



Prediction of unsaturated soil hydraulic conductivity using air permeability: Regression approach

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ABSTRACT

A close correlation between water conductivity ($K(\theta)$) and air permeability (K_a), measured at various water contents, is expected due to tight dependence of water filled porosity to air filled porosity of soils. Finding such a relation will greatly facilitate the prediction of unsaturated water conductivity ($K(\theta)$). So, the purpose of the current investigation was to find out if a reliable relation or function between the two permeabilities can be established. In this regard, $K(\theta)$ and K_a were measured by pressure plate outflow and variable head methods, respectively, at the range of 0 to -100 kPa matric potential (ψ_m). A linear regression function between relative water conductivity ($K_r(\theta)$) and K_a ($\log K_r(\theta) = a + b \log K_a$) with the correlation coefficient (R) from 0.884 to 0.999 were established for the 22 examined soils. The overall R for 128 data pairs ($K_r(\theta)$ and K_a) became 0.821 (being significant at $P < 0.01$) with the slope (b) of -2.54 and intercept (a) of -10.93. For the comparison propose $K_r(\theta)$ were also predicted from *RETC* using experimental *SMC* data and van Genuchten and Brooks-Corey models. The reliability of the $K_r(\theta)$ prediction from K_a based on root mean square error (*RMSE*), geometric mean error ratio (*GMER*), and geometric standard deviation of error ratio (*GSDER*) criteria became considerable greater than those predicted from the two mentioned models.

Key words: Air permeability, Pedo-transfer function, Porous media, Water conductivity.

INTRODUCTION

In assessment of soil and ground water contamination risk or soil remediation activities, reliable prediction of soil hydraulic characters such as matric potential ($h(\theta)$), unsaturated water conductivity ($K(\theta)$), relative water conductivity ($K_r(\theta)$), and soil water diffusivity ($D(\theta)$) functions are often required. To achieve this goal generally two approaches of direct and indirect measurements have been employed.

Major limitations in their direct measurement either at laboratory or field are associated with not only sampling issues but also with time-consuming procedures. Measuring of characters such as K_s , as a reference for $K(\theta)$ prediction, may often be accompanied by some degree of alteration in pore size and structure during the measurement, which may lead to unrealistic figures.

To avoid these problems, several models as pedo-transfer functions (*PTFs*) have been developed to predict $h(\theta)$ and $K(\theta)$. However, validation or calibration of the mentioned *PTFs* still requires some kinds of direct or experimental measurements. In the other words, *PTFs*

developments have not totally eliminated the necessity of the laboratory or field measurements and, therefore, the problems associated with them still challenge soil physicists. So soil scientist always were trying to adopt some new methods which are user-friendly and fast in $K(\theta)$ predictions. Probably, linking $K(\theta)$ to soil air permeability (K_a) is in line with the last object.

Considering flow phenomena in porous media, although, Klinkenberg (1941) mentioned that flow mechanism of the gas in porous media is not exactly as same as the liquid one, their transports in soil follow the basic concepts of the fluid flow. Klinkenberg (1941) demonstrated that gases does not stick to the walls of the pores as liquid does. The last term has been named 'slip' meaning that the layer of gas is in motion next to the surface sliding on pores walls. However, further investigation of the Klinkenberg theory showed that the permeability to gas should be expected to approach as one for liquid at the high gas pressures (Long *et al.*, 1988). Considering the last sentence, soil scientist came up with a promising idea to link $K(\theta)$ to K_a for its fast prediction.

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Although, there is no report of any analytical approach which uses air permeability to predict unsaturated hydraulic conductivity ($K(\theta)$) since Klinkenberg theory, several studies have related K_s to K_a empirically due to easier and much rapid measurements of K_a compared to K_s . For example, Blackwell *et al.* (1990) presented two linear equations predicting K_s from K_a at -5 kPa based on 38 (0.055 m³ volume) and 22 (0.005 m³ volume) undisturbed core samples taken, respectively, from the intact and deep ripped, gypsum amended soils. Their research indicated that the volume and depth of samples did not alter the nature of the equation derived between K_s and K_a . Poulsen *et al.* (1999) developed an equation to predict K_s based on total and air filled porosity at -10 kPa matric potential. Loll *et al.* (1999) carried out similar study with emphasizing on the application of predicted K_s in infiltration modeling. Chief *et al.* (2008) also have correlated K_a to K_s reporting an applicable predictive relation with overall RMSE of the 0.0551 m d⁻¹.

In spite of the cited studies carried out for estimating K_s from K_a , predicting $K(\theta)$ from K_a , as far as the authors know, has not yet been investigated. Therefore, the aim of this research was to study about the possibility of fast and reliable prediction of relative water conductivity ($K_r(\theta)$) from K_a . Relative water conductivity, the ratio between unsaturated and saturated soil water conductivities, is a dimensionless character of soil which is presumed to be easily correlated to K_a . Note that the relative hydraulic conductivity, $K_r(\theta)$ varies from 0 (when $\theta = 0$) up to 1 (when $\theta = \theta_s$).

MATERIALS AND METHODS

Soil Samples and Laboratory Measurements: Twenty-two soil series with eight various textural classes (sand to silty clay loam) were selected from Karaj, Varamin and Urmia plains in Iran. Undisturbed core samples were taken by manual sampler from 0.05-0.1 m depth at three replicates. Bulk and particle densities were measured according to Jacob & Clarke (2002) and soil texture by hydrometer (Gee & Or, 2001). After saturating the samples by calcium chloride solution (0.01 mol L⁻¹), saturated hydraulic conductivity was measured by constants or falling pressure method (Table 1) dependent on the soil texture class (Klute & Dirksen, 1986). Volumetric water content of each core sample at 2.5, 3.5, 7 kPa suctions were determined by water hanging column and at 10, 20, 30, 50 and 100 kPa by pressure plate apparatus. The laboratory method proposed by Kirkham & Powers (1972) was applied to the direct measurement of K_a in undisturbed soil cores after their equilibration at various suction in hanging columns or pressure plate apparatus. Air was discharged through the soil core from a closed container of constant volume but with falling pressure. As the air was discharged, pressure within the container was recorded as a function of time. The permeability is then was calculated from Eq. (1):

$$K_a = -2.303 \frac{V \eta \delta_s (\log P_2 - \log P_1)}{A P_a \Delta t} \quad [1]$$

where η is air viscosity (N.sec m⁻²), V is volume of the container (m³), P_a equals to atmospheric pressure (Nm⁻²), P_1 and P_2 (mH₂O) were measured by a manometer connected to the container at time t_1 and t_2 , respectively, $\Delta t = t_2 - t_1$ was the duration of air flow through the soil core, δ_s and A were the length (m) and cross section area (m²). The K_a represents air permeability in Darcy, being the number of cubic meters of fluid (air) of 1N sec m⁻² viscosity passes in one second through a unit cross area of the soil core under the pressure gradient of 1Nm⁻² per meter. It is equivalent to 10⁻⁶ m² intrinsic permeability.

Pressure plate multistep outflow method (Gardner, 1956) was applied to measure $K(\theta)$ at 5 or 7 various suctions within 0-100 kPa range. The core samples were subjected to the given gas pressure and the volumes of outflow as a function of time were recorded at each pressure increment. The expression for hydraulic conductivity has been proposed as:

$$K(\theta) = \frac{4\beta Q_0 \rho_w g L^2}{\pi^2 V \Delta P} \quad [2]$$

Q_0 is total outflow volume (m³) at the pressure increment (ΔP), Q is the volume (m³) of water released at various times (t , sec) over the ΔP , V and L represent volume (m³) and length (m) of the soil core, β is the slope of the regression line (sec⁻¹) plotted as $\log[Q_0 - Q]$ against time (t), P_w is water density (kg m⁻³), g is acceleration of gravity (m sec⁻²), $K(\theta)$ is unsaturated hydraulic conductivity (m sec⁻¹) at average suction P_1 and P_2 , and ΔP equals to ($P_2 - P_1$) in N m⁻². Finally, relative water conductivity ($K_r(\theta)$) was calculated using the following equation:

$$K_r(\theta) = \frac{K(\theta)}{K_s} \quad [3]$$

Reliability Analysis: van Genuchten and Brooks-Corey models (van Genuchten, 1980) as reference models were used to check the suggested model reliability. Using van Genuchten and Brooks-Corey models, the $K_r(\theta)$ at various suctions were estimated applying SMC experimental data and RETC software. RETC as a computer program is usually used to analyze the soil water retention and hydraulic conductivity functions of unsaturated soils which are key parameters in any quantitative description of water flow into and through the unsaturated zone of soils¹.

Statistical Criteria: Regression analysis using SPSS 15 was applied to adopt linear regression. Table 2 depicts the number of data pair's which were applied for regression adoption in each soil texture class. Finally, the following criteria beside correlation coefficients (R) were employed for the comparison proposes.

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^n (X_{mi} - X_{pi})^2 \right]^{1/2} \quad [4]$$

$$GMER = \exp \left(\frac{1}{n} \sum_{i=1}^n \ln \varepsilon_i \right) \quad [5]$$

$$GSDER = \exp \left[\frac{1}{n-1} \sum_{i=1}^n [\ln \varepsilon_i - \ln GMER]^2 \right]^{1/2} \quad [6]$$

¹<http://retc.software.informer.com/6.0/>.

$X_{m,i}$ and $X_{p,i}$ refer to the measured and predicted $K(\theta)$ at specified suctions or water contents, respectively, and ε_i denotes their ratio.

$$\varepsilon_i = \frac{X_{p,i}}{X_{m,i}} \quad [7]$$

The root mean square error (RMSE) would be equal to zero if the predicted and measured $K(\theta)$ for the all examined samples were equal. Geometric mean error ratio (GMER) and geometric standard deviation of error ratio (GSDER) were also applied as the reliability criteria proposed by Wagner *et al.* (2001) for the $K(\theta)$ prediction.

RESULTS AND DISCUSSION

Physical characters of 22 examined soils were depicted by Table 1. With a coefficient of variation (CV) 184.2%, K_s have the greatest variation among the selected characters. Such a variation in K_s seems primarily has been originated from the large variations in organic matter content and texture (particularly sand, CV=55.7%) among the examined soils. The CV as large as 190% has been documented and reported (Hillel 2004) for the soil populations.

Values of the measured $\log K_r(\theta)$ ($= \kappa(\theta)/K_s$) were plotted vs. $\log K_a$. The regression parameters (a and b) and correlation coefficients (R) of the all 22 examined soils are

presented by Table 1. The R ranged between 0.884 and 0.999. Excluding soils number 8, R values of greater than 0.915 indicate a very close and highly significant ($P < 0.01$) correlation between $K_r(\theta)$ and K_a , and implies that a reliable prediction of $K_r(\theta)$ from K_a is promising. For soil number 8, large fraction of macro-pores probably caused slightly lower R between K_a and $K_r(\theta)$. Negative slopes (b) demonstrate that with increasing K_a (decrease in water filled pores) $K_r(\theta)$ diminishes. The logarithmic nature of the regression implies that the rate of decrease in $K_r(\theta)$ is much rapid than the rate of increase in K_a . This is expected because of exponential or power dependence of $K(\theta)$ to θ (Hillel, 2004). The slope b ranged from -1.77 to -4.320 and the values of intercept a ranged between -9.26 and -16.18 except for soils number 6 and 22. The given a and b for soils number 6 and 22 were clearly out of those reported ranges (Table 1). For soil number 22, it seems to be due to higher shrinkage of core samples during the K_a measurement. Space developed between the walls of soil core and its cylinder at suctions greater than 30 kPa led to unrealistic high K_a values. But there seems no clear reason for soil number 6. With large number of soils, the regression coefficients a and b might be correlated to some soil physical characteristics such as texture, D_b , mean weight diameter (MWD) and etc., and be directly predictable from them. These aspects require more investigation.

TABLE 1. Some physical characters and the regression and correlation coefficients (a , b and R) between $\log K_r(\theta)$ and $\log K_a$ for the 22 examined soils. $K_r(\theta)$ and K_a denote relative water and air permeability's measured at 0-100 kPa suction range.

Soil No.	Soil texture	Sand %	Silt %	D_b (Kg m ⁻³)	K_s (m sec ⁻¹)	Θ_s %	b	a	$R^{\pm}$	N
1	Sandy loam*	53.0	30.0	1460	2.10E-05	41.4	-3.925	-15.17	0.984	5
2	Silty loam*	19.0	64.0	1390	5.97E-06	42.2	-2.122	-10.03	0.915	7
3	Loam*	34.0	41.0	1360	1.33E-06	59.1	-2.955	-11.74	0.962	7
4	Loam*	41.0	36.0	1390	1.36E-06	52.4	-2.632	-10.95	0.952	7
5	Silty Clay Loam**	18.0	43.0	1270	1.86E-06	54.0	-2.103	-9.263	0.918	7
6	Silty clay**	10.0	44.0	1230	4.75E-06	56.3	-5.525	-18.68	0.967	7
7	Loam*	38.0	42.4	1470	1.28E-05	55.0	-4.289	-16.18	0.922	7
8	Sand*	89.5	5.3	1490	8.16E-05	42.6	-4.175	-14.57	0.884	7
9	Clay loam**	24.8	43.4	1550	6.67E-07	40.1	-3.239	-10.82	0.981	7
10	Sandy loam*	67.3	22.0	1520	1.19E-05	41.1	-4.320	-15.15	0.976	7
11	Sandy clay loam**	64.2	8.6	1620	5.59E-06	65.2	-3.077	-12.80	0.999	5
12	Sandy clay loam**	59.0	13.1	1630	3.12E-06	65.4	-2.389	-10.84	0.986	5
13	Silty clay**	14.0	40.0	1510	1.46E-06	73.4	-2.286	-10.07	0.964	5
14	Silty clay**	18.0	42.0	1550	2.45E-06	75.6	-2.261	-10.12	0.973	5
15	Sandy clay loam**	59.9	15.4	1390	5.83E-06	62.1	-3.502	-12.91	0.967	5
16	Loam*	41.0	46.7	1280	1.20E-05	75.6	-2.844	-12.61	0.994	5
17	Silty loam*	22.8	51.7	1440	3.24E-06	79.0	-2.795	-12.00	0.990	5
18	Loam*	31.8	48.7	1540	6.24E-06	66.0	-1.770	-10.19	0.990	5
19	Loam*	30.1	46.0	1480	6.03E-06	78.0	-3.604	-13.64	0.982	5
20	Silty loam*	25.8	53.7	1500	4.74E-06	82.0	-2.091	-10.58	0.978	5
21	Silty clay**	15.8	41.1	1460	1.65E-06	67.0	-3.102	-11.30	0.989	5
22	Loam*	46.5	33.3	1460	6.75E-06	64.0	-11.10	-23.87	0.956	5
All soils	-	-	-	-	-	-	-2.540	-10.92	0.820	128
CV (%)	-	55.7	41.4	6.8	183.7	12.4	40.3	14.3	18	-
Mean	-	37.41	36.9	1450	9.19E-06	0.482	-3.160	-12.25	0.956	-

K_s was measured by constant (*) and falling (**) head methods. N : number of data points

± All the obtained R were significant at $P < 0.01$

Regression between $\log K_r(h)$ and $\log K_a$ for all 22 soils in the range of 0 to 100 kPa is depicted by Figure 1. The overall slope (b) and intercept (a) are -2.54 and -10.93, respectively which are close to the their corresponding mean values in Table 1.

$$\log K_r(\theta) = a \log K_a + b \quad [8]$$

The above equation is similar to that found by Loll *et al.* (1999) relating K_s to K_a measured at a fixed -10 kPa matric potential. The $R = 0.820$ for all 22 soils is relatively lower than those R for the individual soils (Table 1), implying the degrees of dependence of $K_r(\theta)$ to K_a among 22 soils are not the same.

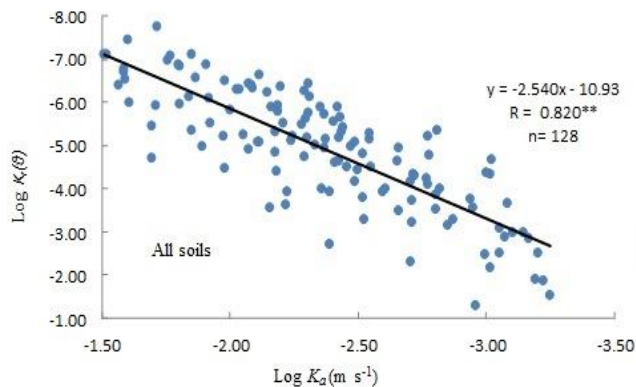


FIG 1: Regression equation and coefficient of correlation (R) between relative water ($K_r(\theta)$) and air (K_a) permeability for the all 22 soil cores

Table and Figure 2 show that $K_r(\theta)$ was better correlated to K_a when soils were grouped according to their textural classes.

According to Table 2, high R for each soil texture class shows that the obtained a and b can be used to predict $K_r(\theta)$ satisfactorily from the measured K_a in other soil with the same texture. There is also no particular trend in the variation of R or a and b of the regression equations with soil textural class. For loam soils, the measured data of $K_r(\theta)$

TABLE 2. The regression^y and correlation coefficients (a , b and R) between $\log K_r(\theta)$ and $\log K_a$ in eight soil textural class. $K_r(\theta)$ and K_a denote relative water and air permeability's measured at 0-100 kPa suction range.

Textural class	Number data pairs	a	b	R^2
Sandy loam	12	-4.12	-15.16	0.961
Silty loam	17	-2.34	-10.87	0.925
Loam	36	-3.02	-12.55	0.936
Silty Clay Loam	7	-2.10	-9.26	0.842
Silty clay	22	-3.29	-12.54	0.947
Sand	7	-4.18	-14.57	0.781
Clay loam	7	-3.24	-10.82	0.963
Sandy clay loam	15	-2.99	-12.18	0.969
Mean	-	-3.16	-12.25	0.915

^y: $\log K_r(\theta) = a \log K_a + b$

and K_a of soil number 22 were neglected to compute a and b because of its mentioned problem during the K_a measurements.

For evaluating the reliability of the prediction, three statistical criteria were computed and presented in Table 3. First, the $K_r(\theta)$ were predicted by the using obtained a and b for each soil texture classes. Then they were compared with measured data. Values of RMSE ranged from 0.175 to 0.959 except soil number 22. The value of RMSE for soil number 22 was 1.955 (Table 3). The lower RMSE shows the more reliability of model. Doussan & Ruy (2009) and Neyshabouri *et al.* (2013) predicted $K(\theta)$ by using soil bulk electrical conductivity and matric potential or PSD with RMSE about 1. Wagner *et al.* (2001) have also compared some PTFs to predict $K(\theta)$ and the best PTF resulted in RMSE = 1.28 to 2.96.

Other criteria used for evaluating the reliability of prediction are G_{MER} and G_{SDER} . The G_{MER} values smaller or greater than unit value, respectively, implies under or over-prediction relative to the experimental values. As G_{SDER} deviates from one, the reliability of the prediction decreases. For all the soils except soils number 3, 4, and 22, obtained G_{MER} were almost 1, the closet value of G_{MER} to unity means the highest reliability of $K_r(\theta)$ prediction. Soils number 3, 5 to 8, and 22 had the less prediction reliability according to their G_{SDER} values. Criteria in Table 3 show the highest and lowest reliability for soil number 12 and 22, respectively.

TABLE 3. Reliability criteria* ($RMSE$, G_{MER} , G_{SDER}) for the $K_r(\theta)$ predicted from measured K_a .

Soil No.	RMSE	G_{MER}	G_{SDER}
1	0.601	0.89	1.04
2	0.485	1.06	1.13
3	0.619	1.17	1.18
4	0.605	1.12	1.14
5	0.375	1.01	1.16
6	0.653	1.00	1.20
7	0.630	0.95	1.16
8	0.690	1.00	1.20
9	0.226	0.99	1.08
10	0.493	1.11	1.08
11	0.371	0.94	1.02
12	0.197	1.01	1.03
13	0.275	0.99	1.07
14	0.252	0.97	1.06
15	0.440	1.05	1.07
16	0.482	0.92	1.05
17	0.175	0.99	1.03
18	0.959	0.85	1.18
19	0.287	1.04	1.05
20	0.359	0.95	1.06
21	0.398	1.07	1.06
22	1.955	1.32	1.13

* The lowest values for $RMSE$ and the nearest values of G_{MER} and G_{SDER} to 1 indicate the most reliable prediction of $K_r(\theta)$.

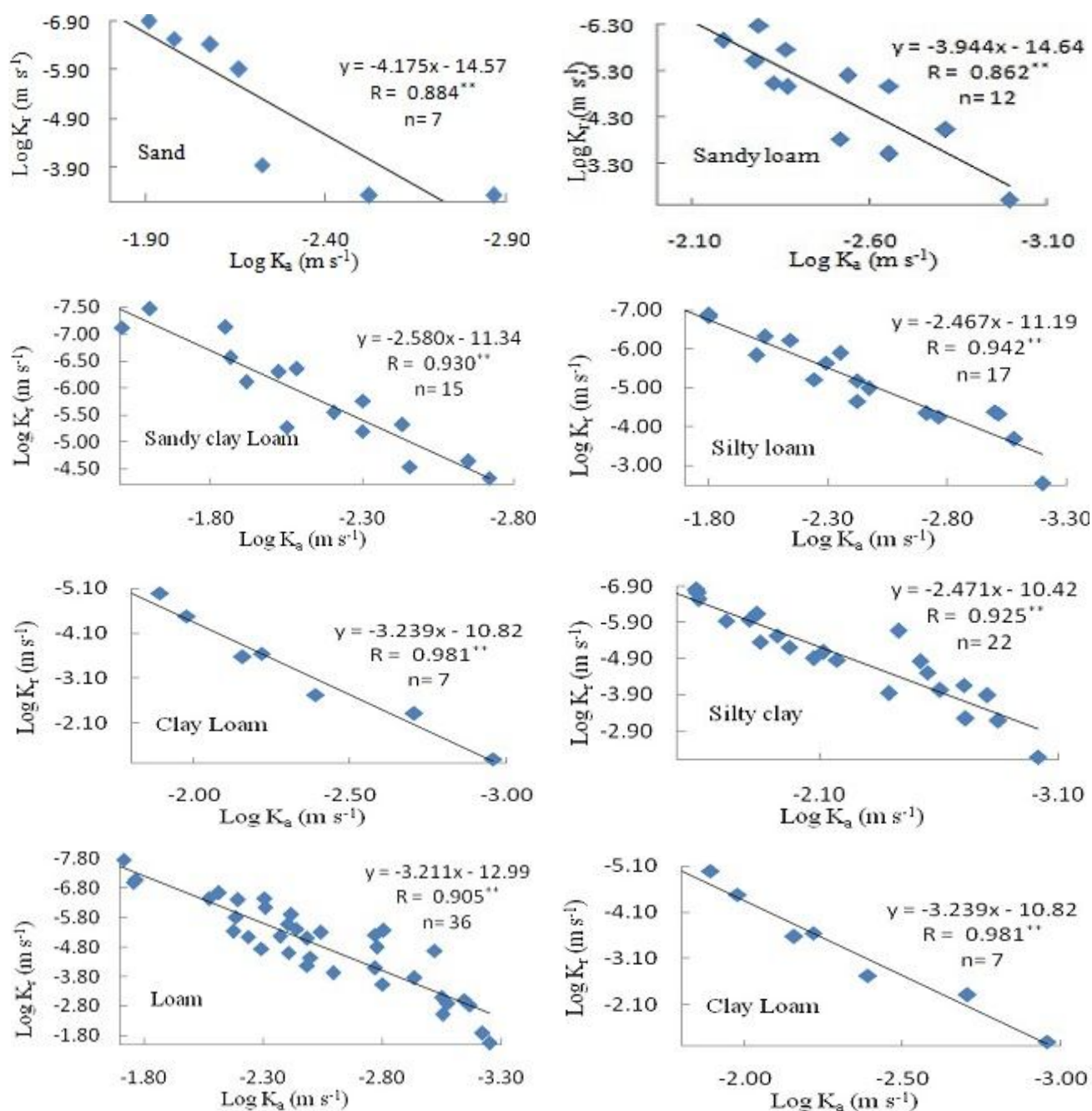


FIG 2: Regression equation and correlation coefficients (R) between relative water ($K_r(\theta)$) and air (K_a) permeability for different soil texture

Table 4 depicts the averages of three reliability criteria computed for comparing the predicted and measured $K_r(\theta)$ by using our proposed model and van Genuchten and Brooks-Corey models (van Genuchten, 1980). To predict $K_r(\theta)$ by our proposed model, the reported regression coefficients (a and b) in Table 2 were used. For van Genuchten and Brooks-Corey models the $K_r(\theta)$ at various suctions were estimated by using SMC experimental data and RETC software. Average $RMSD$ of 0.651 is much lower for the regression method implying

that $K_r(\theta)$ has been predicted with greater reliability than the two methods.

TABLE 4. Comparison of the prediction reliability of $K_r(\theta)$ from measured K_a and from van Genuchten and Brooks-Corey models (van Genuchten, 1980).

Prediction method	Average of $RMSD$	$1 - \frac{1}{n} \sum_{i=1}^n GMER_i$	Average of $GSDER$
van Genuchten-Mualem	1.053	-0.022	1.207
Brooks-Corey-Mualem	0.996	0.200	1.259
Regression method (from K_a)	0.651	-0.019	1.099

The second criterion for comparing the reliability of the prediction was *GMER*. Value of the expression $1 - \frac{1}{n} \sum_{i=1}^{22} GMER_i$ equal to 1 corresponds to an exact match between the measured and predicted $K_r(\theta)$. It being >1 implies over-prediction and <1 under prediction of $K_r(\theta)$ relative to the measured values. Table 4 again reveals that $K_r(\theta)$ predicted from K_a are more reliable than those predicted by van Genuchten and Brooks-Corey models that currently are employed in many studies. Negative value for implies $1 - \frac{1}{n} \sum_{i=1}^{22} GMER_i$ that van Genuchten model and also our regression model for 22 soils produced slightly under prediction where as Brooks-Corey slightly over prediction of $K_r(\theta)$. The proposed model had the lowest average value of *GSDER* for the 22 examined soils compared to those predicted by the two other models.

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CONCLUSIONS

- 1- For the 22 examined soils results revealed an existence of strong and significant ($P < 0.01$) correlation between K_a and $K_r(\theta)$ in the range of 0 to -100 kPa matric potential.
- 2- If the relationship for the large number of soils could be generalized, it appears a very effective way for $K_r(\theta)$ prediction.
- 3- Reliability of the estimates turned to be better than the well known models such as van Genuchten or Brooks-Corey.
- 4- Possibility of determining the regression equation coefficients relating $K_r(\theta)$ to K_a from the easily measured soil attributes needs further investigation.