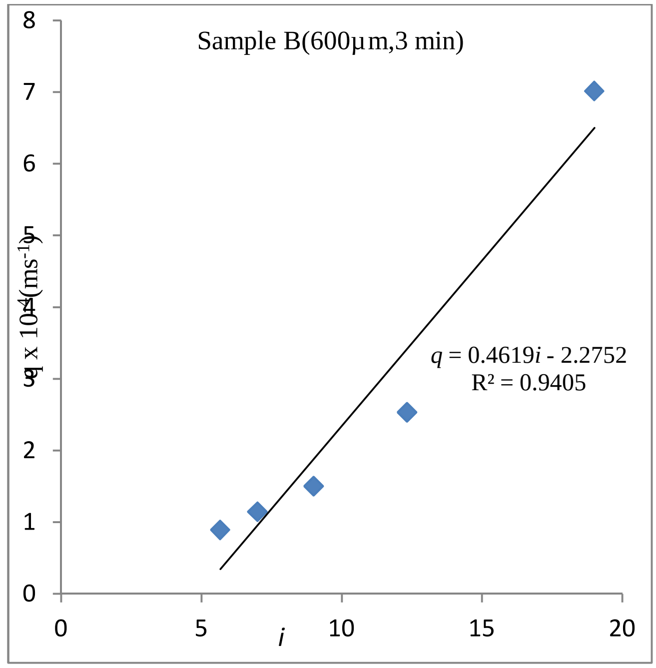

Fig. 9: Volume flux against hydraulic gradient (sample B, 3 min.)

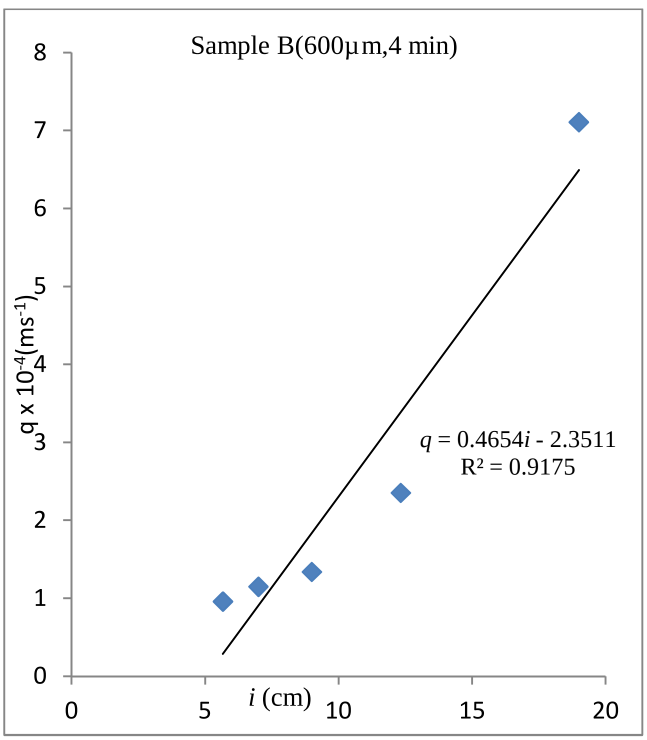

Fig. 10: Volume flux against hydraulic gradient (sample B, 4 min.)

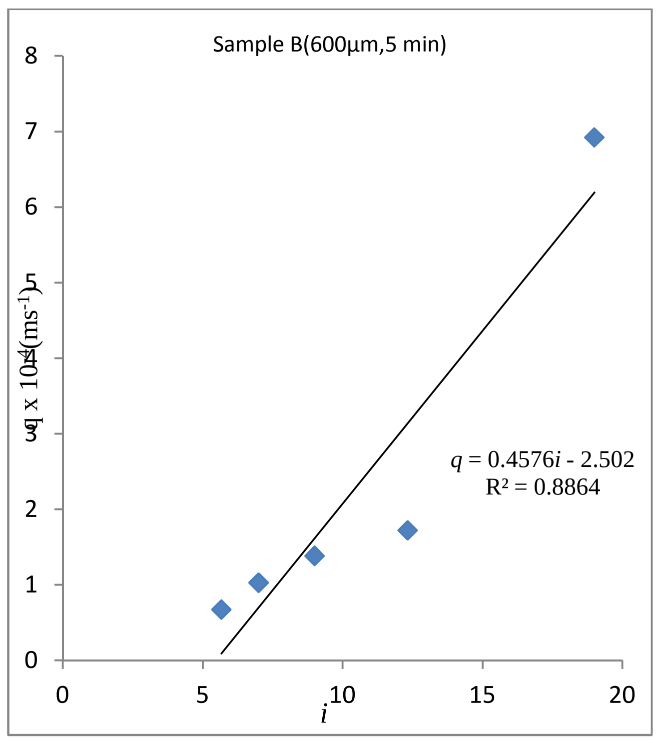

Fig. 11: Volume flux against hydraulic gradient (sample B, 5 min.)

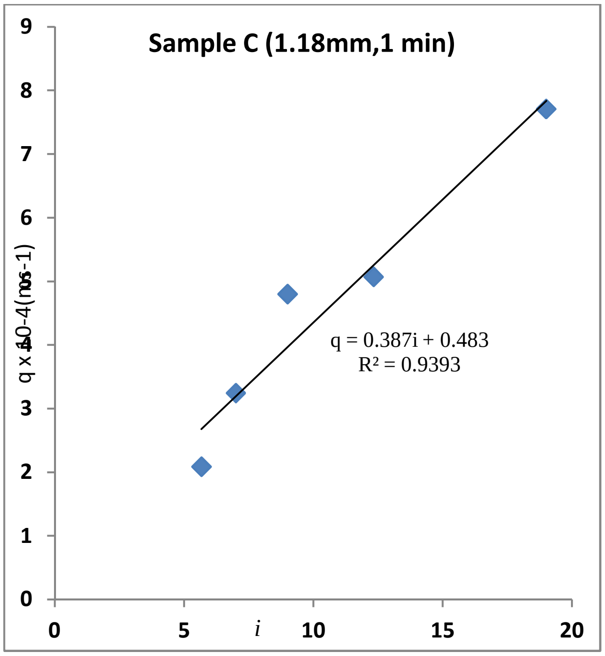

Fig. 12: Volume flux against hydraulic gradient (sample C, 1min.)

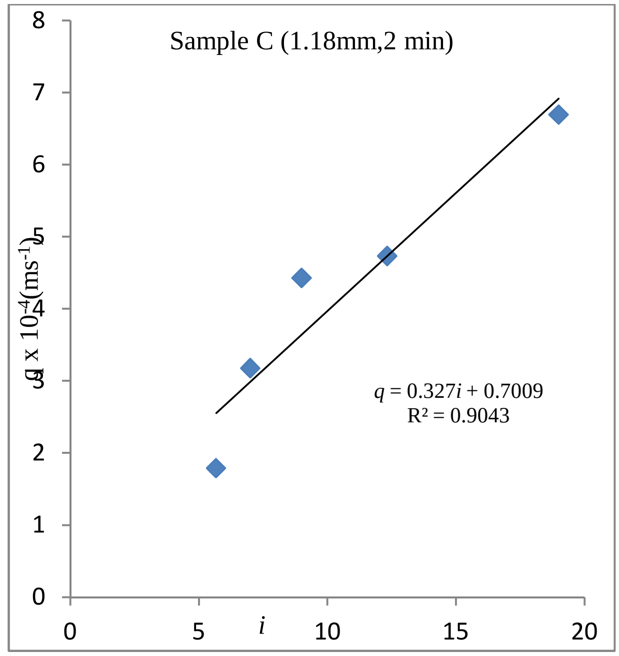

Fig. 13: Volume flux against hydraulic gradient (sample C, 2 min.)

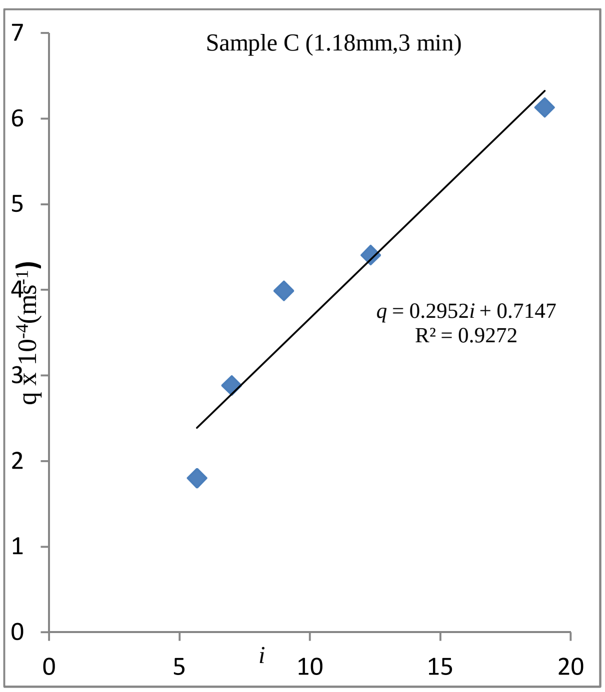

Fig. 14: Volume flux against hydraulic gradient (sample C, 3 min.)

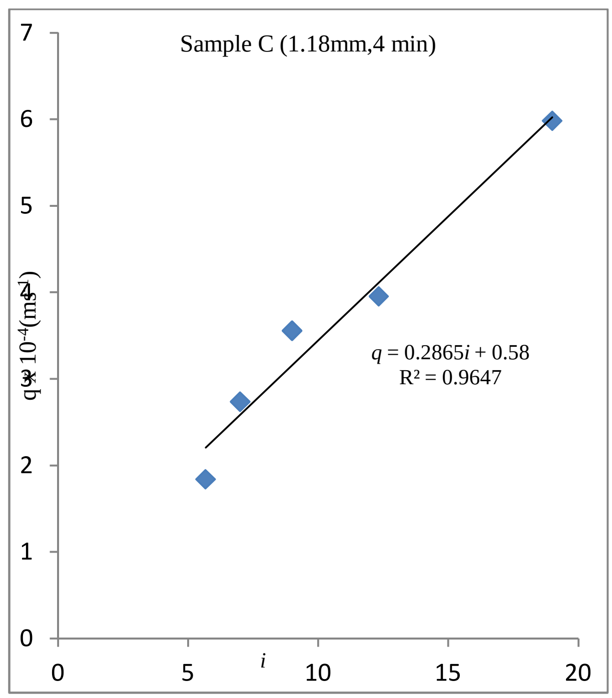

Fig. 15: Volume flux against hydraulic gradient (sample C, 4 min.)

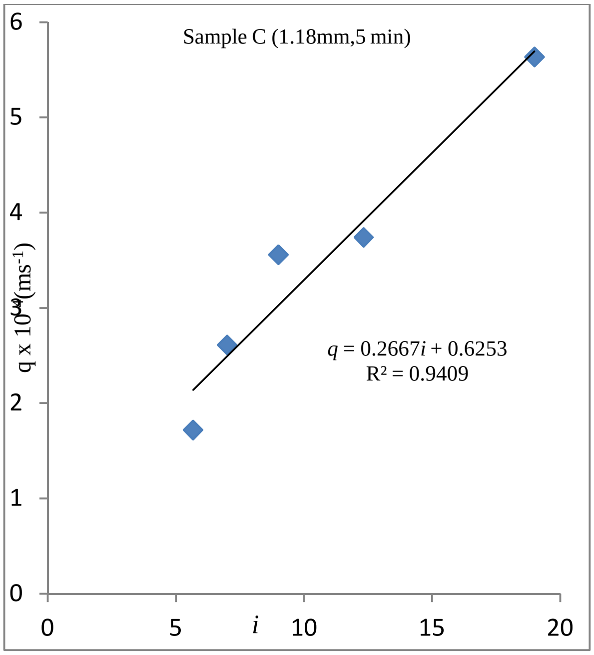

Fig. 16: Volume flux against hydraulic gradient (sample C, 5 min.)

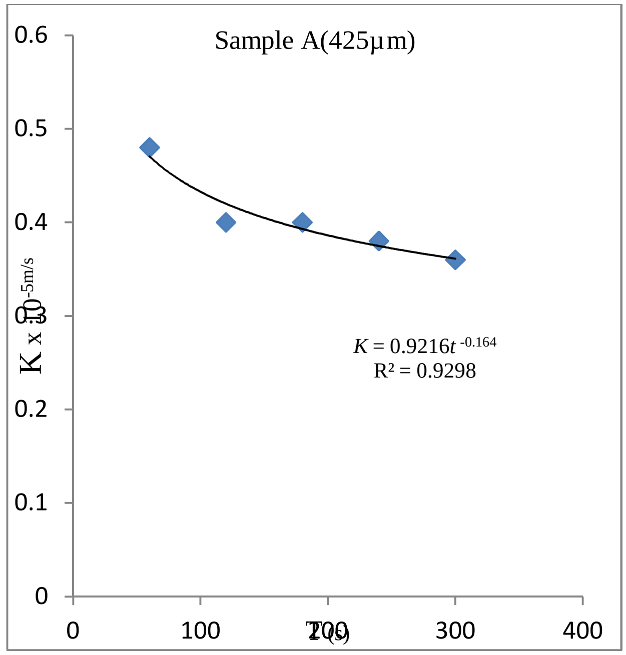

Fig. 17: hydraulic conductivity against time (sample A)

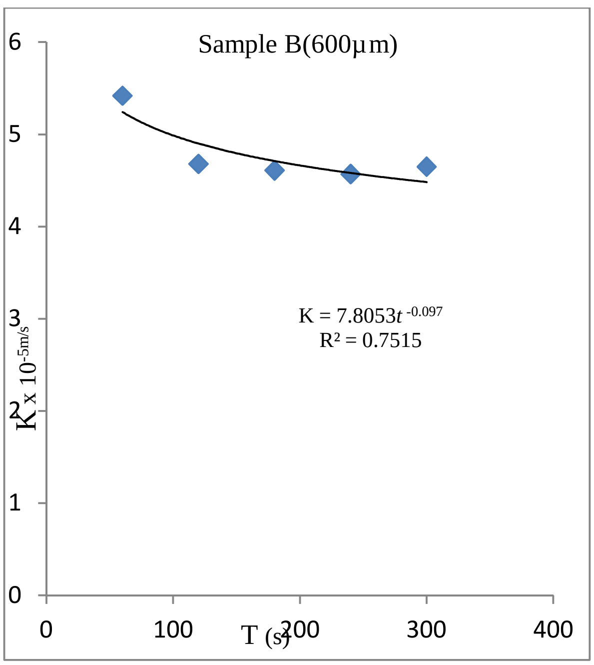

Fig. 18: hydraulic conductivity against time (sample B)

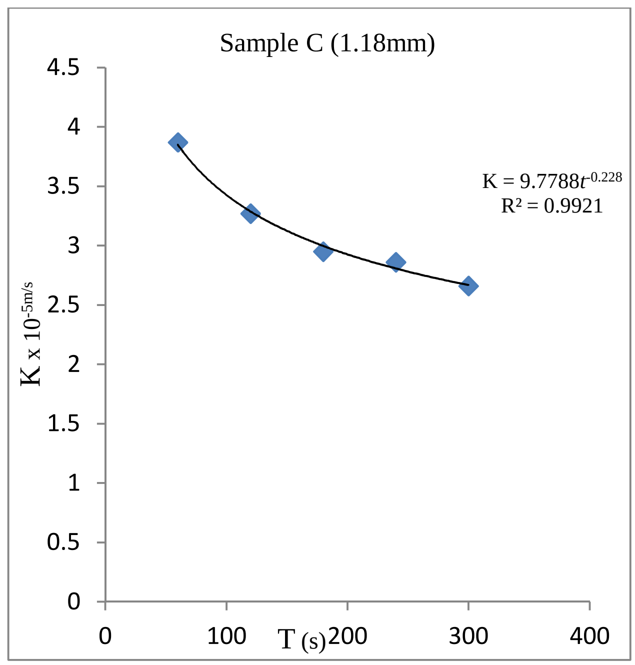

Fig. 19: hydraulic conductivity against time (sample C)

Table 4: hydraulic conductivity and permeability at different time

Time (s)	K x 10^{-5} (m/s)	k x 10^{-12} (m^2)
SAMPLE A		
60	0.480	0.4896
120	0.400	0.408
180	0.400	0.408
240	0.380	0.3876
300	0.360	0.3672
SAMPLE B		
60	5.42	5.53
120	4.68	4.77
180	4.61	4.70
240	4.57	4.66
300	4.65	4.10
SAMPLE C		
60	3.87	3.95
120	3.27	3.34
180	2.95	3.01
240	2.86	2.92
300	2.66	2.713

Furthermore, by best curve fitting, the $K - i$ curve yield $K=0.9216t^{-0.164}$, $K=7.8053t^{-0.097}$ and $K=9.7788t^{-0.228}$ for samples A, B and C respectively (Figs. 17-19). These equations show that hydraulic conductivity values decline with increase in time and can only be zero whenever time, t is zero.

It is clear that hydraulic conductivity vis-à-vis permeability is strongly influenced by time. The classic law of Darcy is almost universally employed to analyze the flow of fluid through soils and sands. In the analysis and modeling of groundwater flow such as infiltration of water in soils by Darcy's law as related to irrigation, there is possibility of overestimate or underestimate of volume of water supply to plant due to variability of hydraulic conductivity by Darcy's law. The understanding and introduction of declination of permeability with time is reformed or take into consideration for accurate estimation of volume of water available for plants grow especially in surface irrigation. If a constant permeability of soils as proposed by Darcy's is assumed there might be either excess or shortage of water.

Moore and co-workers[3, 4] obtained very good fit for the relationship between the saturated hydraulic conductivity of the surface seal at time t, initial saturated hydraulic conductivity, and final saturated hydraulic conductivity. It was found that hydraulic conductivity decline exponential with time. The equations obtained show that as time increase, the value of hydraulic conductivity will never be zero. The present study result corroborates with Moore's results, because as time of infiltration and seepage is increasing with time, zero hydraulic conductivity will never occur except when time of infiltration is zero, and this is a reasonable condition.

The equation obtained by Moore requires a prior knowledge of both initial and final saturated hydraulic conductivity for computation or estimation of saturated hydraulic conductivity at a particular time. However, saturated hydraulic conductivity can be obtained by the new proposed equation from this study without any prior information like Moore's equation. It should be noted that infiltration of water into soils is a continuous process, whereby the determination of the initial and final saturated hydraulic conductivity might not be relevant or difficult to obtain. Thus, Moore's equation may not be applicable for accurate estimation of volume of water available for plant in irrigation. Although, Moore's equation may be applicable in some other areas. In addition, the present equation or model is simple and practically useful because once the time is known, the hydraulic conductivity can be predicted for proper management in water irrigation, especially in surface irrigation.

Conclusion

A considerable amount of research has been conducted for the filtration of water into (and through) soils. The present study considered the laboratory test of one-dimensional vertical infiltration through clay of different particle sizes subjected to different hydraulic head. The hydraulic conductivities were determined at one minute the interval while permeabilities were obtained by Hubert King's relation. The results show that saturated hydraulic conductivity vis-à-vis permeability decline or decrease with increase in time. The equation obtained from $K - t$ curves shows that the declination of permeability will never be zero, expect at an initial state or stage before the commencement of infiltration process (that is at time zero). Also the equation obtained is simple and practically useful for estimation of the permeability at a particular time, for accurate estimate of the volume of water available for plant grows in surface irrigation.

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