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Investigation of Empirical Models for Hydraulic Conductivity from Grain-size Distribution

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Abstract

Seven empirical models for calculating hydraulic conductivities in soils based on grain-size distribution were investigated in this study. The results were compared with hydraulic conductivity of soils computed using the constant head permeability test. Three samples were collected from three trial pits in different locations along the bank of the stream located downstream of National Root Crops Research Institute's earth dam Umudike, Abia state Nigeria. The samples were subjected to sieve analysis and the constant head permeability tests using standard methods. Hydraulic conductivities in soils computed from the empirical formulae were each compared with hydraulic conductivity calculated using the constant head formula. Results showed that mean hydraulic conductivities for constant head, Hazen, Breyer, Kozeny-Carman, USBR, Kozeny, Terzaghi and Slitcher models were 18.16 m/d, 35.52 m/d, 34.80 m/d, 30.50 m/d, 25.86 m/d, 19.08 m/d, 15.66 m/d and 10.86 m/d respectively. ANOVA results for pairwise comparison indicated that Kozeny formula gave the best performance with a p-value of 0.78 at 0.05 critical value. This was followed by Terzaghi, USBR and Slitcher with p-values of 0.44, 0.11 and 0.059 respectively, while the Kozeny-Carman, Hazen and Breyer performed poorly with p-values of 0.03, 0.008 and 0.007 respectively. Confirmatory test using the Dunnett simultaneous tests for level mean - control mean, computed adjusted p-value was highest at 1.000 for Kozeny model. In all the tests, Kozeny, Terzaghi, Slitcher and USBR performed well with p-values 1.000, 0.923, 0.117, and 0.092 above the critical value of 0.05, while the Breyer, Hazen, and Kozeny-Carman performed poorly with p-values 0.000, 0.000 and 0.004 below the same critical value. Further research is recommended to address the contradictory results from various researchers.

Keywords: **Comparison, Empirical formulae, Constant head, Permeability, Grain-size distribution**

1. Introduction

The hydraulic conductivity of K of soils is of great importance in relation to some geotechnical problems, including the determination of seepage losses, settlement computations, and stability analysis. The development, management, and protection of groundwater resources also demand reliable estimates of hydraulic conductivities. Accurate estimates of K in the field environment are limited by the lack of precise knowledge of the aquifer geometry and hydraulic boundaries (Uma *et al*., 1989). The cost of field operations and associated wells can be very prohibitive as well. Laboratory tests, on the other hand , present formidable problems in the sense of obtaining representative samples and, very often, long testing times (Boadu, 2000). Alternatively, methods of estimating hydraulic conductivity from grain-size distribution and volumetric characteristics have been used to overcome these problems. Grain-size methods are comparably less expensive and do not depend on the geometry and hydraulic boundaries of the aquifer. Because information about the textural properties of soils is more easily obtained, a potential alternative for estimating hydraulic conductivity of soils is from grain-size distribution. Models of porous media exist that use pore-size distribution parameters to calculate hydraulic conductivity, however, parameter estimation requires expensive and complicated commercial equipment (Boadu, 2000).

The objective of this paper is to compare hydraulic conductivities obtained from laboratory tests (i.e. the constant head) with that obtained from grain-size distribution methods so as to ascertain their reliabilities. Hydraulic conductivities from laboratory tests are believed to be reliable, widely accepted and has been in use for decades, so that hydraulic conductivities from empirical models may be misleading unless comparative studies are carried out between result of hydraulic conductivity obtained from laboratory test and those computed from empirical models based on grain-size distribution.

Hydraulic conductivity k is the ease with which a fluid flows through a granular medium and it is a function of both the medium and the permeating fluid (Strobel, 2005). The most reliable means to obtain hydraulic conductivity is through aquifer pumping tests or laboratory measurement of permeability via constant head and variable head permeability tests respectively.

Determination of k by constant head permeability test is done using Darcy's law (1856):

$$k = \frac{ql}{Ah} \qquad (1)$$

Where q is volume of water flowing per unit time, l is length of soil sample in the Perspex cylinder, A is the cross-sectional area of the of soil sample.

Predictive methods of estimating hydraulic conductivities from grain-size distribution through quantitative relations have been developed by analogy to pipe flow and flow in capillaries (Kozeny, 1927; Carman, 1937). Besides predictive methods, empirical relations have also been employed (Hazen, 1911; Krumbein and Monk, 1942; Morrow *et al*., 1969; Berg, 1970; Alyamani and Sen, 1993; Koltermann and Gorelick 1995).

A commonly accepted relationship was proposed by Hazen (1911) and given as;

$$k = Ad_{10}^2 \qquad (2)$$

Where $k =$ hydraulic conductivity (cm/s): $A =$ constant; and $d_{10} =$ effective diameter or grain-size at which 10% of the grains are finer. On the other hand, Vukovic and Soro (1992) had a contrary view and summarized several empirical methods from former studies and presented a general formula:

$$k = \frac{g}{\upsilon} . C . f(n) . d_e^2 \qquad (3)$$

where $k =$ hydraulic conductivity; $g =$ acceleration due to gravity; $\upsilon =$ kinematic viscosity; C= sorting coefficient; $f(n) =$ porosity function, and $d_e =$ effective grain diameter. The kinematic viscosity (ν) is related to dynamic viscosity μ and the fluid (water) density (ρ) as follows:

$$\nu = \frac{\mu}{\rho} \qquad (4)$$

The values of C, $f(n)$, and d_e are dependent on on the different methods used in the grain-size analysis. According to Vukovic and Soro (1992), porosity (n) may be derived from the empirical relationship with the coefficient of grain uniformity (U) as follows:

$$n = 0.255(1 + 0.83^{U}) \quad (5)$$

Where U is the coefficient of grain uniformity and is given by;

$$U = \frac{d_{60}}{d_{10}} \quad (6)$$

Here $\boldsymbol{d_{60}}$ and $\boldsymbol{d_{10}}$ in the formula represent the grain diameter in (mm) for which, 60% and 10% of the sample respectively, are finer than.

To account for the distribution of the grain-size curve, Masch and Denny (1966) used the median grain-size d_{50} as the distribution's representative size in an endeavor to correlate permeability with grain size. Krumbein and Monk (1942) expressed the hydraulic conductivity (Darcy) of unconsolidated sands, with a lognormal grain-size distribution function with approximately40% porosity, by an empirical equation of the form:

$$k = (760d_w^2)exp(-1.13\sigma_{\psi}) \quad (7)$$

Where $d_w =$ geometric mean diameter (by weight) in millimeters; and $\sigma_{\psi} =$ standard deviation of the ψ distribution function ($\psi = -log_2 d$, for d in millimeters). The introduction of ψ onverts the lognormal distribution function for the grain diameters into a normal distribution function ψ. Berg (1970) modified the equation of Krumbein and Monk (1942) to account for the variation in porosity and determined the permeability variation with porosity of different systematic packing of uniform spheres using a semi-theoretical/empirical method.

Former studies have presented the following formulae which take the general form presented in equations (2) and (3) above but with varying $\boldsymbol{C}, \boldsymbol{f(n)}$, and $\boldsymbol{d_e}$ values and their domains of applicability. The hydraulically based Kozeny-Carman model is well known:

$$k = \left(\frac{\rho_w g}{\mu}\right)\frac{\phi^3}{(1-\phi)^2}\left(\frac{d_m^2}{180}\right) \quad (8)$$

Where $k =$ hydraulic conductivity; $\rho_w =$ fluid density; $\mu =$ fluid viscosity; $\phi =$ porosity; and $d_m =$ representative grain size. The Kozeny-Carman equation is one of the most widely accepted and used derivations of permeability as a function of the characteristics of the soil medium. This equation was originally proposed by Kozeny (1927) and was then modified by Carman (1937, 1956) to become the Kozeny-Carman equation. It is not appropriate for either soil with effective size above 3 mm or for clayey soils. However, the choice of the representative grain size is critical to the successful prediction of the hydraulic conductivity from the grain-size distribution. In applying this equation, a fixed value of d_m is typically chosen to represent the entire range of grain sizes. Koltermann and Gorelick (1995) assert that the use of the geometric mean over-predicts hydraulic conductivity by several orders of magnitude for soils with significant fines content. In contrast, the authors indicate that the harmonic mean grain size representation under-predicts k by several orders of magnitude for soils with lesser fines content. Their reasoning is that, overall, the harmonic mean puts greater weight on smaller grain sizes, whereas the geometric mean puts greater weight on larger sizes. Thus, the best representative value depends on the type of grain packing and the concentrations of the components by fractal weight. It is clear that successful prediction of hydraulic conductivity demands a representative value that will encompass the range of sizes in the grain-size distribution. Further, accurate knowledge of the state of sorting and the packing is desirable.

Other empirical formulae exist such as the one from;

Hazen: $k = \frac{g}{v} \times 6 \times 10^{-4}[1 + 10(n - 0.26)]d_{10}^2 \quad (9)$

Hazen formula was originally developed for determination of hydraulic conductivity of uniformly graded sand but is also useful for fine sand to gravel range, provided the sediment has a uniformity coefficient less than 5 and effective grain size between 0.1 and 0.3 mm.

Breyer: $k = \frac{g}{\nu} \times 6 \times 10^{-4} log \frac{500}{U} d_{10}^2$ (10)

This method does not consider porosity and therefore, porosity function takes on value 1. Breyer formula is often considered most useful for materials with heterogeneous distributions and poorly sorted grains with uniformity coefficient between 1 and 20, and effective grain size between 0.06 mm and 0.6 mm.

Slitcher: $k = \frac{g}{\nu} \times 1 \times 10^{-2} n^{3.287} d_{10}^2$ (11)

This model is most applicable for grain-size between 0.01 mm and 5 mm.

Terzaghi: $k = \frac{g}{\nu} . C_t . \left(\frac{n - 0.13}{\sqrt[3]{1-n}}\right)^2 d_{10}^2$ (12)

Where $C_t =$ sorting coefficient and range between $6.1 \times 10^{-3} < C_t < 10.7^{-3}$. Terzaghi formula is most applicable for large-grain sand (Cheng and Chen, 2007).

USBR: $k = \frac{g}{\nu} \times 4.8 \times 10^{-4} d_{20}^{0.3} \times d_{20}^2$ (13)

U.S. Bureau of Reclamation (USBR) formula calculates hydraulic conductivity from the effective grain size (d_{20}), and does not depend on porosity; hence porosity function is a unity. The formula is most suitable for medium-grain sand with uniformity coefficient less than 5 (Cheng and Chen, 2007)

Alyamani and Sen: $k = 1300[I_0 + 0.025(d_{50} - d_{10})]^2$ (14)

Where k is the hydraulic conductivity (m/day), I_0 is the intercept (mm) of the line formed by d_{50} and d_{10} with the grain-size axis, d_{10} is the effective grain diameter (mm), and d_{50} is the median grain diameter (mm). it should be noted the terms in the formula above bear the stated units for consistency. This formula therefore, is exceptionally different from those that take the general form of equations (2) and (3) above. It is however, one of the well known equations that also depends on grain-size analysis. This method considers both sediment grain sizes $\boldsymbol{d_{10}}$ and $\boldsymbol{d_{50}}$ as well as the sorting characteristics.

2. Materials and Methods

2.1 *Samples and Sampling Techniques*

Soil samples were collected from three different locations along the bank of the stream downstream of National Root Crop Research Institute's earth dam Umudike, Ikwuano Local Government Area of Abia State, Nigeria. Special core sampling instrument with its accessories were used for sample collection. The core-cutter (sample collection instrument) was pressed down, then hammered into the soil by means of a wooden mallet to 1.5 m depth. Two more samples were collected at 20 m intervals using the same procedure. The metal tube sampler was withdrawn. The soil samples were collected, placed inside a polythene bag and taken to the laboratory for constant head permeability and particle size distribution tests respectively.

2.2 *Experimental Procedure*

The hydraulic conductivity of soil samples were determined by means of the constant head permeability test. The soil specimen, at the appropriate density, was contained in a Perspex cylinders (cores) of lengths 25 cm, 19.5 cm and 22 cm all of diameter 7.5 cm for samples A, B, C and cross-sectional area 44.18 cm^2: the specimen rested on a coarse filter or a wire mesh. A steady vertical flow of water, under a constant total head, was maintained through the soil and the volume of water flowing per unit time (q) was measured. Tappings from the side of the cylinder enabled the hydraulic gradient (h/l) to be measured. Then from Darcy's law:

$$k_{sat} = \frac{VL}{AT\Delta H} \quad (15)$$

Where V is volume of water leached, L is length of core (i.e. sand column in cylinder), A is the cross-sectional area of soil in the cylinder, T is time of flow and ΔH is change in hydraulic head.

A series of tests was run, each at a different rate of flow. Prior to running the tests a vacuum was applied to the specimen to ensure that the degree of saturation under flow was close to 100%.

For the particle size analysis, the particle size distribution was determined by the method of sieving. The soil samples were passed through a series of standard test sieves having successively smaller mesh sizes. The weight of soil retained in each sieve was calculated. Full details of the determination of particle size by the sieving method is given in BS 1377 [1.2] (1975). The results from the particle size analysis were plotted on a semi-log graph and enabled determine the values d_{10}, d_{20}, d_{30}, and d_{60} which are the percentages passing at 10%, 20%, 30% , and 60% finer. Pair-wise comparison were carried out on the data to determine the reliability of the models by subjecting the data to analysis of variance (ANOVA) at 5% level of significance to ascertain if there are correlations between the models for calculating hydraulic conductivities and for reliability purpose. Data was analyzed using SPSS statistical package.

Hypothesis:

Null Hypothesis:

There is no significant difference between the laboratory tests and empirical formulae results.

Alternative Hypothesis:

There is significant difference between the laboratory tests and empirical formulae results.

3. Results and Discussion

From the sieve analysis, the major constituent of the soil samples are coarse gravel and medium sand. Based on British Soil Classification System for Engineering Purposes, samples A and B show that more than 50% of coarse material is of sand size (finer than 2 mm) and are classified as silty sand with group symbol (S-M). While in sample C, more than 50% of coarse material is of gravel size and is classified as slightly silty gravel with group symbol (GW). In table 3, the gradation parameters were presented such as porosity, uniformity coefficient, coefficient of curvature, percent passing at 10%, 20%, 30% and 60% finer respectively.

Table 1. Hydraulic Conductivity Test Results

Samples	T(mins)	ΔH (cm)	Mean Volume (cm^3)	VL	$AT\Delta H$	k_{sat} (m/day)
A	3	25	160.00	4000.00	3313.40	17.38
B	3	30.5	201.33	3926.00	4042.35	13.99
C	3	28	270.83	5958.33	3711.01	23.12

Table 1 show the mean results of hydraulic conductivities from constant head permeability tests conducted on the soil samples. The results are 17.38 m/day, 13.99 m/day, and 23.12 m/day for samples A, B, and C respectively, with an average value of 18.16 m/day.

Table 2: Particle Size Distribution of Samples from Sieve Analysis

Sample	Fine gravel (%)	Coarse gravel (%)	Medium sand %)	Fine sand (%)	Silt and clay (%)	Total (%)
A	9.11	35.65	48.16	4.83	2.25	100
B	9.12	34.80	52.70	3.04	0.34	100
C	9.77	42.22	44.06	3.69	0.26	100

The quantitative analysis results of grading curves are shown in Table 3 below. These were achieved by using certain geometric values known as grading characteristics such as d_{10}, d_{20}, d_{30}, d_{60} to enable compute the uniformity coefficient ($C_u = d_{60}/d_{10}$) and the coefficient of gradation or curvature $[(d_{30})^2/(d_{60} \times d_{10})]$. The soil sample classification indicated that sample A comprised 9.11% fine gravel, 35.65% coarse gravel, 48.16% medium sand, 4.83% fine sand and 2.25% silt and clay. Sample B comprised 9.12% fine gravel, 34.80% coarse gravel, 52.70% medium sand, 3.04% fine sand and 0.34% silt and clay. Sample C was made up of 9.77% fine gravel, 42.22% coarse gravel, 44.06% medium sand, 3.69% fine sand and 0.26% silt and clay.

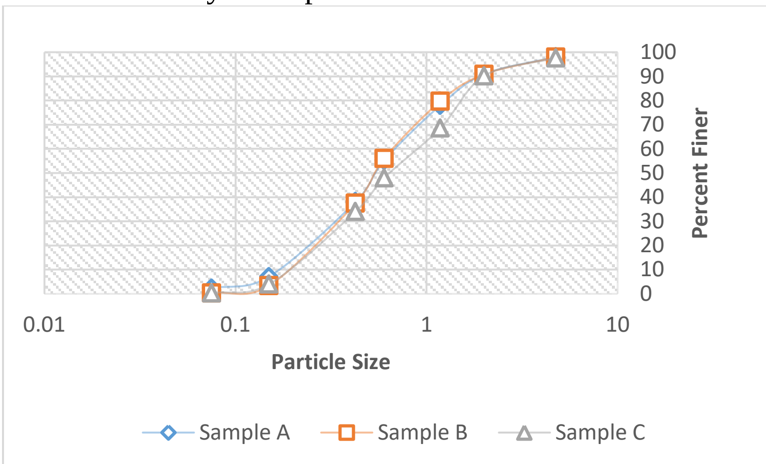

Figure 1: Particle size distribution curves from sieve analysis

Table 3: Gradation Parameters from Grain Size Analysis of Soil Samples

Sample	n	C_u	C_c	D_{10}	D_{20}	D_{30}	D_{60}
A	0.373	4.118	1.213	0.170	0.280	0.380	0.700
B	0.384	3.676	1.272	0.185	0.300	0.400	0.680
C	0.360	4.737	1.007	0.190	0.325	0.415	0.900

Table 4: Hydraulic Conductivity Test Results from Empirical Models

Sample	Hydraulic conductivities (m/day)							
	LAB	K-C	TZ	USBR	BREYER	HAZEN	SLITCHER	KOZENY
A	17.384	26.823	13.800	21.660	30.480	31.206	9.5636	16.810
B	13.986	35.741	17.930	25.390	36.951	38.716	12.371	21.930
C	23.120	28.946	15.230	30.520	36.963	36.624	10.642	18.510

LAB = Laboratory test; K-C = Kozeny-Carman; TZ = Terzaghi; USBR = U.S. Bureau of Reclamation

While in Table 4, hydraulic conductivities from laboratory (constant head) tests and those obtained from empirical models were presented and include the Kozeny-Carman, Terzaghi, USBR, Breyer, Hazen, Slitcher and Kozeny for samples A, B, and C respectively.

Table 5: ANOVA Results for Pairwise Comparison

Factors	SS_b	SS_w	DF_w	MS_w	F	P-value	Results
K-C	228.4132	9.425364	4	21.50993	10.61896	0.03112	Poor
Terzaghi	9.425364	51.43606	4	12.85901	0.732977	0.440177	Better
USBR	88.78246	82.18689	4	20.54672	4.321004	0.106179	satisfactory

Breyer	415.0612	70.59572	4	17.64893	23.51764	0.008342	Poor
Hazen	451.6393	72.67668	4	18.16917	24.85745	0.007567	Poor
Slitcher	80.0308	46.64487	4	11.66122	6.862989	0.058816	satisfactory
Kozeny	1.267743	56.24244	4	14.06061	0.090163	0.778929	excellent

A Statistical technique, analysis of variances ANOVA was carried out to check the statistical significance between the laboratory experiment and the empirical formulae results. P-value which is the criteria was used to infer the significant level using the probability level of 95% or 0.05. Microsoft excel analytical software was used for this computation. When the p-value is more than the critical value which is 0.05, then there exists no significant difference between the compared data sets and vice versa. From the results, Kozeny formula performed excellent with a p-value of 0.78; Terzaghi formula performed better with a p-value of 0.44 while Kozeny-Carman, Breyer and Hazen formula performed poorly with a p-value of 0.03, 0.008 and 0.0076 respectively. USBR and Slitcher formulae performed satisfactorily with a p-value of 0.106 and 0.059 respectively. The detailed results of the ANOVA is presented in table 5 above.

When ANOVA test has significant findings, Dunnett test is used to identify the pairs with significant difference. Based on the complexity, different components in the models and characteristics of the models, there is need to use other analytical software to check and affirm the results obtained. These will serve as confirmatory tests as in the results obtained from ANOVA presented in Table 5.

3.1. Dunnett Multiple Comparisons with a Control

Dunnett's test was performed by computing a Student's t-statistic for each experimental or treatment group where the statistic compares the treatment group to a single control group. Since each comparison has the same control in common, the procedure incorporated the dependencies between these comparisons. In particular, the t-statistics were all derived from the same estimate of the error variance which was obtained by pooling the sums of squares for error across all (treatment and control) groups. The formal test statistic for Dunnett's test is either the largest in absolute value of these t-statistics (if a two-tailed test is required), or the most negative or most positive of the t-statistics (if a one-tailed test is required) (Dunnett, 1955). The statistical results is shown in Table 6 below.

Table 6: Grouping Information using the Dunnett Method and 95% Confidence

Factor	N	Mean	Grouping
LAB (control)	3	18.16	A
HAZEN	3	35.52	
BREYER	3	34.80	

K-C	3	30.50	
USBR	3	25.86	A
KOZENY	3	19.08	A
TZ	3	15.66	A
SLITCHER	3	10.86	A

Means not labeled with the letter A are significantly different from the control level mean.

From Table 6, the Hazen, Breyer and Kozeny-Carman models were not labeled with the letter A and as a result they are significantly different from the control which is laboratory (constant head) test. The USBR, Kozeny, Terzaghi and Slitcher models were labeled with the letter A which indicate that there are no significant difference between them and the control. These results are in agreement with the one presented in Table 5 above.

3.2: Dunnett Simultaneous Tests for Level Mean - Control Mean

For k groups, ANOVA was used to look for a difference across k group means as a whole. Since there is a statistically significant difference across k means then a multiple comparison method was used to look for specific differences between pairs of groups. The reason that two sample methods should not be used to make multiple pair-wise comparisons is that they are not designed for repeat testing in a "data dredging" manner. For this purpose the Dunnett test is adopted and the result presented in Table 7.

Table 7: Dunnett Simultaneous Tests for Level Mean - Control Mean

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
K-C - LAB	12.34	2.96	(3.69, 20.99)	4.17	0.004
TZ - LAB	-2.51	2.96	(-11.16, 6.14)	-0.85	0.923
USBR - LAB	7.69	2.96	(-0.96, 16.34)	2.60	0.092
BREYER - LAB	16.63	2.96	(7.99, 25.28)	5.62	0.000
HAZEN - LAB	17.35	2.96	(8.70, 26.00)	5.87	0.000
SLITCHER - LAB	-7.30	2.96	(-15.95, 1.35)	-2.47	0.117
KOZENY - LAB	0.92	2.96	(-7.73, 9.57)	0.31	1.000

Individual confidence level = 99.01%

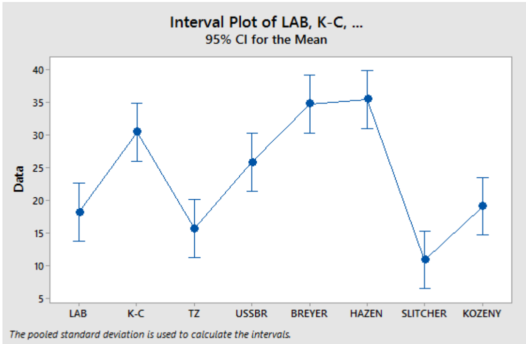

Fig.2: Plot of confidence interval for the mean with corresponding empirical models

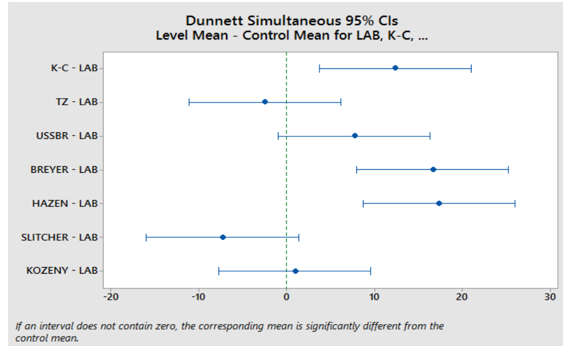

Fig. 3: Plot of difference of levels with corresponding 95% confidence intervals

The adjusted p-value as shown in the Dunnett test result above indicates which pairs within a family of comparisons are significantly different. It is evident from Table 7 that adjusted p-value agree with what obtains in Table 5 because Kozeny formula is the best with adjusted p-value of 1.000 followed by Terzaghi, Slitcher and USBR with adjusted p-values of 0.923, 0.117 and 0.092, this showed no significant difference with the control. With adjusted p-values of 0.004, 0.000 and 0.000 for Kozeny-Carman, Breyer and Hazen models, significant difference exist between these models and the control . Mean values of hydraulic conductivities obtained from samples A, B, and C for each of the models were plotted against the corresponding models as shown in Fig. 2. If an interval does not contain zero, the corresponding mean is significantly different from the control mean. This is shown in Fig. 3 and it can be seen that intervals in Kozeny-Carman/Laboratory, Breyer/Laboratory, and Hazen/Laboratory do not contain zero and their means are significantly different from the control mean an indication of poor performance. The intervals in Terzaghi/Laboratory, USBR/Laboratory, Slitcher/Laboratory and Kozeny/Laboratory contain zero and indicate no significant difference from control, here the Slitcher model appear to give the best result in conformity with the work of Aminifard and Siosemarde, (2014). They showed that Slitcher model is the best for estimation of hydraulic conductivity with root mean square error (RMSE) of 6.78, mean absolute error (MAE) of 5.73, relative error (RE) of 26.71 and deviation time (DT) of 1.46, while results from the work of (Odong, 2007) stated that Kozeny-Carman formula proved to be the best estimator of most samples analyzed, and may be, even for a wide range of other soil types. Hussain and Nabi (2016) have a contrary view, they affirmed that out of the seven empirical formulae that Kozeny-Carman, Hazen and Breyer reliably estimated hydraulic conductivities of various soil samples well within the known ranges while the other formulae Slitcher, Terzaghi, USBR, Alyamani and Sen methods underestimated the results as compared to constant head method results for all samples. From the results of the adjusted p-value, Kozeny and Terzaghi were the best at 1.0 and 0.923 respectively while Breyer and Hazen where the worst at 0. It can be seen that there exists high level of contradictions in the findings from different researchers and therefore further researches are recommended.

Conclusion

Studies from both the laboratory and grain-size distribution for estimation of hydraulic conductivities from three soil samples A, B, and C showed that mean value of hydraulic conductivity of soils from constant head tests was 18.16 m/day. Mean values for Hazen, Breyer, Kozeny-Carman, USBR, Kozeny, Terzaghi and Slitcher models were 35.52 m/d, 34.80 m/d, 30.50 m/d, 25.86 m/d, 19.08 m/d, 15.66 m/d and 10.86 m/d respectively. In the ANOVA for pair-wise comparison, Kozeny formula was the best with a p-value of 0.78 against a critical value of 0.05 or 95% confidence interval. This result was confirmed using the Dunnett simultaneous tests for level mean - control mean in which adjusted p-value for Kozeny-Laboratory comparison was found to be 1.0 being the highest. These results indicate that Kozeny formula is the best in estimation of hydraulic conductivity and was followed by Terzaghi, Slitcher and USBR with adjusted p-values of 0.923, 0.117, and 0.092, while the Breyer, Hazen and Kozeny-Carman formulae performed poorly with adjusted p-values of 0.000, 0.000 and 0.004 respectively. Although various researchers hold different views based on the outcome of their researches, further research is recommended to resolve these anomaly.

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